Part V

COGNITIVE AND NEURAL CONSTRAINTS ON HUMAN THOUGHT

CHAPTER 19

Thinking in Working Memory

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Introduction

It is not an accident that this discussion of working memory is positioned near the center of a volume on thinking and reasoning. Central to higher-level cognitive processes is the ability to form and manipulate mental representations (see Doumas & Hummel, Chap. 4). Working memory is the cognitive construct responsible for the maintenance and manipulation of information and therefore is neccessary for many of the types of complex thought described in this book. Likewise, the development and failures of working memory are critical to understanding thought changes with development (see Halford, Chap. 22) and aging (see Salthouse, Chap. 24) as well as many types of higher-level cognitive impairments (see Bachman & Cannon, Chap. 21). In spite of its obvious importance for thinking and reasoning, working memory's role in complex thought is just beginning to be understood. In this chapter, we review several dominant models of working memory, viewing them from different methodological perspectives, including dual-task experiments, individual differences, and cognitive neuroscience.

Multiple Memory Systems?

Although the idea of separate primary memory is credited to William James (1890), Waugh and Norman (1965) and Atkinson and Shiffrin (1968) developed the idea of distinct primary (i.e., short-term) and secondary (i.e., long-term) memory components into defined models of the human memory system. These multicomponent models of memory were supported by observations from many different studies during the 1950s and 1960s. Perhaps the most familiar justification for separate short-term and long-term memory systems is the serial position effect (e.g., Murdock, 1962). During list learning, the most recently studied items show an advantage when tested immediately – an advantage that goes away quickly with a delay in test provided that participants are prevented from rehearsing. This *recency effect* is presumably the result

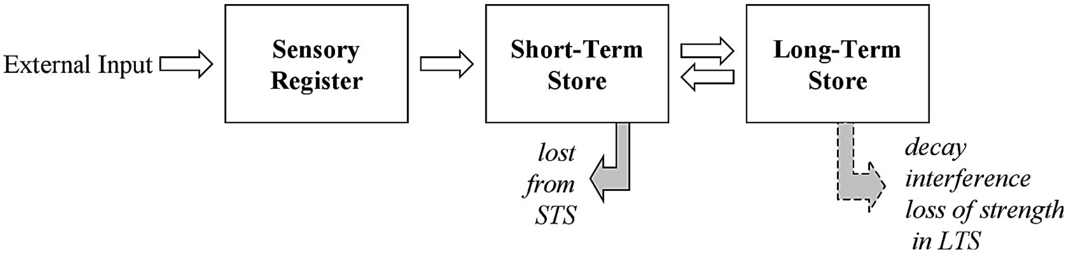

Figure 19.1. Atkinson and Shiffrin's (1968) multicomponent memory model.

of quickly unloading short-term memory at test. In contrast, the first items in the list show an advantage that withstands a delay period. This *primacy effect* presumably occurs because these initial items have been stored in long-term memory through practice. Conrad (1964) provided another important finding justifying distinct systems when he observed that errors in short-term remembering were usually phonological whereas long-term memory was dominated by semantic coding. This suggested that rehearsal or storage systems were different between the two types of memory. Yet another important finding was that, although the capacity of long-term memory was seemingly limitless, short-term memory as observed in a simple digit-span task was of limited capacity (Miller, 1956) – a finding confirmed using many other experimental paradigms. Lastly, around this same era, neuropsychological evidence began to emerge suggesting that at least parts of the short- and long-term memory systems were anatomically distinct. Milner's (1966) famous amnesic patient, HM, with his long-term memory deficits but preserved short-term digit span, and Shallice and Warrington's (1970) patient, KF, with his intact long-term memory but grossly impaired digit span, presented a double dissociation favoring at least partially distinct short- and long-term memory systems. Atkinson and Shiffrin's (1968) memory model was typical of models from the late 1960s with distinct sensory, short-term, and long-term memory stores (Figure 19.1). Short-term memory was viewed as a short-term buffer for information that was maintained by active rehearsal. It was also believed to be the mechanism by which information was stored in long-term memory.

A Multi-component Working Memory Model

While exploring the issues described in the previous section, Baddeley and Hitch (1974) proposed a model that expanded short-term memory into the modern concept of *working memory* – a term that has been used in several different contexts in psychology.[1] Baddeley (1986) defined working memory as "a system for the temporary holding and manipulation of information during the performance of a range of cognitive tasks such as comprehension, learning, and reasoning" (Ref. 3, p. 34). In a recent description of his working-memory model, Baddeley (2000) proposed a four-component model (Figure 19.2), including the *phonological loop*, the *visuospatial sketchpad*, the *central executive*, and the model's most recent addition, the *episodic*

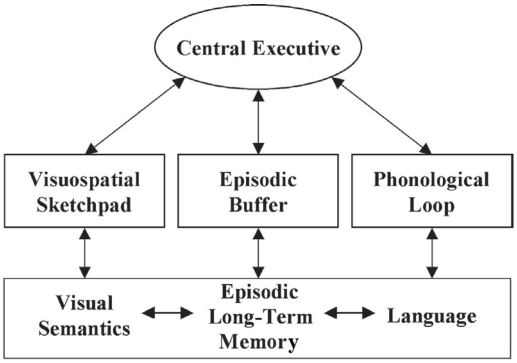

Figure 19.2. Baddeley's (2000) four-component working memory model.

buffer. This model has primarily been conceptualized based on results from behavioral dual-task paradigms and neuropsychology. For instance, using behavioral methods, Baddeley and Hitch (1974) reasoned that they could identify the separable elements of working memory by looking for task interference. If you assume the various components of working memory are capacity limited, then if the simultaneous performance of a secondary task degrades performance of a primary task, these two tasks must tap a common limited resource – particularly if there exists another primary task that is unaffected by performance of the secondary task and is affected by a different secondary task that does not affect the first primary task. Likewise, neuropsychological evidence such as the existence of patients with selectively disabled verbal (e.g., patient KF, Shallice & Warrington, 1970) and visual (e.g., de Renzi & Nichelli, 1975) digit span suggested that verbal and visual working-memory systems are somewhat separable as well.

