Toward Characterizing the Neural Correlates of Component Processes of Cognition

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Johnson, M. R., & Johnson, M. K. (2009). Toward characterizing the neural correlates of component processes of cognition. In F. Rosler, C. Ranganath, B. Roder, & R. H. Kluwe (Eds.), *Neuroimaging of human memory.*
New York: Oxford University Press.

Introduction

Human cognition is a challenging area of inquiry. Ironically, the same intricacies of the mind that allow us to examine it also frustrate our progress; getting our thinking devices to understand their own mechanisms of operation sometimes feels like chasing one's shadow. The mind's flexibility requires many concepts to describe its many functions: For example, in the domain of memory, we use different terms for "remembering" how to ride a bicycle and "remembering" the events of the day the training wheels came off (procedural vs. declarative memory [Cohen & Squire, 1980]), or for remembering the phone number we just looked up (working memory [Baddeley, 1992; Baddeley & Hitch, 1974]) and our phone number from childhood (long-term memory). We categorize memory by its informational content (e.g., episodic vs. semantic memory [Tulving, 1983]), by the types of processes we think are engaged (e.g., familiarity vs. recollection [Atkinson & Juola, 1974; Jacoby & Dallas, 1981; Mandler, 1980; Tulving, 1985]; shallow vs. deep encoding [Craik & Lockhart, 1972]; or perceptual vs. reflective processing [Johnson & Hirst, 1991]), or by the brain regions that are involved (e.g., the medial temporal lobe vs. the basal ganglia [Poldrack & Packard, 2003; Poldrack & Rodriguez, 2004]).

Such broad categorizations of memory are not necessarily mutually exclusive; for instance, whether one is able to recollect a stimulus or merely recognize it as familiar may have something (but not everything) to do with whether it was initially encoded deeply or shallowly (see Yonelinas, 2002). In turn, such seemingly different subjective experiences as a feeling of familiarity or of more embellished recollection may involve partially overlapping brain structures. A closely related issue specific to process-oriented approaches is that key concepts may be complex and involve multiple sub-processes. For example, even simple working memory tasks require encoding, maintenance, updating, and selection processes. One such task sometimes used to operationalize the process of "working memory" is the N-back task, which minimally requires one not only to perceive the features of a stimulus, construct an internal representation of it, and add that representation to an existing queue of N previously presented stimuli, but also to compare the first and last representations to decide if they are the same, recall the appropriate action to take, make a button press or other overt response, and remove the oldest representation from the queue. Furthermore, some of these sub-processes could easily be shared with a number of other cognitive tasks which may or may not be considered "working memory" tasks per se. Also, as the complexity of a task grows, there is the increasing likelihood that different people will use different strategies (i.e., differing combinations or sequences of component processes) to perform the task (Johnson et al., 2005). Thus, for multiple reasons, the greater the complexity of a task or a proposed cognitive process, the more difficult it may be to characterize. At the same time, general concepts used to characterize mental activity during complex tasks, for example, "working memory," "executive function," and "cognitive control," likely share some or many of the same underlying cognitive and neural components.

While general constructs such as working memory, executive function, and cognitive control focus attention on important domains and help organize findings, researchers also recognize the importance of unpacking these complex ideas into constituent elements (e.g., structures or processes): for example, the work of Baddeley and colleagues in characterizing the phonological loop, visuo-spatial sketchpad, and central executive subcomponents of working memory (Baddeley, 1984, 1996; Baddeley, Lewis, & Vallar, 1984; Baddeley & Lieberman, 1980; Salame & Baddeley, 1982) or the work of Cohen, Carter and others in dissociating elements of cognitive control, particularly the role of the anterior cingulate cortex (ACC) in detecting conflict (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Carter et al., 1998; Kerns et al., 2004; MacDonald, Cohen, Stenger, & Carter, 2000). In our lab, we have found it useful to adopt a component-process approach, using a model that defines a set of basic "building blocks" of cognition that, when combined, could form the many more complex operations of which the mind is capable. Here, we first provide an overview of this model and then describe studies using neuroimaging to test and more completely characterize its component processes.

A Component-Process Model: The MEM Framework

The framework we have used to guide our investigation of the neural correlates of cognition is the Multiple-Entry, Modular (MEM) framework (Johnson, 1992; Johnson & Hirst, 1993; Johnson & Reeder, 1997). At different times, MEM has been discussed in the context of a "memory" model (Johnson, 1992) or a model of "cognition" more generally construed (Johnson & Reeder, 1997) because it is both: One of the core features of MEM is that each processing component is assumed to create memory records of its own processing. Thus, there is no distinction in MEM between components that store memory representations and those that perform ongoing information processing. Though this idea was initially articulated in a primarily cognitive context (Johnson, 1983; Kolers & Roediger, 1984), work in the neurosciences and in computational modeling has provided support for the idea that long-term storage of memory representations of a stimulus is mediated in cortex by changes in synaptic strength in the circuits that were initially used to perceive and/or think about that stimulus (McClelland, McNaughton, & O'Reilly, 1995; Mishkin, 1982; Miyashita, 1993; Squire & Alvarez, 1995).

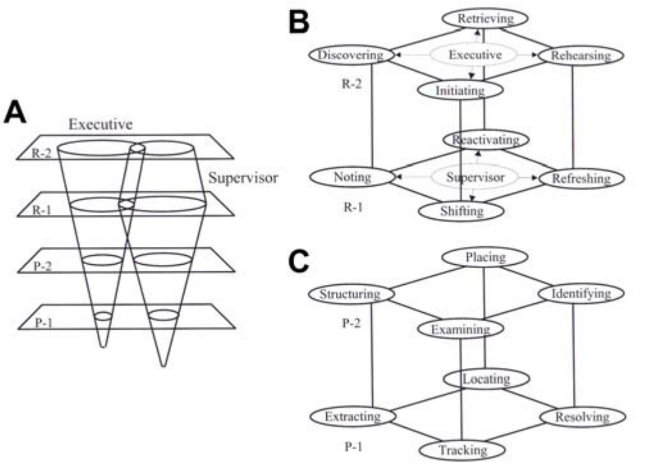

Figure 1. The MEM architecture. (A) Cones representing executive and supervisor agendas. The width of a cone as it passes through the R-2, R-1, P-2, and P-1 subsystems indicates the degree to which each type of agenda is involved with processing at these levels. (B) Eight reflective component processes associated with R-2 and R-1 levels of processing. (C) Eight perceptual component processes associated with P-2 and P-1 levels of processing.

In the MEM architecture (Figure 1), the most fundamental distinction is between components that serve Perceptual (P) versus Reflective (R) forms of processing (Johnson, 1983, 1997; Johnson & Hirst, 1993; Johnson & Reeder, 1997). These are organized into two perceptual subsystems (P-1 and P-2) shown in Figure 1C and two reflective subsystems (R-1 and R-2) shown in Figure 1B. Each of the four subsystems includes component processes. P-1 processes may be, in a sense, considered "lower-level" versions of P-2 processes, and likewise R-1 processes may be considered "lower-level" versions of R-2 processes. As represented by the vertical placement of the planes in Figures 1B and 1C, the subsystems reflect a hypothesized hierarchy related to their evolutionary history and the degree to which the processes in each generate an experience of conscious awareness or control: P-1 processes are associated the least with conscious awareness/control, followed by increasing awareness/control from P-2, R-1, and R-2 processes, respectively.

Low-level perceptual processes (P-1) include *locating* stimuli, *resolving* stimulus configurations (e.g., detecting edges), *tracking* stimuli, and *extracting* invariants from perceptual arrays (e.g., cues specifying the rapid expansion of features in the visual field that indicates a stimulus is coming toward you). Although, as noted above, we are generally unaware of the processing that occurs at the P-1 level, the learning that occurs within P-1 can allow us to improve in, for example, understanding an unfamiliar accent or catching a baseball. Higher-level perceptual processes (P-2) include *placing* objects in spatial relation to each other, *identifying* objects, *examining* or perceptually investigating stimuli (e.g., guided by perceptual schemas), and *structuring* or abstracting a pattern of organization from temporally extended stimuli (e.g., syntactic structure from language). These processes generate and allow us to learn about our phenomenal perceptual world of objects and events (e.g., that round objects roll and apples are often red and can be eaten).

The MEM reflective R-1 and R-2 subsystems propose processes that allow us to sustain, revive, organize, and manipulate information that may no longer be present in the immediate perceptual environment. R-1 component processes include *noting* relations among stimuli or thoughts, *shifting* attention, *refreshing* active information so that it is foregrounded relative to competing information, and *reactivating* information that is not currently active. The proposed component processes of R-2 are conceptually analogous to those in R-1, but are more deliberate (controlled). They include *discovering* (e.g., looking for relations), *initiating* (processes or sequences of processes), *rehearsing* (to keep information active), and *retrieving* (e.g., remembering via systematic self-cuing). Comparing *reactivating* versus *retrieving* illustrates the difference between R-1 and R-2 processes. One example of *reactivating* is when a memory record is (non-deliberately) activated by a partial match between ongoing reflection or perception and records of previous processing, for example, when a current thought or stimulus brings to mind relatively automatically the memory of a previous similar situation or stimulus. In contrast, an example of *retrieving* is when a person deliberately uses some strategy to systematically search their memory. For example, in trying to retrieve the name of a restaurant, one might try to think of people who would likely have told them about a restaurant (Baddeley, 1982; Reiser, 1986).