Using this type of methodology, Baddeley has suggested that the phonological loop and visuospatial sketchpad are modality-specific *slave systems* that are responsible for maintaining information over short periods of time. The phonological loop is responsible for the maintenance and rehearsal of information that can be coded verbally (e.g., the digits in a digit-span task). It is phonemically sensitive (e.g., Ted and Fred are harder to remember than Ted and Bob), and its capacity is approximately equal to the amount of information that can be subvocally cycled in approximately 2 seconds. Baddeley (1986) argues that these two characteristics of verbal working memory are best explained by two components: (1) a *phonological store* that holds all of the information that is currently active and is sensitive to phonemic interference effects and (2) an *articulatory loop* that is used to refresh the information via a process of time-limited subvocal cycling. The articulatory loop is specifically disrupted by the common phonological loop secondary task, *articulatory suppression* (i.e., repeating a word or number vocally). Thus, verbal span is constrained by both the amount of information to be maintained and the time that it takes to rehearse it. In contrast to the phonological loop, the visuospatial sketchpad has been more difficult to describe. In a dual-task experiment, Baddeley (1986) asked subjects to simultaneously perform a pursuit rotor task (i.e., track a spot of light that followed a circular path with a stylus) while performing either a verbal or spatial memory task previously developed by Brooks (1968; Figure 19.3). The verbal task required subjects to remember a sentence (e.g., "A bird in hand is not in the bush") and scan through each word deciding whether it was a noun or not. The correct pattern of output for this example would be: NO, YES, NO, YES, NO, NO, NO, NO, YES. In the visual memory task, participants are first shown a block letter with one corner marked with an asterisk (Figure 19.3). They are then asked to imagine the letter and, beginning at the marked corner, judge whether each corner is an outside corner or not. Thus, in both the verbal and visual memory tasks, participants are required to hold a modality-specific object in memory and inspect it, answering yes or no to questions about their inspection. Baddeley found that the visual memory task, but not the verbal memory task, seriously degraded pursuit rotor tracking performance.

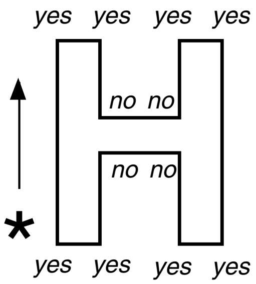

Figure 19.3. The Brooks (1968) letter task. Participants are to image a block letter and then decide whether each corner of the letter is an outside edge.

Logie (1995) has argued for a visual similarity effect analogous to the phonemic similarity effect used to support the phonological store. Participants were visually presented strings of upper- and lowercase letters (e.g., "KcPs" or "gBrQ"). Letters were chosen based on the similarity of their lower and uppercase characters. Thus Kk, Cc, Pp, Ss were visually similar while Gg, Bb, Rr, Qq were visually dissimilar. To discourage use of the phonological loop to perform the task, participants performed simultaneous articulatory suppression. After a retention period, participants had to write down the letter sequence in correct order and case. Logie found that participants made significantly more errors when the letter cases were visually similar. This finding suggests the existence of a visual store analogous to the phonological store in the phonological loop. It is possible that a visual rehearsal loop analogous to the articulatory loop exists; however, to date evidence is limited to introspective accounts of mnemonics. What is clear is that both visual and spatial qualities of stimuli can be stored in the short term; however, the independence of systems responsible for visual and spatial memory is the topic of much debate (see Logie, 1995).

The third component of Baddeley's working memory model, the central executive, was initially a catch-all for the working-memory-processes necessary for certain cognitive abilities that did not fit cleanly into the phonological loop or visuospatial sketchpad. This category included many of the cognitive abilities discussed in this book, including reasoning, problem solving, and language. For instance, Shallice and Warrington's (1970) patient KF had a drastically degraded verbal span (i.e., two letters) with relatively intact language comprehension. Believing that both of these abilities required working memory, Baddeley and Hitch (1974) reasoned that verbal span and language comprehension must use separate working-memory modules. To test this hypothesis, they devised a short-term memory load task that balanced maintenance load and time (Baddeley & Hitch, 1974). For instance, a low-load condition might require participants to remember three numbers, outputting them every 2 seconds, while a high-load condition might require participants to remember six numbers, outputting them every 4 seconds. Participants performed this secondary task while simultaneously performing a primary task involving auditory language comprehension. They found that language comprehension only suffered at high concurrent memory load and not under lower memory load conditions. At low memory load, participants had sufficient resources to carry out the comprehension task; however, at high memory load there were insufficient resources for language comprehension. Adding the results of this study to many other similar experiments and the neuropsychological evidence from patients like KF, Baddeley and Hitch postulated that comprehension and digit span utilizes separate modules of working memory that taps a common resource pool.

Given the amorphous nature of the cognitive tasks for which the central executive was necessary, Baddeley (1986) initially embraced Norman and Shallice's (1980; 1986) concept of a *Supervisory Attentional System* as a model for the central executive. Norman and Shallice suggested that most well-learned cognitive functions operate via *schemata*, or sets of actions that run automatically. Although many schemata may be shared by most individuals (e.g., driving a car, dialing a telephone, composing a simple sentence, etc.), additional schemata may be acquired through the development of specific expertise (e.g., writing lines of computer code, swinging a golf club, etc.). At many times during an ordinary day, we must perform more than one of these schemata concurrently (e.g., talking while driving). Norman and Shallice suggest that when we must perform multiple schemata, their coordination or prioritization is accomplished via the semi-automatic *Contention Scheduler* and the strategically controlled Supervisory Attentional System. The Contention Scheduler uses priorities and environmental cues (e.g., a car quickly pulls in front of me), whereas the Supervisory Attentional System tends to follow larger goals (e.g., convincing my wife that I'm a good driver). Thus, when the car rapidly pulled in front of me, I pressed the brake on the car and then proceeded to tell my wife how attentive I am while on the road. One important characteristic of the Supervisory Attentional System as a model of the central executive was that it was sensitive to capacity limits. According to Norman and Shallice, capacity limits constrain thinking and action during (1) complex cognitive processes such as reasoning or decision making; (2) novel tasks that have not developed schemata; (3) life-threatening or single, difficult tasks; and (4) functions that require the suppression of habitual responses.

Baddeley (1986) suggested that the Supervisory Attentional System provided a useful framework for understanding random generation, a task frequently associated with the central executive. In random generation, a participant is asked to generate a series of random responses from a predetermined list (e.g., integers from 0 to 9, for instance: 1,8,4,6,0,7,6, 8,4,5,6,1,2). Response patterns from this task usually exhibit two characteristics: (1) certain responses appear at much lower frequencies than others (e.g, 3 or 9 did not appear whereas 1,4,6, and 8 appeared repeatedly) and (2) stereotyped responses (e.g., 4,5,6 or 1,2) are much more common than other equally likely two- or three-number sequences (Baddeley, 1966). Baddeley suggested that the higher-order goal of randomness is at odds with the dominant schemata for the production of numbers (i.e., counting). Thus, random generation potently requires the services of the Supervisory Attentional System to override or inhibit the dominant schemata. When random number generation is performed with another working-memory–intensive task, the resources available to the Supervisory Attentional System (i.e., central executive) are in even more demand and responses become more stereotyped (Baddeley et al., 1998).

Although the Supervisory Attentional System describes an important ability that underlies complex cognitive processes such as language comprehension and problem solving, it fails to offer a tenable account of how, short of a homunculus, this direction would occur. Acknowledging this problem, Baddeley's current model of the central executive fractionates the central executive in the hope that by understanding precisely what the central executive does we might learn how it does it. Baddeley (1996) suggested four arguably distinct central executive functions: "(1) the capacity to coordinate performance on two separate tasks, (2) the capacity to switch retrieval strategies as reflected in random generation, (3) the capacity to attend selectively to one stimulus and inhibit the disrupting effect of others, and (4) the capacity to hold and manipulate information in long-term memory, as reflected in measures of working memory span" (Ref. 4, p. 5). Thus, Baddeley argued that the central executive is important for task switching, inhibition of internal representations or prepotent responses, and the activation of information in long-term memory during an activity that requires the active manipulation of material. In comparison to the slave systems, relatively little attention has been paid to the central executive utilizing dual-task methodologies.

The last and most recently added component of Baddeley's working-memory model is the episodic buffer. One problem encountered by a modal working-memory model is the need for integration. How can a complex problem requiring the integration of information across modalities be solved if all the information is being held in separate distinct buffers? This binding problem, whether it is binding information within a modality or across modalities, is one of the central challenges for a working-memory system capable of high-level cognition (see Doumas & Hummel, Chap. 4). To address this issue, Baddeley (2000) has proposed a third type of buffer that uses a multidimensional code. Thus, this buffer can maintain information from several modalities that has been bound together by the central executive. Fuster, Bodner, and Kroger (2000) have found evidence of the existence of neurons in prefrontal cortex that seem to be responsible for this type of function. Another important function of the episodic buffer is serving as a scratchpad for the development of new mental representations during complex problem solving. There are many examples of situations requiring the functions ascribed to the episodic buffer, but the methods for studying such a resource utilizing the task-interference paradigm are still under development.

Embedded-Processes Working-Memory Model

Although Baddeley's multi-component working-memory model has dominated the field for much of the past thirty years, there are alternative conceptions of working memory. Cowan (1988, 1995) has proposed a model that tightly integrates short- and long-term memory systems with attention. In his Embedded-Processes working-memory model (Figure 19.4), Cowan defines working memory as the set of cognitive processes that keep mental representations in an easily accessible state. Within this system, information can either be within the *focus of attention*, which Cowan believes is capacity limited, or in *active memory*, which Cowan suggests is time limited. The focus of attention is similar to James's (1890) concept of primary memory and is equated to the information that is currently in conscious awareness. In contrast, active memory, a concept similar to Hebb's (1949) cell assemblies or Ericsson and Kintsch's (1995) long-term working memory, refers to information that has higher activation either from recently being in the focus of attention or through some type of automatic activation (e.g., priming). In the Embedded-Processes model, a central executive, somewhat similar to Norman and Shallice's (1980, 1986) Supervisory Attention System, is responsible for bringing information into the focus of attention while an automatic recruitment of attention mechanism can bring information into active memory without previously having been in the focus of attention.