Importantly, though in MEM we refer to "component processes," "subsystems," or "modules," a central tenet of the framework is that complex behaviors are constructed from flexibly recruited combinations and interactions of such components. MEM components should not be construed as "modular" in the sense intended by Fodor (1983). MEM *agendas*, similar to the concepts of schemas, scripts, or plans (e.g., Miller, Galanter, & Pribram, 1960; Norman & Shallice, 1986; Stuss & Benson, 1986), coordinate and combine component processes to achieve one's goals (e.g., identify an object, recall a shopping list, plan one's weekend activities). Agendas may be specific or general, simple or complex, well-learned or newly formed; but in each case, an agenda constitutes a plan (e.g., representation of a goal) for cognition that includes one or more component subprocesses. In Figures 1A and 1B, *supervisor* refers to agendas that are predominantly active in subsystem R-1 and *executive* refers to those agendas predominantly active in subsystem R-2. Supervisor agendas tend to be simpler and more rote or schematized, whereas executive agendas are more complex, deliberate, and analytic. In both cases, agendas constitute the mechanisms of controlling cognition and monitoring outcomes.

Supervisor and executive agendas often invoke sequences of subprocesses that occur at multiple levels of processing. Hence, they are depicted as two cones in Figure 1A that pass through planes corresponding to the R-2, R-1, P-2, and P-1 subsystems. The width of each cone as it passes through a plane represents the degree to which executive or supervisor processes are presumed to recruit processes within that subsystem. Thus, although the primary domains of the supervisor and executive are subsystem R-1 and R-2, respectively, both supervisor and executive agendas are hypothesized to be able to influence, and draw upon, all four subsystems, although to different degrees. Importantly, supervisor and executive agendas are capable of influencing each other, as indicated by the overlap in the two reflective subsystems in Figure 1A. This feature of the MEM architecture provides a mechanism for self-reflection and other forms of complex cognition.

MEM is a mid-level model of cognition; MEM component subprocesses are not indivisible (in fact, see Johnson & Hirst, 1993, and Johnson & Reeder, 1997, for discussions of ways in which some component processes might be further decomposed). Rather, MEM attempts to provide a general framework for reducing the vast space of human cognition to combinations of a relatively small and manageable number of components. (In this endeavor, we express the implicit hope that human cognition might follow a Pareto principle of sorts; i.e., fully describing a system as complex and flexible as the human mind could require a "model" as complex as the system itself, but we can nevertheless aspire to create models that capture a large proportion of the mind's functions with a manageably small degree of complexity.) MEM also provides a means of organizing the results of investigations directed at more fine-grained levels of analysis than represented in MEM, namely by grouping finer subdivisions within a MEM component subprocess (e.g., within *rehearsing* or *identifying*). MEM is primarily a process-based model rather than a content-based one. Thus people are thought to be capable of performing operations like *tracking*, *identifying*, *reactivating*, etc., on a wide range of modalities of percepts and thoughts (e.g., auditory, pictorial, tactile, emotional, semantic). For example, one could further divide *identifying* into identifying based on visual information, identifying based on auditory information, etc.

MEM and Neuroimaging

Just as conceptual psychological models like MEM can be informed by and help provide a context for investigating and understanding findings from neuropsychological studies of brain damaged patients (e.g., disrupted explicit memory and preserved acquisition of emotional associations, Johnson, Kim, & Risse, 1985), there should be a synergistic relation between such models and findings from neuroimaging. Research using neuroimaging has grown explosively since the early- to mid-1990s, and the knowledge base of replicable findings has grown to the point that we can begin to reason bidirectionally about the relationships between cognition and brain activity. Although there is some controversy over the productivity of the relation between cognitive psychology and neuroimaging, (e.g., Uttal, 2001; but see Henson, 2005), the final judgment will rest on how much this partnership contributes to a cumulative science of mental function. The advantages and potential limitations of an additional source of new hypotheses and constraints in theorizing (i.e., neuroimaging evidence) are analogous to advantages and limitations following from procedures and traditions of other approaches (e.g., mathematical models; computer simulations). In any event, the challenges of using neuroimaging techniques such as functional magnetic resonance imaging (fMRI) to adduce evidence about theoretical constructs are not in principle greater or different than those of using cognitive/behavioral methods. Attempting to find the correspondence between cognitive operations and brain activity shares many problems with attempting to operationalize theoretical cognitive processes in cognitive-behavioral studies. Just as it is difficult to find a "pure" behavioral index of a particular cognitive process, it is also difficult to relate tasks to activated brain regions or interactions between regions in a one-to-one manner. And, just as we can classify cognitive processes at different levels of abstraction, brain structures can also be classified at different levels (e.g., genes, molecules, cells, circuits, gyri, or cerebral hemispheres). In both domains the challenge is to find appropriate levels of abstraction that capture a maximal amount of variance in the observed data with a minimal amount of theoretical complexity. When the structure in question is large, it may be that different theoretical labels can describe similar amounts of variance, producing multiple models of roughly equal validity. For example, the idea that prefrontal cortex (PFC) is involved in cognitive control (Miller & Cohen, 2001) and the idea that PFC represents information in working memory (Courtney, 2004) may be equally apt accounts at a general level of description.

With resolutions typically on the order of a few millimeters, current functional neuroimaging methods afford a moderate degree of spatial discriminability, reliably localizing regions of maximal activity to a portion of a particular gyrus/sulcus, but not to a particular cell layer or cortical column. We began with the question of whether the mid-level spatial resolution afforded by fMRI would be appropriate for the mid-level "conceptual resolution" of a cognitive model like MEM.

The *Refresh* Process

We have initially focused our neuroimaging studies on the component process of *refreshing*: the act of thinking of, or foregrounding, a representation of a thought or percept which was activated just a moment earlier and has not yet become inactive. We reasoned that if fMRI can provide a neural picture of this relatively simple process, we can then test hypotheses about other processes to assess whether distinct component processes as proposed in MEM could be dissociated neurally.

We also hypothesized that refreshing is likely to play a role in more complex constructs frequently discussed in the neuroimaging literature, especially working memory and executive function. This is because refreshing acts as both a basic maintenance process (i.e., refreshing a representation has the effect of prolonging its activation) as well as a manipulation process (i.e., by virtue of selecting or biasing one representation relative to others [Johnson et al., 2005; Raye, Johnson, Mitchell, Greene, & Johnson, 2007]). By characterizing the behavioral and neural correlates of refreshing, we hoped to shed further light on how refreshing contributes to more complex tasks, and perhaps explain in terms of shared component processes some of the common brain activity observed in neuroimaging studies of diverse tasks (e.g., Duncan & Owen, 2000).

Behavioral Correlates of Refreshing

In a behavioral study of the refresh process, Johnson and colleagues (Johnson, Reeder, Raye, & Mitchell, 2002) projected words onto a computer screen one at a time, and participants were instructed to read and say all words aloud as quickly as possible. Response times were recorded using a voice key apparatus. Some words were presented only once (*read* condition), some were followed immediately by the same word again (*repeat* condition), and some were followed immediately by a dot (•) that signaled participants to think of the just-previous word and say it aloud (*refresh* condition). A surprise recognition memory test for the words from the three conditions, randomly intermixed with new words, was administered a few minutes after the conclusion of the incidental encoding task.

Two effects of primary interest were observed. First, whereas participants were faster to say words in the *repeat* condition than in the *read* condition (consistent with repetition-priming effects [Tulving & Schacter, 1990]), they were slower to say words in the *refresh* condition than in the *repeat* and *read* conditions. Thus, a clear behavioral dissociation was observed between the R-1 process of *refreshing* and the P-2 process of *identifying* (the MEM perceptual subprocess most directly tested by the *read* and *repeat* conditions), given similar conceptual content. These results suggested that it could be possible to dissociate these processes neurally as well. It is important to recognize that, even in a task as simple as this, the *refresh* condition probably involved additional component processes in that participants had to *note* the dot and *initiate* a refresh. However, a control experiment revealed no difference between response times in the *read* condition and a condition in which participants were instructed merely to say "dot" when the dot appeared, suggesting that the observed difference in response times between the *read* and *refresh* conditions was indeed primarily due to the process of refreshing word representations.

The second result of interest was greater recognition memory for words in the *refresh* condition than either the *repeat* or *read* conditions (and, as one would expect, greater memory for words in the *repeat* condition than in the *read* condition). This again demonstrates the dissociability of the refresh process from perceptual processes, and it is consistent with the MEM idea that separate (and thus potentially behaviorally distinguishable) memory records are created for information handled by each component subprocess. It is worth mentioning that later studies of the refresh process using different classes of stimuli sometimes show no advantage of *refresh* over *repeat* conditions for subsequent recognition memory (Johnson et al., 2005). This suggests that people are better able to refresh some stimuli than others, or that during the recognition memory test, people draw upon memory records generated by different MEM component processes to varying degrees depending on the type of stimulus (e.g., perhaps people rely relatively more on R-1 and R-2 records when tested with word stimuli but relatively more on P-1 and P-2 records for pictures of people or abstract patterns).

Basic Neural Correlates of Refreshing

Early fMRI investigations of the refresh process confirmed our initial hypothesis that it would be possible to distinguish relatively basic component subprocesses of cognition from one another via functional neuroimaging. Raye and colleagues (Raye, Johnson, Mitchell, Reeder, & Greene, 2002, Experiment 1) performed an event-related fMRI study with similar conditions to those described above in the behavioral study by Johnson and colleagues (2002). As shown in Figure 2A, there were three conditions (*read*, *repeat* and *refresh*), randomly intermixed. In the *read* condition, the critical item was preceded by a different, novel word; in the *repeat* condition, the critical item was preceded by the same word; and in the *refresh* condition, a dot cued participants to think back to the just-presented word. The initial part of the hemodynamic activity should thus be comparable (reflect reading a word) in all conditions, and differences in hemodynamic activity between conditions should reflect differences in processing occurring during the second part of the trial, associated with reading a word for the first time, reading a word again, or refreshing a word.