A critical distinction between Cowan's Embedded-Processes model and Baddeley's multi-component model is how the two models deal with the topic of maintenance of information. As previously discussed, Baddeley hypothesizes modality-specific buffers for the short-term storage of information that coordinate with the Episodic Buffer, which is responsible for storing integrated information. In contrast, Cowan suggests that information is maintained in working memory simply by activating its representations in long-term memory via short-term – specific neurons in the prefrontal or parietal cortices. This latter view suggests that information from different modalities will behave differently to the extent that they are coded differently in long-term memory, a view somewhat at odds with findings of phonological errors in short-term memory tasks and semantic errors in long-term memory tasks. Cowan counters this objection by noting that different codes are used in the storage of information in long-term memory and, depending on the nature of the task, different codes are likely to be more important. Likewise, Baddeley has argued that short-term and long-term memory systems are distinct based on neuropsychological evidence suggesting that short-term and long-term systems can be dissociated and therefore must be distinct systems. This argument, however, relies to some extent on the belief that the individual short- and long-term systems are anatomically unitary, an assumption that seems unlikely given recent evidence from cognitive neuroscience. Fuster has argued, based on results from single-cell recording in nonhuman primates, that neurons in prefrontal cortex are responsible for maintaining information in working memory (Fuster & Alexander 1971); however, disrupting circuits between this area and more posterior or inferior regions associated with long-term storage of information can also result in working-memory deficits (Fuster, 1997). Recent evidence from electrophysiology in humans seems to confirm that areas in prefrontal cortex and areas associated with long-term storage of information are temporally coactive during working-memory tasks (see Ruchkin et al., 2003, for a review).

A second important distinction between Baddeley's multi-component working-memory model and Cowan's

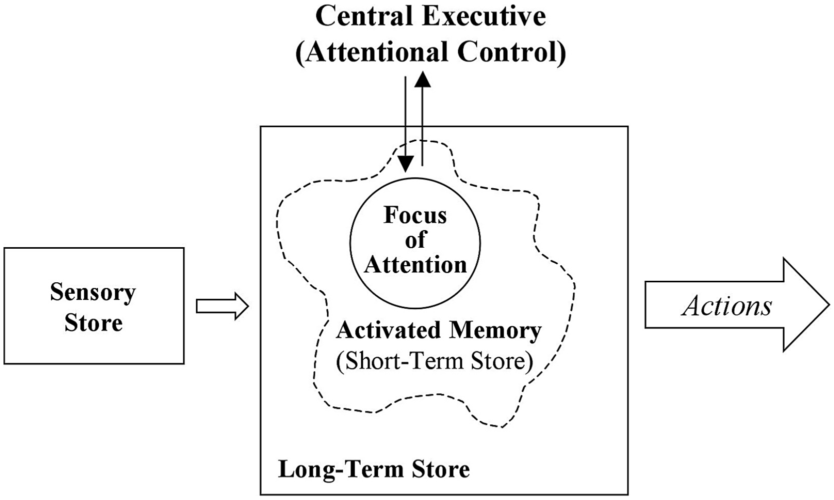

Figure 19.4. Simplified diagram of Cowan's (1988) Embedded-Processes Model.

Embedded-Processs model is modality specificity. Specifically, Baddeley has proposed independent modules within working memory for maintaining information from different modalities (e.g., visual or verbal). In contrast, Cowan suggests only a domain-general central executive that, in turn, can activate networks for various modalities of information stored in long-term memory. Baddeley also proposes a domain-general central executive, so the main distinction between the models is whether information to be maintained in working memory is loaded into domain-specific buffers or whether it is simply activated in long-term memory. From our earlier discussion, there seems to be no doubt that it is easier to maintain a certain quantity of information across several modalities than to maintain the same amount of information within just a single modality. Although this observation does not necessitate independent buffers, it does suggest that capacity limitations may be somewhat domain-specific.

Reasoning and Working Memory: Using the Task-Interference Paradigm

Although the task-interference paradigm has been very useful in exploring working memory slave systems, relatively little has been done using this technique to study high-level cognition or the central executive. Central to high-level cognitive processes is the ability to form and manipulate mental representations. Review of the functions of the central executive in either Baddeley or Cowan's models suggests that the central executive should be critical for thinking and reasoning – a hypothesis that has been confirmed in several studies. In their seminal work on working memory Baddeley and Hitch (1974) asked participants to perform a reasoning task in which they read a simple sentence containing information about the order of two abstract terms (i.e., A and B). Their task was to judge whether a letter sequence presented after the sentence reflected the order of the terms in the statement. For instance, a TRUE statement would be "A not preceded by B" followed by AB (Ref. 7, p. 50). Baddeley and Hitch varied the statements with respect to statement voicing (i.e., active or passive), negation, and verb type (i.e., precedes or follows). They found that low concurrent memory loads (i.e., one to two items to remember) had no effect on reasoning accuracy or response time; however, high concurrent memory load (i.e., six items to remember) had a reliable effect on response time. Depending on the emphasis of the instructions used, they found that the decrement in performance was either in the reasoning task or the memory task. There was no statistical interaction between concurrent memory and the reasoning task difficulty.

Several other researchers have investigated how working memory is important for deductive reasoning. Gilhooly et al. (1993), utilizing methods similar to Baddeley and Hitch, asked participants to perform verbal syllogisms (Evans, Chap. 8, for a description of syllogistic reasoning) of varying levels of complexity. In a first experiment, participants either viewed the premises of the syllogisms visually, all at once, or heard the premises read one at a time. Gilhooly et al. hypothesized that verbal presentation would result in a higher working-memory load because participants would have to maintain the content of the premises before they were able to solve the problem. They found this result: Participants made more errors in the verbal condition than in the visual condition. An error analysis indicated that the errors made were the result of not remembering the premises correctly, not errors made in the process of integration of information between premises. In a second experiment, they had participants perform the syllogism task visually while performing one of three different secondary tasks. They found that only random number generation interfered with performance of syllogisms. Gilhooly et al. concluded that the central executive is critical for relational reasoning and the phonological loop (as interfered with by articulatory suppression) may be involved to a lesser extent. They also concluded that the visuospatial sketchpad, as interfered with by spatial tapping (i.e., tapping a fixed pattern with the fingers), was not important for performing verbal syllogisms and thus argued against models of reasoning that are at least in principle dependent on involvement of visual working memory (e.g., Kirby & Kosslyn, 1992; Johnson-Laird, 1983). In a similar study, Toms, Morris, and Ward (1993) found no evidence that a variety of secondary tasks loading on either the phonological loop or visuospatial sketchpad had any effect on either reasoning accuracy or latency. Of the secondary tasks they used, only a high concurrent memory load (i.e., six digits) affected reasoning performance, and this effect appeared to be limited to difficult syllogisms.

Klauer, Stegmaier, and Meiser (1997) had participants perform syllogisms and spatial reasoning tasks that involved transitive inference (see Halford, Chap. 22, for a description of transitive inference tasks). The spatial reasoning problems varied in complexity from simple transitive inference (e.g., "The circle is to the right of the triangle. The square is to the left of the triangle." See Ref. 44, p. 13) to more complicated transitive inference problems that required greater degrees of relational integration. Klauer et al. had participants perform a visual tracking task (i.e., follow one object on a screen filled with distractor objects) while listening to the premises of the reasoning problems. They found that this visuospatial secondary task interfered with spatial reasoning but had little effect on syllogism performance. In another experiment, Klauer et al. presented syllogisms or spatial reasoning problems either auditorally (as in the previous experiment) or visually on a computer screen. While performing these primary tasks, participants performed random generation either verbally or spatially, by pressing keys in a random pattern. They found that both forms of random generation affected both syllogism and spatial reasoning performance; however, spatial random generation caused somewhat less interference than verbal random generation – a finding consistent with Baddeley et al.'s (1998) extensive study of random generation. In their final experiment, Klauer et al. found that articulatory suppression (i.e., counting repeatedly from 1 to 5) had a mild effect on syllogism and spatial reasoning latencies. Overall, Klauer et al. found evidence for involvement of the central executive (as interfered with by random generation) and somewhat less interference by slave system tasks consistent with the modality of the reasoning task.

Unlike the examples of deductive and spatial reasoning we discussed previously, analogical reasoning frequently requires the extensive retrieval of semantic information in addition to the relational processing characteristic of all types of reasoning (see Holyoak, Chap. 6, for a detailed discussion of analogical reasoning). Waltz et al. (2000) had participants perform an analogical reasoning task while performing one of several secondary tasks. In the analogical reasoning task (adapted from Markman & Gentner, 1993), participants studied pairs of pictures of scenes with multiple objects (see Figure 6.3 in Holyoak, Chap. 6). For instance, one problem showed a boy trying to walk a dog in one picture while the companion picture showed a dog failing to be restrained by a leash tied to a tree. Participants were asked to study each picture and pick one object in the second picture that "goes with" a target object in the first picture. In the example problem in Figure 6.3, the man in the first picture is a *featural* match to the boy in the second picture while using an analogy the boy is a *relational* match to the tree in the second picture. Participants were simply asked to select one object; they were thus free to complete the task based on either featural similarity or make an analogical mapping and inference, answering based on relational similarity. Waltz et al. found that participants who maintained a concurrent memory load or performed verbal random number generation or articulatory suppression (i.e., saying the word "the" once each second) gave fewer relational responses than a control group not performing a dual task. In a recent extension with this task, my lab replicated Waltz et al.'s articulatory suppression finding (i.e., saying the English nonword "zorn" once each second) and also found a similar effect for a visuospatial working-memory dual task (manually tapping a simple spatial pattern).

In the previous studies, the extent of interference with the analogy task was similar for both central executive (concurrent memory load and verbal random number generation) and slave system (articulatory suppression and spatial tapping) dual tasks. One explanation of these results is that analogical reasoning is more resource demanding than the deductive and spatial reasoning tasks previously discussed, and thus even the slave system tasks cause significant interference. Another possibility is that analogical reasoning places greater demands specifically on the modality-specific slave systems of working memory than other forms of relational reasoning. To investigate this issue, Morrison, Holyoak, and Truong (2001) had participants perform either a verbal or visual analogy task, while performing articulatory suppression (i.e., saying the nonword "zorn" once a second), spatial tapping (i.e., touching one of four red dots each second in a predetermined pattern), or verbal random number generation. In the verbal analogy task, participants verified verbal analogies, such as BLACK:WHITE::NOISY:QUIET, answering either TRUE or FALSE via a floor pedal. In the visual analogy task, participants performed Sternberg's (1977) People Pieces analogy task. In this task, participants verify whether the relational pattern of characteristics between two cartoon characters is the same or different than between a second pair of characters. Morrison, Holyoak, and Truong found that, for verbal analogies, articulatory suppression and verbal random number generation resulted in an increase in analogy error rate, whereas only verbal random number generation increased analogy response time for correct responses. Spatial tapping had no reliable effect on verbal analogy performance. In contrast, for visual analogy, both spatial tapping and verbal random number generation resulted in more analogy errors, whereas only random generation increased analogy response time. Articulatory suppression had no reliable effect on visual analogy performance. Thus, there seems to be a modality-specific role for working memory in analogical reasoning.