Regions in which activity in the *refresh* condition was significantly greater than in both the *repeat* and *read* conditions included a region of left dorsolateral prefrontal cortex (DLPFC; middle frontal gyrus, Brodmann area 9; see Figure 2B) as well as two left parietal regions. The refresh-related DLPFC activity was of particular note due to that region's strong associations with working memory and general executive functioning, in which the refresh process is presumed to play a part. Raye and colleagues suggested that reported DLPFC activity in various working memory tasks (e.g., Cohen et al., 1997; Petrides, Alivisatos, Meyer, & Evans, 1993; Smith & Jonides, 1999) may have been due, in part, to refresh-related activity. Experiments 2 and 3 reported by Raye et al. were control experiments intended to rule out alternative sources of the observed activity in DLPFC. Experiment 2 used a blocked design to verify that the observed activity was not due to task-switching (i.e., effects of performing different conditions from trial to trial). Experiment 3 demonstrated that refresh-related DLPFC activity was not due to the need to interpret a symbolic stimulus (i.e., the dot cue). Participants merely read or refreshed words silently, indicating that reflection is sufficient to identify refresh-related changes in neural activity without the need for an overt response.

Several subsequent fMRI studies of refreshing (Johnson, Mitchell, Raye, & Greene, 2004; Johnson, Raye, Mitchell, Greene, & Anderson, 2003; Johnson et al., 2005) confirmed and extended the results found by Raye and colleagues (2002). For example, a study investigating age-related differences in refreshing using the same design identified the same refresh-related DLPFC region in a new sample of young adults (compare Johnson et al., 2004, and Raye et al., 2002). Johnson and colleagues (2003) identified somewhat different regions of left DLPFC associated with refreshing words, objects, and abstract patterns, suggesting that information type affects the part of DLPFC that is maximally activated by refreshing. Across studies with different types of stimuli (e.g., auditory and visual words, objects, abstract patterns, pictures of people, locations), refresh-related activity has consistently been observed in left lateral PFC, primarily distributed along the middle frontal gyrus (see Figure 2D). Refresh-related activity has also been seen, but less often, in right PFC. The exact location of left PFC activity and the presence and extent of right-hemisphere refresh activity may depend not only on the type of information refreshed but also on the other types of information being refreshed in the same study and the other types of operations being engaged (Johnson et al., 2005).

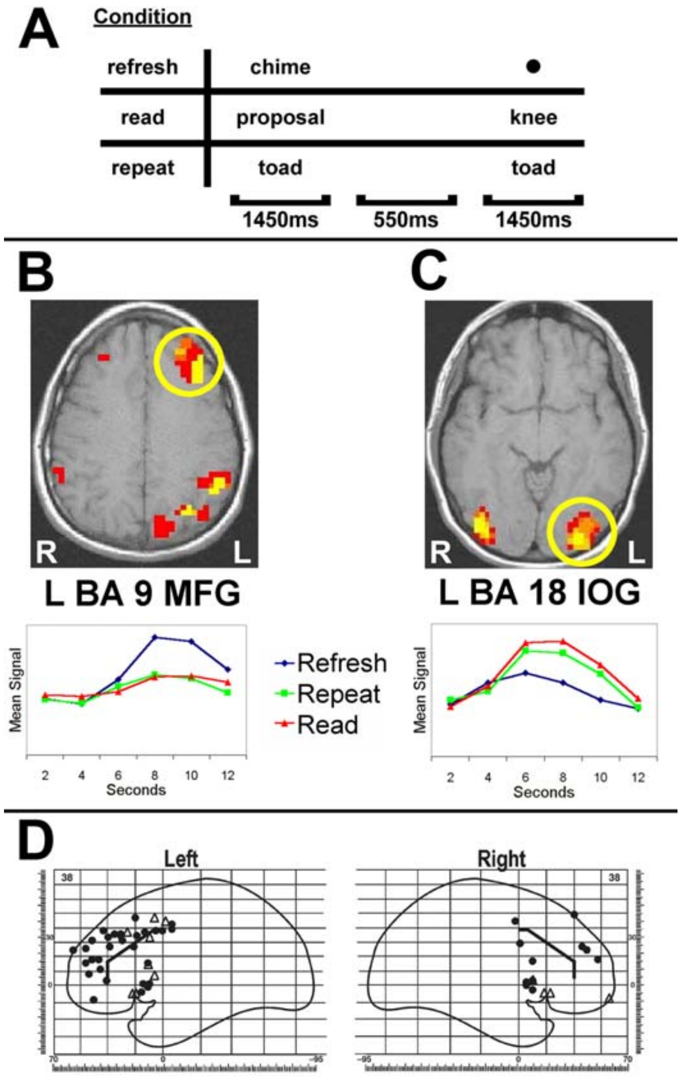

Figure 2. (A) Examples of the *refresh*, *read*, and *repeat* conditions used in Raye et al. (2002) and other studies. (B) Greater activity for refreshing than reading or re-reading word stimuli in left DLPFC. Adapted from Raye et al. (2002). (C) Greater activity for reading or re-reading word stimuli than refreshing in left occipital cortex. Adapted from Raye et al. (2002). (D) Maxima of refresh-related activity plotted for several studies. Circles indicate refreshing a single item, triangles indicate refreshing one of three items. Middle frontal gyrus is above the line, inferior frontal gyrus below. Adapted from Johnson et al. (2005). BA: Brodmann area, IOG: inferior occipital gyrus, MFG: middle frontal gyrus.

Distinguishing Activity Associated with Different Component Reflective Processes

It is important to compare the network of areas that are associated with refreshing to those associated with other reflective component processes, to more precisely identify which activation patterns are specific to the process of refreshing, which are specific to other component processes, and which are shared. Observing different patterns of activation between refresh and other reflective component processes would suggest that the observed refresh-related activity is specific to that process. Conversely, similar patterns of activation between refresh and other reflective processes could suggest that, as they are operationalized, either (a) refreshing and other component processes invoke a common component such as process *initiation*, or (b) the two proposed component processes are not different, at least at the cognitive and neural levels of analysis afforded by the MEM framework and fMRI, respectively. Naturally, the comparison between refreshing and another component process could also yield a mixture of shared and distinct brain regions, or an outcome in which two processes might differ not in the areas activated but in the relative magnitude of activation in the same areas.

Johnson and colleagues (2003) compared the results of an fMRI experiment that included refreshing visually presented words and line drawings of objects (Experiment 1) with an experiment requiring participants to *note* (another R-1 process) whether or not a visually presented word or object was the same as one which had been presented previously (Experiment 2). The primary intent of analyzing these two data sets together was to examine whether PFC activity appeared to be functionally organized around the type of component process invoked (i.e., *refreshing* versus *noting*), the type of information involved (e.g., words versus drawings), a combination of both organizational schemes, or neither (that is, some PFC areas might be flexibly recruited for multiple component processes and types of information, and thus not exhibit organization by either process or type or information). The results of Experiment 1 identified separate (but nearby) areas in left DLPFC for *refreshing* words versus drawings, whereas the results of Experiment 2 identified separate (but nearby) areas of right PFC that were activated for *noting* the repetition of words versus drawings. The fact that different regions were activated for different materials (holding operation constant within each experiment) supported a role of information type in the functional organization of PFC. Furthermore, a statistical comparison of the two experiments revealed an area of left DLPFC that was active for *refreshing* (across information type) but not for *noting*. Thus, the results of this study supported a functional organization of PFC both by type of information and type of process.

Other findings have also indicated that activity in different areas within left PFC may be differentially involved in refreshing versus other R-1 component processes. Johnson and colleagues (2005) presented the results of a meta-analysis that identified refresh-related areas of frontal cortex by pooling data across several studies, which allowed them to examine task-related activity both in regions that typically occur and in regions that may not have been significant in each study when analyzed separately. Two areas of particular interest were a typical area of left DLPFC (middle frontal gyrus, Brodmann areas 9/6) similar to that reported by Raye and colleagues (2002) and a less frequently observed area of left anterior PFC (middle/superior frontal gyri, Brodmann areas 10/46). The DLPFC area showed greater variability in magnitude of activation across refresh studies compared to the anterior PFC area. This suggested that activity in the DLPFC area may reflect the nature of what is being represented whereas the anterior area may be serving a more general function such as process initiation. To test this hypothesis, Raye and colleagues (2007) performed an fMRI study in which brain activity in a *refresh* condition (as before, presentation of a word followed by a dot cuing participants to refresh the word) was compared to activation in an *act* condition (presentation of a word followed by a square cuing participants simply to press a button), and both were compared to a *read* condition (presentation of a word followed by another, different word).