In summary, all of the reasoning tasks described in the previous section are interfered with by dual tasks considered to tap the central executive (e.g., random number generation or concurrent memory load). The deductive reasoning tasks reported require the manipulation and the alignment of premises that are provided in the problem. In addition to these operations, analogical reasoning may require the reasoner to retrieve information from semantic memory (e.g., the relations that bind the terms in the analogy) and then map the resulting relational statements (and in some cases make an inference that requires retrieving a term that completes the analogy).

To evaluate the extent that working-memory resources are necessary for semantic memory retrieval and relational binding, my lab went on to examine the component processes in working memory is necessary for analogical reasoning. We wondered whether working memory is necessary for the simple process of relational binding or only becomes necessary when multiple relations need to be maintained and compared during the analogical mapping process. To address this question, we used the stimuli from the verbal analogy task but simply asked participants to verify relational statements instead of comparing two of them as in the analogy task. Thus, participants would respond TRUE to a statement like “black is the opposite of white” and FALSE to the statement “noisy is the opposite of noisier.” As in the verbal analogy task, articulatory suppression and verbal random number generation affected performance with spatial tapping also having a smaller, but reliable effect. Thus, relational binding, not just maintenance and mapping, require use of the working-memory system, including the modality-specific slave systems.

Individual Differences in Working Memory

An alternative to Baddeley’s dual-task methodology uses individual differences to study working memory. Daneman and Carpenter (1980) first used this approach to investigate how working memory was involved in language comprehension. They developed a reading span task that required subjects to read several sentences and then later recall the last word of each sentence in the correct order. The participant’s span is typically defined as the maximum-sized trial with perfect performance. This measure correlated relatively well with individuals’ reading comprehension ability. Unlike a simple short-term memory-span task, the working-memory–span task required the subjects to do a more complex task while also remembering a list of items. In this way, the span task is believed to tap both the maintenance (slave system) and manipulation (central executive and episodic buffer) aspects of working memory. Other span tasks have been developed to vary the nature of the task that participants perform and what they maintain. For example, Turner and Engle (1989) asked participants to solve simple arithmetic problems and then remember a word presented at the end of each problem. In the n-back task (Figure 19.5; Smith & Jonides, 1997 for a complete description), the manipulation task is changed to having to continuously update the set of items. Using this approach, researchers have found working-memory capacity to be an important predictor of performance in a broad range of higher cognitive tasks, including reading comprehension (Daneman & Carpenter, 1980), language comprehension (Just & Carpenter, 1992), following directions (Engle, Carullo, & Collins, 1991), reasoning (Carpenter, Just, & Shell, 1990; Kyllonen & Christal, 1990), and memory retrieval (Conway & Engel, 1994).

Researchers using working-memory-span measures typically measure participants’ working-memory span using one or more measures and then use this to predict performance on another task. A high correlation suggests that working memory is an important target for the task. More sophisticated studies collect a variety of other measures of information processing ability (e.g., processing speed or short-term memory span) and use either multiple regression or structural equation modeling to determine whether these various abilities are separable with respect to the target task. Engle and his collaborators (Engle, Kane, & Tuholski, 1999; Kane & Engle, 2003b; see also

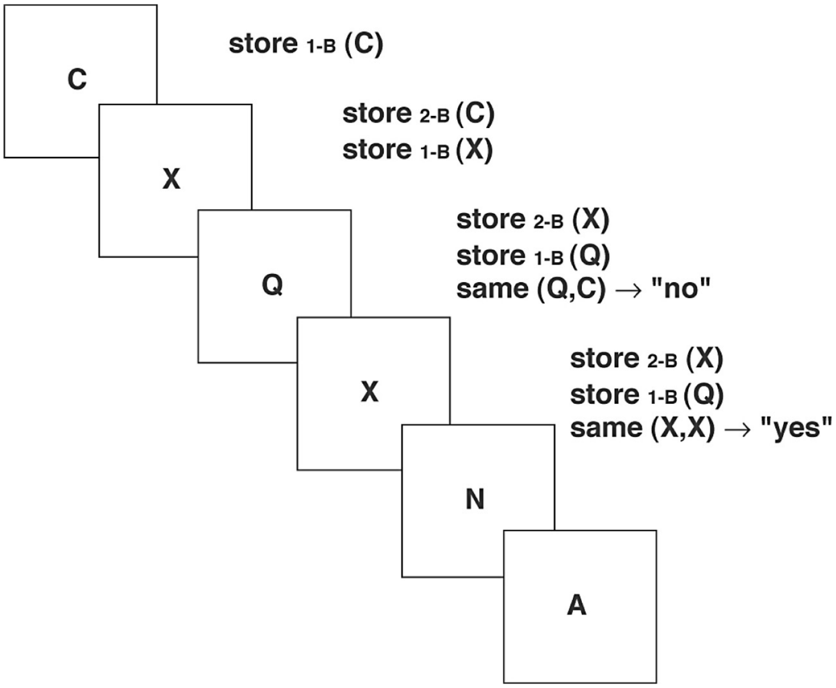

Figure 19.5. The n-back task. Participants see a stream of letters, numbers, or symbols and have to continuously answer whether the current item was the same as the item presented "n-back" in the stream. This task requires maintenance of the current in-set item and continuous updating of this set – an ability considered to be manipulation of the set.

Salthouse, Chap. 24) have used this approach to argue that, although working-memory-span and short-term-memory-span tasks share much variance, it is working-memory capacity that best predicts higher cognitive performance as measured by tasks such as the Ravens Progressive Matrices (see Figure 19.6).

Kane and Engle believe that the ability measured by a working-memory-span task once simple maintenance is stripped away is best described as controlled attention. They have argued that working-memory capacity is a good predictor of task performance in tasks that (a) require maintenance of task goals, (b) require scheduling competing actions or responses, (c) involve response competition or (d) involve inhibiting information irrelevant to the task (Engle, Kane, & Tuholski, 1999). This list is very similar to the functions that Baddeley (1996) attributes to the central executive. Obviously, these are the types of cognitive processes that are omnipresent in high-level cognition. They are also the types of cognitive abilities necessary to perform traditional tests of fluid or analytical intelligence such as the Ravens Progressive Matricies (1938), leading researchers to hypothesize that working-memory capacity is the critical factor that determines analytical intelligence (see Kane & Engle, 2003a; Sternberg, Chap. 31).

The Where, What, and How of Working Memory and Thought

So far, we have suggested that there are at least two important aspects of working memory for human thinking – a modality-specific maintenance function that is capable of preserving information over short periods of time and a manipulation or attentional control function that is capable

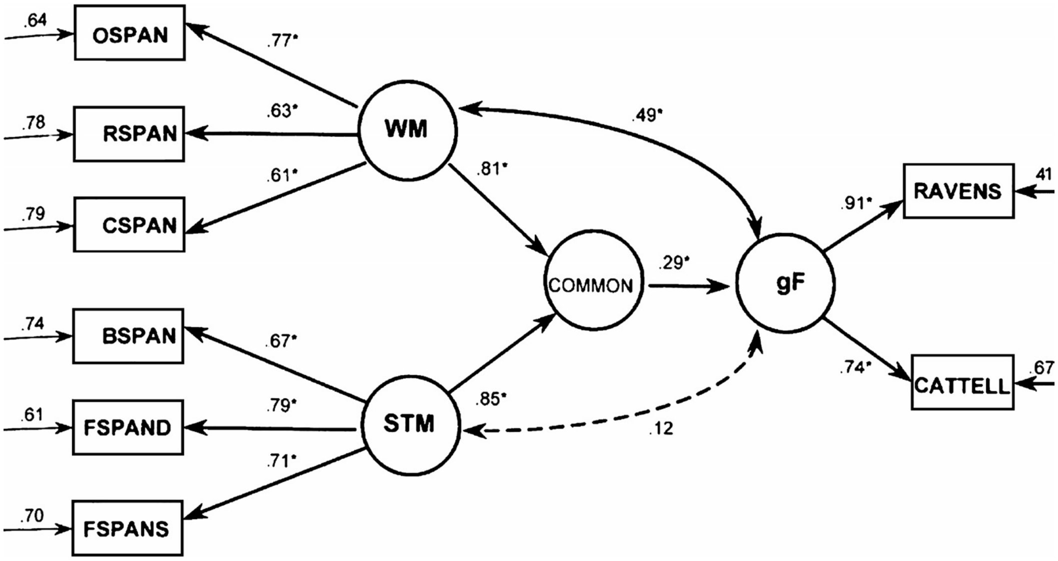

Figure 19.6. Structural Equation Model of the relationship of working memory and short-term memory and their role in analytic problem solving and intelligence. From Engle, Kane, and Tuholski (1999).

of activating, operating, and updating this information during conscious thought. Recently, cognitive neuroscientists have devoted much effort to answering the question of *where* in the brain these working memory mechanisms operate. This topic is beyond the scope of this chapter [see Goel, Chap. 20, for a more detailed treatment of the cognitive neuroscience of problem solving and Chein, Ravizza, and Fiez (2003) for a recent appraisal of the ability of Baddeley and Cowan's models to account for recent neuroimaging findings]; however, we know that at least several areas of the prefrontal and parietal corticies are critical for these functions. Although these areas may be specific to working memory, there is mounting evidence from both electrophysiology and functional magnetic resonance imaging (fMRI) that working memory is the result of activation of networks involving many brain regions.[2] A more interesting question than where, is *how* working memory operates thinking. Unfortunately, much less attention has been given to this question; however, several of the computational approaches outlined in this book begin to address this topic.[3]

It is the belief of many of the authors in this volume that high-level cognition is intrinsically relational in nature, a position long argued by many scientists (see Fodor and Pylyshyn, 1988; Spearman, 1923). In this account, one critical function for working memory to accomplish is the flexible binding of information stored in long-term memory. Working memory must also be able to nest relations to allow more complex knowledge structures to be used. Halford (Chap. 22) has referred to this factor as *relational complexity*. As the relational complexity of a particular problem increases, so do the demands placed on working memory. Goals are a particular subclass of relations that are especially important in deductive reasoning (see Goel, Chap. 20). Maintaining the complex goal hierarchies (high relational complexity) necessary for solving complex problems such as those encountered in chess or in tasks such as the Ravens Progressive Matrices or the Tower of Hanoi makes great demands on the working memory system (see Lovett & Anderson, Chap. 17; Carpenter, Just, & Shell, 1990; Newman et al., 2003). Most work directed at understanding how the brain implements working memory has focused on relatively simple tasks in which processing of relations is minimal.