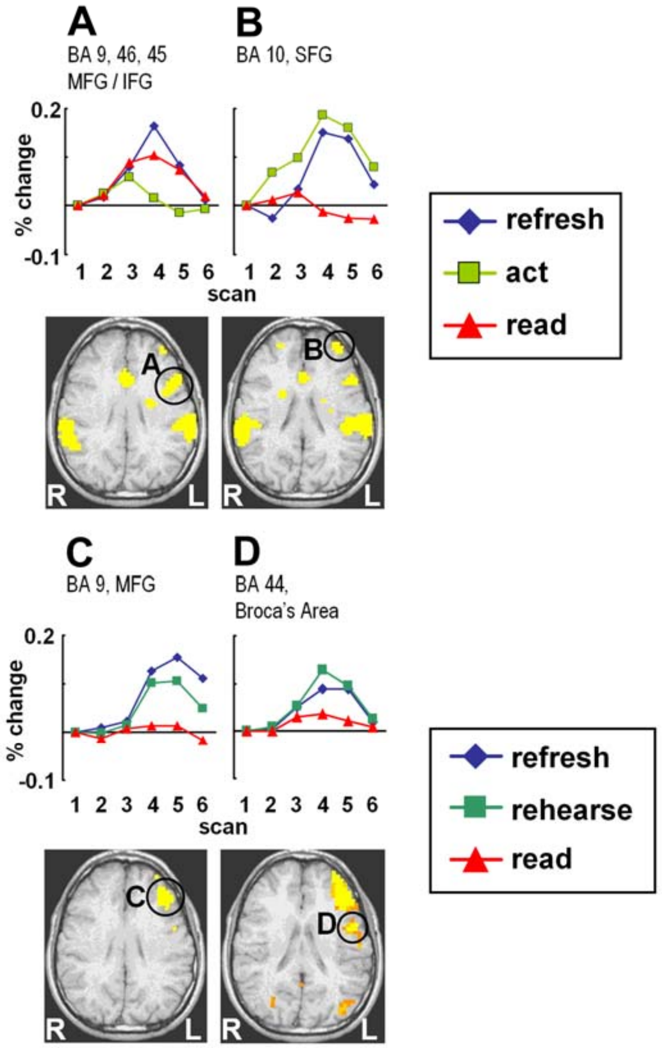

Figure 3. Data from Raye et al. (2007). (A) Greater activity for the *refresh* condition than the *act* condition in left DLPFC. (B) Similar activity for the *refresh* and *act* conditions in left anterior PFC. (C) Greater activity for the *refresh* condition than the *rehearse* condition in left DLPFC. (D) Greater activity for the *rehearse* condition than the *refresh* condition in Broca's area. All panels adapted from Raye et al. (2007). See text for details. BA: Brodmann area, IFG: inferior frontal gyrus, MFG: middle frontal gyrus, SFG: superior frontal gyrus.

Consistent with Raye and colleagues' (2007) hypothesis, an area of left DLPFC was more active for the *refresh* than the *act* condition (see Figure 3A).[1] This difference between the *refresh* and *act* conditions in left DLPFC is consistent with the hypothesis that this area is involved in foregrounding and/or maintaining a representation. In contrast, in a left anterior PFC area (superior frontal gyrus; Brodmann area 10, see Figure 3B) there was no difference in activity between the *refresh* and *act* conditions, although activity was greater in both than in the *read* condition, suggesting that left anterior PFC is associated with the component process of *initiating* rather than foregrounding a representation per se. Other investigators have emphasized the importance of DLPFC in selective attention, task management (e.g., maintaining a task context), or manipulation of information (e.g., D'Esposito, Postle, Ballard, & Lease, 1999; MacDonald et al. 2000; Miller & Cohen, 2001; Petrides, 2000; Smith & Jonides, 1999). All of these proposed DLPFC functions involve foregrounding some information so that it has a competitive advantage (is more available) or confers a competitive advantage over (biases, e.g., Miller & Cohen, 2001) other information. We have proposed that refreshing is one mechanism by which such foregrounding occurs. It has also been suggested that anterior PFC (or frontopolar cortex), is involved in processing internally generated information (Christoff & Gabrieli, 2000), establishing "task sets" (Passingham & Sakai, 2004), maintaining information about contexts and goals (Courtney, 2004), or monitoring and integrating subgoals (Braver & Bongiolatti, 2002). We have proposed that a common theme uniting these proposals is a shared demand for *initiating* (or *shifting* between) different agendas, or different active representations or stimulus features. In the case of studies contrasting refreshing with relatively automatic processes such as reading words, DLPFC may be sufficient. For more complex stimuli, or for negotiating between multiple non-automatic agendas (e.g., *refresh*, *act*), anterior PFC may be required.

A second experiment by Raye and colleagues (2007) compared *refreshing* to the R-2 process of *rehearsing*. For the *refresh* condition, a word was presented followed by the letter "V," cuing participants to refresh the visual aspect of the just-presented word. For the *rehearse* condition, a word was presented followed by the letter "S," cuing participants to subvocally say the just-presented word twice. In the MEM framework, *rehearsing* is a distinct component R-2 process that is located just above the R-1 process of refreshing (see Figure 1B). This proximity indicates some similarity in function – in this case, both are mechanisms for keeping representations active. However, refreshing is a simpler, briefer, and relatively more automatic process, while rehearsing (for verbal information) typically involves more deliberate, subvocal repetition, often of multiple items, over several seconds. As distinct processes, *refreshing* and *rehearsing* should exhibit some differentiation in their neural signatures. Previous studies have located activity related to subvocal rehearsal in left ventrolateral prefrontal cortex (VLPFC) and have distinguished it from other (e.g., storage and executive) components of verbal working memory (Awh et al., 1996; Chein & Fiez, 2001; Smith & Jonides, 1999), providing further support for the hypothesis that rehearse-related activity should be separable from refresh-related activity in left DLPFC. Of course, rehearsal studies typically involve several items, often presented visually and maintained (i.e., converted to a phonological code and cycled through repeatedly) over several seconds. Thus the contrast between thinking once briefly of the appearance of a just-seen stimulus, versus saying it twice subvocally, was intended to be a manipulation that would minimally engage a phonological loop but not result in substantial differences in "time on task" between conditions.

Raye and colleagues (2007; Experiment 2) found two areas of interest that were more active in the *refresh* condition than the *rehearse* condition: an area of left DLPFC (middle frontal gyrus, Brodmann area 9) and an area bridging the precentral and middle frontal gyri (Brodmann area 6). These regions were also both identified as refresh-related areas in the meta-analysis by Johnson and colleagues (2005). A third area of interest was also found that was more active in the *rehearse* condition than the *refresh* condition. It was located in the inferior frontal gyrus (Brodmann area 44/6), including Broca's area. It is worth noting that both the refresh- and rehearse-related areas of interest, though most active in their preferred condition, also showed some activity in the non-preferred condition, although none of the areas showed appreciable activity during the *read* condition. Thus, although the *refresh* and *rehearse* conditions were neurally differentiable from each other, they appeared to show some degree of common activity as well. This is consistent with the MEM hypothesis that the more complex processes along the vertical edges of the cubes in Figure 1 (i.e., those closer to the top of the figure) might, through evolution, be variations of or elaborations upon the more rudimentary processes along the same edge (i.e., those closer to the bottom of the figure). That is, some overlap in brain regions subserving functionally and phylogenetically related processes would be consistent with this speculation.

Raye and colleagues (2007) also reported results of functional connectivity analyses. In Experiment 1, activity in the left anterior PFC region, which was equally active for both *refresh* and *act* trials and appeared to subserve the initiation of non-automatic actions, was more strongly correlated with activity in left DLPFC during *refresh* trials and more strongly with activity in left pre- and post-central gyri during *act* trials. These analyses illustrate a primary assumption of most neuroimaging research: cognitive processes are transactions among regions (e.g., Friston, 1994; Horwitz, 1994; McIntosh & Gonzalez-Lima, 1994). The results also illustrate a primary goal: that once a satisfactory mapping between brain regions and component processes is achieved, data on interactions between brain regions may generate or confirm hypotheses about the interactions between cognitive processes. Here, the correlation results suggest that during *refresh* trials, as a function of the cue, *initiating* (associated with left anterior PFC) plays a role in recruiting *refreshing* (associated with left DLPFC) or, during act trials, plays a role in recruiting a motor response (associated with motor/somatosensory areas in left pre- and post-central gyri). These results are consistent with the predictions of the MEM framework and demonstrate the ways in which different component processes may work together in different circumstances. Of course this account remains a hypothesis to be verified with further studies.

Refreshing as an Executive Function

The above sections have primarily focused on identifying the fundamental neural correlates of the refresh process, distinguishing it from other component cognitive processes, and elaborating on its role in reflective (e.g., working memory) functions that involve both the maintenance and the manipulation of representations. The neuroimaging work described thus far has primarily focused on the prefrontal correlates of refreshing, given the historically strong associations between PFC and the kinds of controlled, executive and working memory functions that the proposed reflective processes in MEM support (e.g., Johnson & Reeder, 1997). For the purposes of the following discussion, we will group these working memory, cognitive control, and other reflective functions together under the general conceptual umbrella of "executive function."

Contemporary theories of PFC executive function (e.g., Miller & Cohen, 2001) suggest that the overarching purpose of the PFC is to direct thought (e.g., manipulate information) in the service of goals (or, in MEM terms, *agendas*) by sending signals to other areas of cortex that bias the flow of information and the patterns of neural activity in those areas. A related theory of working memory is that PFC helps to maintain active representations by modulating activity in the same posterior areas initially used in stimulus perception (Curtis & D'Esposito, 2003; Petrides, 1994; Ranganath & D'Esposito, 2005; Ruchkin, Grafman, Cameron, & Berndt, 2003). These views of executive function and working memory are consistent with the types of processes embodied in the MEM architecture's R-1 and R-2 level functions. If these theories are correct and if the *refresh* process is, as we believe, a basic component of executive function, we should not only find refresh-related activity in PFC but also evidence that refreshing can modulate activity in areas of cortex outside of PFC.

While we have previously reported refresh-related activity in areas beyond PFC, for example, parietal cortex and precuneus (e.g., Raye et al., 2002, 2007), these regions were not our primary focus. Recently, to more completely characterize the neural substrates of the refresh process and provide further evidence for refreshing as an executive function, M. R. Johnson and colleagues (M. R. Johnson, Mitchell, Raye, D'Esposito, & Johnson, 2007) conducted an fMRI study to determine whether refreshing a visual stimulus could modulate activity in posterior regions of cortex thought to primarily support visual perception (i.e., P-1 and P-2 processing). There were four conditions of primary interest, two *refresh* conditions and two *repeat* conditions. In all four conditions, participants initially saw a screen containing two pictures side-by-side; one picture was always of a face and the other of a scene. After a brief, 500 msec delay, in the *Repeat_S* and *Repeat_F* conditions, the scene (face) stimulus was shown a second time; in the *Refresh_S* condition, a dot appeared where the scene stimulus had been, cuing participants to refresh (think back to, visualize) the scene picture; and in the *Refresh_F* condition, a dot appeared where the face stimulus had been, cuing participants to refresh the face picture.

In this study, we also administered a localizer task in order to locate areas of posterior cortex that selectively responded more to either faces or scenes (relative to the other stimulus class) during perception. A priori regions of interest (ROIs) included the parahippocampal place area (PPA; Epstein & Kanwisher, 1998) and fusiform face area (FFA; Kanwisher, McDermott, & Chun, 1997), which were identified bilaterally for each participant. Additional ROIs identified in a group-level analysis included areas of bilateral precuneus, bilateral middle occipital gyrus, and bilateral retrosplenial cortex, all of which responded more during perception of scenes than during perception of faces, and an area of right inferior occipital gyrus, which responded more during perception of faces than during perception of scenes. After these areas were identified, their activity during the main refresh task was assessed to see if it was modulated by which representation was refreshed, that is, by comparing activity in the *Refresh_S* and *Refresh_F* conditions. We also compared activity in these regions between *refresh* and *repeat* trials to examine the relative influences of reflective and perceptual processing, respectively, on activity in posterior perceptual regions.

Refresh-related activity was observed in areas of both DLPFC and anterior PFC, replicating prior work and suggesting that participants were indeed performing the refresh task similar to previous studies. Modulatory effects (i.e., differential activity) from refreshing faces vs. scenes were observed in bilateral PPA (see Figure 4A), bilateral retrosplenial cortex, left middle occipital gyrus, and left precuneus (activity in the *Refresh_S* condition was greater than in the *Refresh_F* condition), and in right FFA and right inferior occipital gyrus (activity in the *Refresh_F* condition was greater than in the *Refresh_S* condition). Importantly, the *Refresh_S* and *Refresh_F* conditions contained identical perceptual input (an initial screen containing one face and one scene, followed by a second screen showing only a dot) with the only difference being whether the dot indicated that participants should refresh the face or the scene. Thus, these results indicate that a brief, basic act of reflection (e.g., refreshing a face or a scene) is sufficient to induce modulatory activity in posterior regions of cortex that activate preferentially to that type of information during perception.

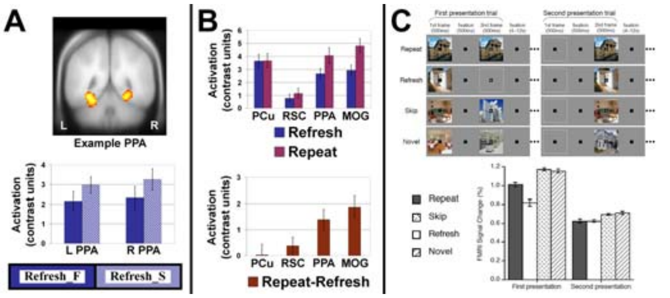

Figure 4. (A) Evidence of modulatory refresh effects in bilateral PPA. Adapted from M. R. Johnson et al. (2007). (B) A gradient for reflection versus perception, with little difference between *refresh* and *repeat* conditions in more anterior/superior scene-selective areas and significantly more activity for *repeat* than *refresh* conditions in more posterior/inferior areas. Adapted from M. R. Johnson et al. (2007). (C) Task description and data from right PPA, adapted from Yi et al. (in press). Refreshing and repeating scene stimuli produced similar degrees of repetition attenuation at a second presentation compared to stimuli that had been seen only once (*skip* condition). See text for details. MOG: middle occipital gyrus, PCu: precuneus, PPA: parahippocampal place area, RSC: retrosplenial cortex.

In addition, we (M. R. Johnson et al., 2007) compared the overall activation difference for *repeat* conditions minus *refresh* conditions (i.e., perceptual activity minus reflective activity) in the four scene-selective ROIs (PPA, retrosplenial cortex, precuneus, and middle occipital gyrus). An anatomical gradient of relative responsiveness to reflection and perception was found, with the most anterior and superior area (precuneus) showing essentially no difference between *refresh* and *repeat* activity, and areas located more posteriorly and inferiorly (in order: retrosplenial cortex, PPA, middle occipital gyrus) showing gradually greater increases in *repeat* activity relative to *refresh* activity (see Figure 4B). This is consistent with the concept represented by the cones in the MEM framework (Figure 1A) – that executive and supervisor processes are capable of recruiting and influencing processes at the perceptual level of processing, though with decreasing efficacy at "lower" (i.e., P-1) levels of perception. Of course, the fact that refreshing influences neural activity in areas involved in perception does not alone show that refreshing influences perception itself. However, the results of a study by Yi, Turk-Browne, Chun, and Johnson (in press) support the hypothesis that an act of refreshing can, in fact, exert an influence on perceptual processing.

Yi and colleagues (in press) scanned participants using fMRI during a refresh task involving scene stimuli. In each condition (see Figure 4C), trials began with the presentation of a novel scene stimulus with a fixation dot followed by a brief blank stimulus with a fixation point. Next, in the *repeat* condition, the same scene was presented a second time; in the *refresh* condition, participants saw a white dot on the fixation point, signaling them to think back to the scene that had just been presented; and in the *skip* condition, another novel scene stimulus was presented. In all three conditions, this sequence constituted the "first presentation" trial. Thus, in the first presentation trial, scenes in the *repeat* condition had been seen twice, those in the *refresh* condition had been seen once and refreshed once, and those in the *skip* condition had been seen once. There were also "second presentation" trials intermixed with these first presentation trials. In second presentation trials, a single scene stimulus was shown, which was the same as a scene that had appeared initially in a first presentation trial. There were also second presentation trials consisting of completely novel items that were seen only once.

The primary intent of this study was to compare repetition attenuation in the PPA for stimuli that had been refreshed to that of stimuli that had been repeated or presented only once. Repetition attenuation is a phenomenon where reduced neural activity is observed in stimulus-specific areas of cortex for stimuli that have been perceived before, compared to the activity for novel stimuli. It is thought to be a signature of neural tuning or sharpening of familiar representations or a reduction in the processing necessary for stimulus identification (Desimone, 1996; Grill-Spector, Henson, & Martin, 2006; Wiggs & Martin, 1998), and indeed greater repetition attenuation for a stimulus is associated with a greater likelihood of subsequent recognition (Turk-Browne, Yi, & Chun, 2006). Thus, as refreshing has been shown to modulate activity in perceptual regions (M. R. Johnson et al., 2007) and is thought, like other reflective processes, to be able to influence perceptual processing (Johnson & Reeder, 1997), Yi and colleagues (in press) hypothesized that refreshing a stimulus would induce repetition attenuation during a subsequent presentation of the stimulus.

Analyzing fMRI signal in the PPA during the "second presentation" trials confirmed this hypothesis (see Figure 4C). In PPA, previously refreshed and repeated stimuli both showed a greater effect of repetition attenuation (i.e., lower overall signal) than stimuli in the *skip* condition that had previously been seen only once. The degree of repetition attenuation was similar for the *repeat* and *refresh* conditions, suggesting that reflection can sometimes have as much of an effect on later perceptual processing as perception itself. Since repetition attenuation in the ventral visual cortex can be considered a form of perceptual memory, this result supports a key prediction of the MEM framework, namely that subsystems interact. Of course, exactly how they interact remains to be clarified. For example, perception and reflection may both affect the same representations. Or, a cue may activate similar perceptually-derived and reflectively generated representations, and this activation may be summed across both types of representations to yield a phenomenal experience or a response in a task.

Selection: The Need for a New Component?

A consequence of refreshing is, presumably, that the refreshed target is foregrounded (stands out) compared to other active representations, which can be considered a form of selection. To investigate the neural correlates of this selective aspect of refreshing, we conducted an fMRI study (Johnson et al., 2005, Experiment 5; Raye, Mitchell, Reeder, Greene, & Johnson, in press) in which participants on each trial saw either 1 or 3 words, followed by either a new word (*read* conditions) or a dot cuing them to refresh the single word (*refresh-1*) or one of the three words (*refresh-3*). Analyses identified four areas of frontal cortex where activity was greater when selectively refreshing 1 of 3 items than 1 of 1, but where the number of items presented did not affect activity in the *read* conditions. These were left DLPFC, left VLPFC, ACC, and a small area in right middle frontal gyrus.

Given that, other than DLPFC, these regions are not always associated with single-item refreshing, one might conclude that the *refresh-3* condition invokes a separate selection process that is a function of VLPFC and/or ACC (e.g., Jonides, Smith, Marshuetz, Koeppe, & Reuter-Lorenz, 1998; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). However, while not always above threshold in an individual study, our meta-analysis suggests that these additional areas are frequently active to some extent during refreshing (Johnson et al., 2005). Thus, the activity seen in the *refresh-3* condition may not reflect a separate selection process; instead, refreshing may involve a network of regions that are active to varying degrees depending on the information refreshed and the amount of competition among active representations. Furthermore, this network may always be engaged, to varying degrees, in the service of steering the stream of ongoing thought. Consistent with this idea, the pattern of activity found during selective refreshing is strikingly similar to the DLPFC-VLPFC-ACC network identified by Duncan and Owen (2000) as being activated by a wide range of cognitive tasks. The common patterns of activity that Duncan and Owen identified across studies may reflect a common reliance on one or more key component processes like refreshing.