The ways in which the brain's distributed architecture is used to process problems that require relation flexibility and relational complexity have just begun to be explored (see Christoff & Gabrieli, 2000; Christoff et al., 2001; Morrison et al., 2004; Prabhakaran et al., 2000; Waltz et al., 1999). Hummel and Holyoak's (1997, 2003; see also Doumas & Hummel, Chap. 4) LISA model solves the binding problem created by the need for the flexible use of information in a distributed architecture. The LISA model dynamically binds roles to their fillers in working memory by temporal synchrony of firing. This allows the distributed information in long-term memory to be flexibly bound in different relations and for the system to appreciate that the various entities can serve different functions in different relations and relational hierarchies. It is possible that one role of the prefrontal cortex is to control this synchrony process by firing the distributed network of neurons representing the actual fillers in long-term memory (see Doumas & Hummel Chap. 4, and Morrison et al., 2004, for a more detailed account of this approach). Although no direct evidence exists for synchrony of binding in high-level relational systems, several studies in animals (e.g., Gray et al., 1989) and in humans (e.g., Müller et al., 1996; Ruchkin et al., 2003) suggest that synchrony may be an important mechanism for other cognitive processes implemented in the brain. This type of system is also consistent with Baddeley's (2000) concept of an episodic buffer that binds information together in working memory.

Implicit in a working-memory system capable of handling relations is not only the ability to precisely activate information in long-term memory but also the ability to deactivate or inhibit it. Consider the simple analogy problem:

BLACK:WHITE::NOISY: ? (1) QUIET
(2) NOISIER

If the semantic association between NOISY and NOISIER is stronger than that between NOISY and QUIET, the correct relational response, QUIET, may initially be less active because of spreading activation in memory than the distractor item, NOISIER. Thus, during reasoning, it may be necessary to inhibit information that is highly related but inconsistent with the current goal (Morrison et al., 2004). This function of working memory has also been ascribed to the prefrontal cortex (see Kane & Engle, 2003b and 2003a; Miller & Cohen, 2001; and Shimamura, 2000, for reviews). Many complex executive tasks associated with frontal lobe functioning (e.g., Tower of Hanoi or London, Analogical Reasoning, Wisconsin Card Sorting) have important inhibitory components [Miyake et al., 2000; Morrison et al., 2004; Viskontas et al. (in press), and Welsh, Satterlee-Cartmell, & Stine, 1999]. Shimamura (2000) suggested that the role of prefrontal cortex is to filter information dynamically – a process that requires the use of both activation and inhibition to keep information in working memory relevant to the current goal. Miller and Cohen (2001) argued that "the ability to select a weaker, task-relevant response (or source of information) in the face of competition from an otherwise stronger, but task-irrelevant one [is one of the most] fundamental aspects of cognitive control and goal-directed behavior" (Ref. 48, p. 170) and is a property of prefrontal cortex. More generally, many researchers believed that inhibition is an important mechanism for complex cognition (see Dagenbach & Carr, 1994; Dempster & Brainerd, 1995; and Kane & Engle, 2003a, for reviews) and that changes in inhibitory control may explain important developmental trends (Bjorklund & Harnishfeger, 1990; Hasher & Zacks, 1988; Diamond, 1990) and individual differences (Dempster, 1991; Kane & Engle, 2003a, 2003b) in complex cognition.

Conclusions and Future Directions

Working memory is a set of central processes that makes conscious thought possible. It flexibly provides for the maintenance and manipulation of information through both activation and inhibition of information retrieved from long-term memory and newly accessed from perception. Relations are critical to thought and the working-memory system therefore must provide for the flexible binding of information. It also allows the problem solver to maintain goals that allow successful navigation of single problems but also allows for integration of various parts of larger problems. Working-memory capacity is limited, and this is an important individual difference that affects and perhaps even determines analytic intelligence. We know that working memory is critically dependent on prefrontal cortex functioning, but likely involves the successful activation and inhibition of large networks in the brain. Maintainence of information in working memory tends to be somewhat modality specific; however, attentional resources typically ascribed to a central executive tend to be more modality independent and allow for the connection of information from different modalities.

The future of working memory research resides in better understanding how these processes operate in the brain. Computational approaches allow researchers to make precise statements about functional processes necessary for a working-memory system to perform thinking and can provide useful predictions for evaluation with cognitive neuroscience methods. Whereas much effort has been placed on understanding where working memory resides in the cortex, much less attention has focused on how it functions. Understanding the neural processes underlying working memory will almost certainly require tight integration of methods that provide good spatial localization (e.g., fMRI) and good temporal information (e.g., electrophysiology) in the brain.

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Notes

1. The term "working memory" was originally used to describe rat behavior during radial arm maze learning [see Olton (1979) for a description of this literature). It was also used by Newell and Simon (1972)] to describe the component of their computational models that holds productions – that is, operations that the model must perform (see also Lovett and Anderson, Chap. 17).
2. Fuster (1997) has long argued for this approach to working memory based on electrophysiological and cortical cooling data from nonhuman primates. In Fuster's model, neurons in prefrontal cortex drive neurons in more posterior brain regions that code for the information to be activated in long-term memory. This perspective is also consistent with Cowan's (1988) Embedded-Processes model. See also Chein, Ravizza, and Fiez, 2003.
3. Both ACT (Lovett and Anderson, Chap. 17) and LISA (Doumas and Hummel, Chap. 4) provide accounts of how working memory may be involved in higher-level cognition. These theories and computational implementations provide excellent starting points for investigating how the brain actually accomplishes high-level thought. An excellent edited volume by Miyake and Shah (1999) reviews many of the traditional computational perspectives on working memory.

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