In its current form, MEM contains no explicit representation of a selection process. An aspect of selection is already embodied in MEM's component processes (e.g., *refreshing* and *shifting* both imply targeting a single representation or process from among alternatives). That is, all of the MEM component processes may inherently involve some degree of selection. Hence, it is not clear what the definition of "selection" would be outside of engaging one of the processes postulated in MEM. Alternatively, it may be that selection should be thought of as a complex action that can be broken down into a combination of extant MEM component processes (e.g., selective *refreshing* = *shifting* among available representations, *noting* the item that corresponds to the cue, and *refreshing* that representation). Or, perhaps we could more succinctly characterize the neural correlates of complex cognition if we add a separate *selecting* process to the MEM model that can be recruited in combination with certain other processes. Theory alone does not tell us whether selecting should be thought of as a mental activity that is inherently a feature of more basic processes, whether it consists of a combination of more basic processes, or whether it is itself a basic process. Neuroimaging data can help us decide among the alternatives by virtue of which explanation provides the most consistent and parsimonious account of the activation patterns observed. Neuroimaging data may also provide a common language for linking corresponding concepts in the literature. For example, Badre and Wagner (2002) have proposed that there is a difference between selecting from active representations and retrieving information from long-term semantic memory. In MEM, this would correspond to the difference between *refreshing* and *reactivating* (or *retrieving*), both of which inherently involve selection. If we operationalize these accounts and observe convergent neural correlates, that would constitute evidence for their conceptual equivalence.

We have found refresh-related areas of DLPFC and ACC that activate more in both *refresh-1* and *refresh-3* compared to their corresponding *read* conditions, but also "selective refresh" areas of DLPFC, VLPFC and ACC exhibiting refresh-related activity only in the *refresh-3* condition (i.e., *refresh-1* activity did not exceed *read-1* activity; Johnson et al., 2005, Experiment 5). One explanation is that selective refreshing causes an increase in activation extent relative to non-selective refreshing activations, producing above-threshold "selective refresh" areas in nearby anatomical regions. On the other hand, if findings consistently show increased activation of a particular area or areas (e.g., Brodmann area 45) when the selection requirements for different cognitive processes are increased, that would support (but not alone require) the idea of selection as a separate component process. An analogy might be made if we imagine a MEM-like component process model of human movement containing processes like *walking*, *swimming*, and *climbing*. While *running* is clearly a more effortful analogue of *walking*, is *running* qualitatively different enough to merit being its own, separate component process? Ultimately, decisions about which constructs to include in a model rely on making judgments about which ideas capture observed phenomena most succinctly and intuitively. For now, we view selection as engaging a process (such as refreshing or retrieving) under conditions of competition. As further data emerge, perhaps it may become apparent that we should add selection as a separate component in the MEM framework.

Conclusions and Future Directions

The concept of "executive function" has been central in theoretical accounts of behavioral studies of cognition and in describing the impact of certain types of brain damage. The MEM model provides a specific characterization of the concept of executive function in terms of component processes of reflection. Our findings suggest that functional neuroimaging has a level of resolution generally compatible with MEM's mid-level vocabulary of theoretical constructs. Consistent with MEM, neuroimaging has provided evidence that component processes such as *refreshing* (DLPFC), *initiating* (anterior PFC), and *rehearsing* (VLPFC) are differentially subserved by different regions of PFC, and that these regions' activity correlates differentially with other brain regions depending on the representations or other processes they interact with.

Refreshing is proposed to serve a broadly useful executive function in that it is a mechanism by which some information is foregrounded relative to other information so that the refreshed information has a competitive advantage. Thus, refreshing is a mechanism for selective attention to activated representations in the absence of ongoing sensory input (i.e., refreshing = reflective, as opposed to perceptual, attention). Consistent with this idea, we have shown that refreshing modulates activity in some of the same representational regions that are active during perception such as the parahippocampal place area and the fusiform face area. In addition, refreshing has functional consequences, for example, benefiting subsequent long-term recognition memory (an explicit memory measure) and producing repetition attenuation during subsequent perception of the same stimulus again (an implicit memory measure). This latter finding is consistent with the idea that refreshing may serve as an important mechanism for the interaction between perception and reflection (e.g., bridging gaps between glances as a complex representation of a scene is built up, affecting what percepts are likely to persist in long-term memory, etc.). Interactions in MEM between processes or subsystems are proposed to be as important as the capacity of components to operate in a more modular fashion (Johnson, 1983). Further specifying how such interactions take place is a major challenge.

Although in our lab we have focused primarily on reflective component processes, the gradient we found showing a decrease in the difference in activity during perception and refreshing in visual processing areas, from middle occipital gyrus to parahippocampus to retrosplenial cortex to precuneus, raises interesting question for further study and clarifying the MEM model. For example, do the representations/functions of these posterior areas map onto different functions of P-level processes in MEM, such as *resolving* and/or *locating* (middle occipital gyrus) vs. *identifying* (e.g., fusiform face area, parahippocampal place area) vs. *placing* objects in relation to each other (e.g., retrosplenial cortex)?

The neuroimaging data obtained to date suggest additional new questions regarding the relation of MEM component processes to other concepts. For example, as noted above, does the model need a separate process of *selecting* or is selectivity inherent in every cognitive operation? Does the maintenance activity conceptualized by Baddeley (1996) as the *visual-spatial sketchpad* have more in common with *refreshing* or *rehearsing*? With respect to the general question of the functional organization of PFC (e.g., Goldman-Rakic, 1995; Smith & Jonides, 1997), when are similar vs. different regions of PFC engaged in refreshing different types of information (e.g., Johnson et al., 2003, 2005)? To what extent does the PFC region engaged to refresh a particular type of information depend on what other information is being processed and, more generally, what does this imply about the relation between brain activity and cognitive concepts?

A limited repertoire of component processes engaged in different combinations in different tasks could help account for the similarity in neural activity found across neuroimaging studies. For example, in 2006 alone, DLPFC activity was reported to be involved in tasks as widely varying as lexical retrieval (de Diego Balaguer et al., 2006), task-set maintenance (Fassbender, Foxe, & Garavan, 2006), divided attention (J. A. Johnson & Zatorre, 2006), tactile decision making (Pleger et al., 2006), episodic memory formation (Summerfield et al., 2006), and temporal discrimination (Tregellas, Davalos, & Rojas, 2006). DLPFC activity could be due to these complex tasks all relying on one or more common component processes, or could be due to the recruitment of distinct component processes that each involve DLPFC (either different areas of DLPFC, or the same areas of DLFPC in concert with different other regions). Duncan and Owen (2000), in a meta-analysis, reported that a common network of mid-VLPFC, mid-DLPFC, and ACC was recruited in a wide range of tasks such as auditory discrimination (Holcomb et al., 1998), visual divided attention (Vandenberghe et al., 1997), self-paced response production (Jahanshahi et al., 1995), task switching (Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000), spatial problem solving (Baker et al., 1996), and semantic processing (Thompson-Schill et al., 1997). Again, this could reflect commonality in component process(es) engaged in all of these tasks, or unique processes all involving this general network of regions. By clarifying specific proposed individual component processes, we should be able to address whether they represent a viable level of analysis for understanding cognitive and brain function in more complex tasks. Does each complex task generate a pattern of neural activity so unique as to challenge the concept of component processes? What types of evidence will justify inferring the operation of a specific cognitive operation from a pattern of brain activity ("reverse inference," Poldrack, 2006; Poldrack & Wagner, 2004)?

As concepts of component processes are refined, including identifying their neural correlates, a component-process approach should be increasingly useful in providing more specific assessments, or "biomarkers," in studies of cognitive impairment, for example, from neurological damage (e.g., lesion-related losses of function) and psychiatric dysfunction (e.g., working memory impairments in schizophrenia [Goldman-Rakic, 1994, 1999]), as well as deficits that emerge in the course of normal, healthy aging (Craik & Jennings, 1992; Hasher & Zacks, 1988; Light, 1991). For example, older adults show a behavioral deficit in refreshing (i.e., relative to young adults, disproportionately slow response times to refresh than to read a word, as well as less long-term memory benefit, Johnson et al., 2002) and they also show reduced activity, relative to young adults, in left DLPFC during refreshing (Johnson et al., 2004). A recent study showing that TMS to left DLPFC slows refreshing in young adults provides converging evidence for the importance of this region for refreshing (Miller, Verstynen, Johnson, & D'Esposito, 2008). It is easy to see how dysfunction in one or two MEM component processes (e.g., *refreshing* and/or *initiating*), could lead to wide-ranging dysfunctions in all complex cognitive acts involving those components (e.g., Johnson et al., 2004; Johnson et al., 2002).

Of course, cognitive deficits of different etiologies have organic correlates that may lie at different levels of abstraction within the nervous system (e.g., systemic genetic/molecular abnormalities in schizophrenia [Owen, Williams, & O'Donovan, 2004] versus a lesion to a specific region of cortex in a stroke patient). Attempting to characterize cognitive dysfunction in terms of a common set of component processes should help connect these different levels of analysis.

In summary, a mid-level cognitive model such as MEM has both analytic and synthetic functions (Johnson, 2007), helping both to generate specific hypotheses and to organize major findings from multiple approaches (cognitive/behavioral, neuropsychological, neuroimaging). With respect to neuroimaging in particular, MEM provides hypotheses about the component processes we should look for in brain activity in particular experiments, and an integrative context for interpreting the brain activity we see across many experiments. Reciprocally, neuroimaging evidence affords us both opportunities to test our conceptual models and direction for revising them, and thus it should help adjudicate among alternative conceptualizations of component cognitive processes. We do not need neuroimaging to ask what we mean by general terms such as executive function, working memory, cognitive control, or reflection, and many elegant cognitive-behavioral experiments have helped clarify such concepts. However, the further agenda of linking cognitive processes to brain function provides one way of deconstructing those concepts for a more specific level of analysis, and may therefore result in a more complete science of cognition.

References

Atkinson, R. C., & Juola, J. F. (1974). Search and decision processes in recognition memory. In D. H. Krantz, R. C. Atkinson, R. D. Luce & P. Suppes (Eds.), *Contemporary developments in mathematical psychology: I. Learning, memory, and thinking* (pp. 243-293). Oxford, England: W. H. Freeman.

Awh, E., Jonides, J., Smith, E. E., Schumacher, E. H., Koeppe, R. A., & Katz, S. (1996). Dissociation of storage and rehearsal in verbal working memory: Evidence from positron emission tomography. *Psychological Science, 7*, 25-31.

Baddeley, A. D. (1982). Amnesia: A minimal model and an interpretation. In L. S. Cermak (Ed.), *Human memory and amnesia* (pp. 305-336). Hillsdale, NJ: Erlbaum.

Baddeley, A. D. (1984). The fractionation of human memory. *Psychological Medicine, 14*(2), 259-264.

Baddeley, A. D. (1992). Working memory. *Science, 255*, 556-559.

Baddeley, A. D. (1996). Exploring the central executive. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 49A*(1), 5-28.

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47-90). San Diego, CA: Academic Press.

Baddeley, A. D., Lewis, V., & Vallar, G. (1984). Exploring the articulatory loop. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 36A*(2), 233-252.

Baddeley, A. D., & Lieberman, K. (1980). Spatial working memory. In R. Nickerson (Ed.), *Attention and performance VIII*. Hillsdale, NJ: Erlbaum.

Badre, D. & Wagner, A.D. (2002). Semantic retrieval, mnemonic control, and prefrontal cortex. *Behavioral and Cognitive Neuroscience Reviews, 1*, 206-218.

Baker, S. C., Rogers, R. D., Owen, A. M., Frith, C. D., Dolan, R. J., Frackowiak, R. S., et al. (1996). Neural systems engaged by planning: A PET study of the Tower of London task. *Neuropsychologia, 34*(6), 515-526.

Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature, 402*(6758), 179-181.

Braver, T. S., & Bongiolatti, S. R. (2002). The role of frontopolar cortex in subgoal processing during working memory. *NeuroImage, 15*(3), 523-536.

Carter, C. S., Braver, T. S., Barch, D. M., Botvinick, M. M., Noll, D., & Cohen, J. D. (1998). Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science, 280*(5364), 747-749.

Chein, J. M., & Fiez, J. A. (2001). Dissociation of verbal working memory system components using a delayed serial recall task. *Cerebral Cortex, 11*(11), 1003-1014.

Christoff, K., & Gabrieli, J. D. E. (2000). The frontopolar cortex and human cognition: Evidence for a rostrocaudal hierarchical organization within the human prefrontal cortex. *Psychobiology, 28*(2), 168-186.

Cohen, J. D., Perlstein, W. M., Braver, T. S., Nystrom, L. E., Noll, D. C., Jonides, J., et al. (1997). Temporal dynamics of brain activation during a working memory task. *Nature, 386*, 604-608.

Cohen, N. J., & Squire, L. R. (1980). Preserved learning and retention of pattern-analyzing skill in amnesia: Dissociation of knowing how and knowing that. *Science, 210*(4466), 207-210.

Courtney, S. M. (2004). Attention and cognitive control as emergent properties of information representation in working memory. *Cognitive, Affective, & Behavioral Neuroscience, 4*(4), 501-516.

Craik, F. I. M., & Jennings, J. M. (1992). Human memory. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (pp. 51-110). Hillsdale, NJ: Lawrence Erlbaum Associates.

Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior, 11*, 671-684.

Curtis, C. E., & D'Esposito, M. (2003). Persistent activity in the prefrontal cortex during working memory. *Trends in Cognitive Sciences, 7*(9), 415-423.

de Diego Balaguer, R., Rodriguez-Fornells, A., Rotte, M., Bahlmann, J., Heinze, H. J., & Munte, T. F. (2006). Neural circuits subserving the retrieval of stems and grammatical features in regular and irregular verbs. *Human Brain Mapping, 27*(11), 874-888.

Desimone, R. (1996). Neural mechanisms for visual memory and their role in attention. *Proceedings of the National Academy of Sciences of the United States of America, 93*(24), 13494-13499.

D'Esposito, M., Postle, B. R., Ballard, D., & Lease, J. (1999). Maintenance versus manipulation of information held in working memory: an event-related fMRI study. *Brain & Cognition, 41*, 66-86.

Dove, A., Pollmann, S., Schubert, T., Wiggins, C. J., & von Cramon, D. Y. (2000). Prefrontal cortex activation in task switching: An event-related fMRI study. *Cognitive Brain Research, 9*(1), 103-109.

Duncan, J., & Owen, A. M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neurosciences, 23*(10), 475-483.

Epstein, R., & Kanwisher, N. (1998). A cortical representation of the local visual environment. *Nature, 392*(6676), 598-601.

Fassbender, C., Foxe, J. J., & Garavan, H. (2006). Mapping the functional anatomy of task preparation: Priming task-appropriate brain networks. *Human Brain Mapping, 27*(10), 819-827.

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology*. Cambridge, MA: MIT Press.

Friston, K. J. (1994). Functional and effective connectivity in neuroimaging: A synthesis. *Human Brain Mapping, 2*(1-2), 56-78.

Goldman-Rakic, P. S. (1994). Working memory dysfunction in schizophrenia. *Journal of Neuropsychiatry & Clinical Neurosciences, 6*(4), 348-357.

Goldman-Rakic, P. S. (1995). Architecture of the prefrontal cortex and the central executive. *Annals of the New York Academy of Sciences, 769,* 71-83.

Goldman-Rakic, P. S. (1999). The physiological approach: Functional architecture of working memory and disordered cognition in schizophrenia. *Biological Psychiatry, 46*(5), 650-661.

Grill-Spector, K., Henson, R., & Martin, A. (2006). Repetition and the brain: Neural models of stimulus-specific effects. *Trends in Cognitive Sciences, 10*(1), 14-23.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation, Vol. 22* (pp. 193-225). New York, NY: Academic Press.

Henson, R. (2005). What can functional neuroimaging tell the experimental psychologist? *The Quarterly Journal of Experimental Psychology: Section A, 58*(2), 193-233.

Holcomb, H. H., Medoff, D. R., Caudill, P. J., Zhao, Z., Lahti, A. C., Dannals, R. F., et al. (1998). Cerebral blood flow relationships associated with a difficult tone recognition task in trained normal volunteers. *Cerebral Cortex, 8*(6), 534-542.

Horwitz, B. (1994). Data analysis paradigms for metabolic-flow data: Combining neural modeling and functional neuroimaging. *Human Brain Mapping, 2*(1-2), 112-122.

Jacoby, L. L., & Dallas, M. (1981). On the relationship between autobiographical memory and perceptual learning. *Journal of Experimental Psychology: General, 110*(3), 306-340.

Jahanshahi, M., Jenkins, I. H., Brown, R. G., Marsden, C. D., Passingham, R. E., & Brooks, D. J. (1995). Self-initiated versus externally triggered movements. I. An investigation using measurement of regional cerebral blood flow with PET and movement-related potentials in normal and Parkinson's disease subjects. *Brain, 118 (Pt 4)*, 913-933.

Johnson, J. A., & Zatorre, R. J. (2006). Neural substrates for dividing and focusing attention between simultaneous auditory and visual events. *NeuroImage, 31*(4), 1673-1681.

Johnson, M. K. (1983). A multiple-entry, modular memory system. *The Psychology of Learning and Motivation: Advances in Research and Theory, 17*, 81-123.

Johnson, M. K. (1992). MEM: Mechanisms of recollection. *Journal of Cognitive Neuroscience, 4*, 268-280.

Johnson, M.K. (1997). Identifying the origin of mental experience. In M.S. Myslobodsky (Ed.), *The mythomanias: The nature of deception and self-deception* (pp. 133-180). Mahwah, NJ: Erlbaum.

Johnson, M. K. (2007). Memory systems: A cognitive construct for analysis and synthesis. In H. L. Roediger, III, Y. Dudai & S. M. Fitzpatrick (Eds.), *Science of memory: Concepts* (pp. 353-357). New York: Oxford University Press.

Johnson, M. K., & Hirst, W. (1991). Processing subsystems of memory. In R. G. Lister & H. J. Weingartner (Eds.), *Perspectives on cognitive neuroscience* (pp. 197-217). New York: Oxford University Press.

Johnson, M. K., & Hirst, W. (1993). MEM: Memory subsystems as processes. In A. F. Collins, S. E. Gathercole, M. A. Conway & P. E. Morris (Eds.), *Theories of memory* (pp. 241-286). East Sussex, England: Lawrence Erlbaum Associates.

Johnson, M. K., Kim, J. K., & Risse, G. (1985). Do alcoholic Korsakoff's syndrome patients acquire affective reactions? *Journal of Experimental Psychology: Learning, Memory, & Cognition, 11,* 22-36.

Johnson, M. K., Mitchell, K. J., Raye, C. L., & Greene, E. J. (2004). An age-related deficit in prefrontal cortical function associated with refreshing information. *Psychological Science, 15*(2), 127-132.

Johnson, M. K., Raye, C. L., Mitchell, K. J., Greene, E. J., & Anderson, A. W. (2003). fMRI evidence for an organization of prefrontal cortex by both type of process and type of information. *Cerebral Cortex, 13*, 265-273.

Johnson, M. K., Raye, C. L., Mitchell, K. J., Greene, E. J., Cunningham, W. A., & Sanislow, C. A. (2005). Using fMRI to investigate a component process of reflection: Prefrontal correlates of refreshing a just-activated representation. *Cognitive, Affective, & Behavioral Neuroscience, 5*(3), 339-361.

Johnson, M. K., & Reeder, J. A. (1997). Consciousness as meta-processing. In J. D. Cohen & J. W. Schooler (Eds.), *Scientific approaches to consciousness* (pp. 261-293). Mahwah, NJ: Erlbaum.

Johnson, M. K., Reeder, J. A., Raye, C. L., & Mitchell, K. J. (2002). Second thoughts versus second looks: An age-related deficit in reflectively refreshing just-activated information. *Psychological Science, 13*(1), 64-67.

Johnson, M. R., Mitchell, K. J., Raye, C. L., D'Esposito, M., & Johnson, M. K. (2007). A brief thought can modulate activity in extrastriate visual areas: Top-down effects of refreshing just-seen visual stimuli. *NeuroImage, 37,* 290-299.

Jonides, J., Smith, E. E., Marshuetz, C., Koeppe, R. A., & Reuter-Lorenz, P. A. (1998). Inhibition in verbal working memory revealed by brain activation. *Proceedings of the National Academy of Sciences of the United States of America, 95*, 8410-8413.

Kanwisher, N., McDermott, J., & Chun, M. M. (1997). The fusiform face area: A module in human extrastriate cortex specialized for face perception. *Journal of Neuroscience, 17*, 4302-4311.

Kerns, J. G., Cohen, J. D., MacDonald, A. W., 3rd, Cho, R. Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303*(5660), 1023-1026.

Kolers, P. A., & Roediger, H. L., III. (1984). Procedures of mind. *Journal of Verbal Learning and Verbal Behavior, 23*, 425-449.

Light, L. L. (1991). Memory and aging: Four hypotheses in search of data. *Annual Review of Psychology, 42*(1), 333-376.

MacDonald, A. W., 3rd, Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science, 288*(5472), 1835-1838.

Mandler, G. (1980). Recognizing: The judgment of previous occurrence. *Psychological Review, 87*, 252-271.

McClelland, J. L., McNaughton, B. L., & O'Reilly, R. C. (1995). Why there are complementary learning systems in the hippocampus and neocortex: Insights from the successes and failures of connectionist models of learning and memory. *Psychological Review, 102*(3), 419-457.

McIntosh, A. R., & Gonzalez-Lima, F. (1994). Structural equation modeling and its application to network analysis in functional brain imaging. *Human Brain Mapping, 2*(1-2), 2-22.

Miller, B. T., Verstynen, T., Johnson, M. K., & D'Esposito, M. (2008). Prefrontal and parietal contributions to refreshing: An rTMS study. *NeuroImage, 39,* 436-440.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24*, 167-202.

Miller, G. A., Galanter, E., & Pribram, K. H. (1960). *Plans and the structure of behavior*. New York: Holt, Rinehart, and Winston.

Mishkin, M. (1982). A memory system in the monkey. *Philosophical Transactions of the Royal Society of London - Series B: Biological Sciences, 298*(1089), 83-95.

Miyashita, Y. (1993). Inferior temporal cortex: Where visual perception meets memory. *Annual Review of Neuroscience, 16*, 245-263.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation, Vol. 4* (pp. 1-18). New York: Plenum Press.

Owen, M. J., Williams, N. M., & O'Donovan, M. C. (2004). The molecular genetics of schizophrenia: New findings promise new insights. *Molecular Psychiatry, 9*(1), 14-27.

Passingham, D., & Sakai, K. (2004). The prefrontal cortex and working memory: Physiology and brain imaging. *Current Opinion in Neurobiology, 14*(2), 163-168.

Petrides, M. (1994). Frontal lobes and working memory: Evidence from investigations of the effects of cortical excisions in nonhuman primates. In F. Boller & J. Grafman (Eds.), *Handbook of neuropsychology, vol. 9* (pp. 59-82). Amsterdam: Elsevier Science.

Petrides, M. (2000). Dissociable roles of mid-dorsolateral prefrontal and anterior inferotemporal cortex in visual working memory. *Journal of Neuroscience, 20*(19): 7496-7503.

Petrides, M., Alivisatos, B., Meyer, E., & Evans, A. C. (1993). Functional activation of the human frontal cortex during the performance of verbal working memory tasks. *Proceedings of the National Academy of Sciences of the United States of America, 90*, 878-882.

Pleger, B., Ruff, C. C., Blankenburg, F., Bestmann, S., Wiech, K., Stephan, K. E., et al. (2006). Neural coding of tactile decisions in the human prefrontal cortex. *Journal of Neuroscience, 26*(48), 12596-12601.

Poldrack, R. A. (2006). Can cognitive processes be inferred from neuroimaging data? *Trends in Cognitive Sciences 10*(2), 59-63.

Poldrack, R. A., & Packard, M. G. (2003). Competition among multiple memory systems: Converging evidence from animal and human brain studies. *Neuropsychologia, 41*(3), 245-251.

Poldrack, R. A., & Rodriguez, P. (2004). How do memory systems interact? Evidence from human classification learning. *Neurobiology of Learning and Memory, 82*(3), 324-332.

Poldrack, R. A., & Wagner, A. D. (2004). What can neuroimaging tell us about the mind? Insights from prefrontal cortex. *Current Directions in Psychological Science, 13*(5), 177-181.

Ranganath, C., & D'Esposito, M. (2005). Directing the mind's eye: Prefrontal, inferior and medial temporal mechanisms for visual working memory. *Current Opinion in Neurobiology, 15*(2), 175-182.

Raye, C. L., Johnson, M. K., Mitchell, K. J., Greene, E. J., & Johnson, M. R. (2007). Refreshing: A minimal executive function. *Cortex, 43*, 135-145.

Raye, C. L., Johnson, M. K., Mitchell, K. J., Reeder, J. A., & Greene, E. J. (2002). Neuroimaging a single thought: Dorsolateral PFC activity associated with refreshing just-activated information. *NeuroImage, 15*(2), 447-453.

Raye, C. L., Mitchell, K. J., Reeder, J. A., Greene, E. J., & Johnson, M. K. (in press). Refreshing one of several active representations: Behavioral and fMRI differences between young and older adults. *Journal of Cognitive Neuroscience*.

Reiser, B. J. (1986). The encoding and retrieval of memories of real-world experiences. In J. A. Galambo, R. P. Abelson, & J. B. Black (Eds.), *Knowledge structures* (pp. 71-99). Hillsdale, NJ: Lawrence Erlbaum Associates.

Ruchkin, D. S., Grafman, J., Cameron, K., & Berndt, R. S. (2003). Working memory retention systems: A state of activated long-term memory. *Behavioral & Brain Sciences, 26*(6), 709-728.

Salame, P., & Baddeley, A. D. (1982). Disruption of short-term memory by unattended speech: Implications for the structure of working memory. *Journal of Verbal Learning & Verbal Behavior*.

Smith, E. E., & Jonides, J. (1997). Working memory: a view from neuroimaging. *Cognitive Psychology, 33*(1), 5-42.

Smith, E. E., & Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science, 283*, 1657-1661.

Squire, L. R., & Alvarez, P. (1995). Retrograde amnesia and memory consolidation: A neurobiological perspective. *Current Opinion in Neurobiology, 5*(2), 169-177.

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

Summerfield, C., Greene, M., Wager, T., Egner, T., Hirsch, J., & Mangels, J. (2006). Neocortical connectivity during episodic memory formation. *PLoS Biology, 4*(5), e128.

Thompson-Schill, S. L., D'Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. *Proceedings of the National Academy of Sciences of the United States of America, 94*(26), 14792-14797.

Tregellas, J. R., Davalos, D. B., & Rojas, D. C. (2006). Effect of task difficulty on the functional anatomy of temporal processing. *NeuroImage, 32*(1), 307-315.

Tulving, E. (1983). *Elements of episodic memory*. Oxford, England: Clarendon Press.

Tulving, E. (1985). Memory and consciousness. *Canadian Psychology, 26*, 1-12.

Tulving, E., & Schacter, D. L. (1990). Priming and human memory systems. *Science, 247*(4940), 301-306.

Turk-Browne, N. B., Yi, D.-J., & Chun, M. M. (2006). Linking implicit and explicit memory: Common encoding factors and shared representations. *Neuron, 49*(6), 917-927.

Uttal, W. R. (2001). *The new phrenology: The limits of localizing cognitive processes in the brain*. Cambridge, MA: The MIT Press.

Vandenberghe, R., Duncan, J., Dupont, P., Ward, R., Poline, J. B., Bormans, G., et al. (1997). Attention to one or two features in left or right visual field: A positron emission tomography study. *Journal of Neuroscience, 17*(10), 3739-3750.

Wiggs, C. L., & Martin, A. (1998). Properties and mechanisms of perceptual priming. *Current Opinion in Neurobiology, 8*(2), 227-233.

Yi, D.-J., Turk-Browne, N. B., Chun, M. M., & Johnson, M. K. (in press). When a thought equals a look: Refreshing enhances perceptual memory. *Journal of Cognitive Neuroscience*.

Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language, 46*(3), 441-517.

Acknowledgements

Preparation of this chapter was supported by NIH grants AG15793 and AG09253. We thank Marvin Chun, Carol Raye, Nicholas Turk-Browne, and Do-Joon Yi, as well as the editors and reviewers, for their comments on this manuscript.

Footnotes

[1] In Figure 3A, in DLPFC, although there was less activity in the read than refresh condition, there was more activity in the read than act condition. In other studies, there was little activity in DLPFC in the read condition (compare Figure 3A with Figures 2B and 3C). This suggests that participants may have sometimes spontaneously refreshed in the read condition. One possibility is that such uncued refreshes are more likely to occur on read trials in some task contexts than others.

Abbreviations and Acronyms

ACC: Anterior cingulate cortex
BA: Brodmann area
DLPFC: Dorsolateral prefrontal cortex
FFA: Fusiform face area
fMRI: Functional magnetic resonance imaging
IFG: Inferior frontal gyrus
IOG: Inferior occipital gyrus
MEM: Multiple-Entry, Modular model of memory and cognition
MFG: Middle frontal gyrus
MOG: Middle occipital gyrus
PCu: Precuneus
PFC: Prefrontal cortex
PPA: Parahippocampal place area
ROI: Region of interest
RSC: Retrosplenial cortex
SFG: Superior frontal gyrus
VLPFC: Ventrolateral prefrontal cortex