What is Working Memory, and How is it “Working" In the Brain?

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Abstract

Working memory plays vital roles in virtually any type of our behaviors and cognitive tasks, including learning and decision-making. In this paper, the nature and the structure of working memory system are discussed. Working memory is characterized by a short duration of retention and severely limited capacity. This paper analyzes various approaches to study the characteristics of working memory and theoretical models of the underlying core processes. Finally, this paper also discusses an ongoing debate on whether working memory relies on a distinct mechanism from the long-term memory system.

Keywords: Psychology, Working Memory, Cognitive Science, Memory Systems

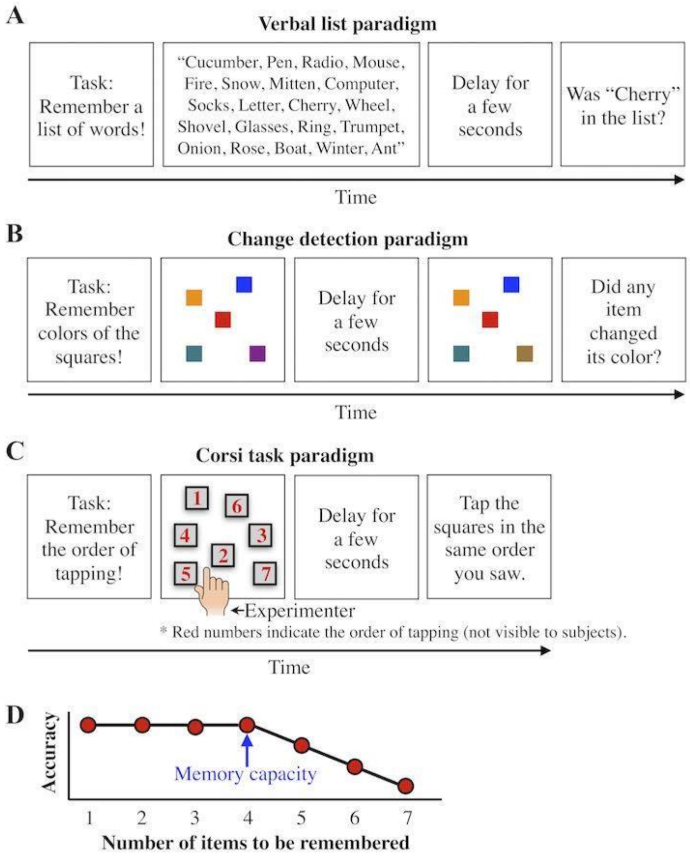
Introduction

Task #1: Do not use a pen and paper: Mentally add 118 and 367.
Task #2: Follow the instructions in your recipe book to bake a loaf of banana bread.
Task #3: Choose the right size for a sweater for your grandmother in a gift shop. Task #4: Read and comprehend this sentence.

To complete these and many other complex tasks, we always need to rely on our memory system in our brain. Consider the first example (i.e., Task #1) shown above. First of all, you will need to create a temporary memory representation for the two numbers to be added. Because the operation will take some time, your memory for the two numbers needs to survive at least for several seconds, until you complete the task. While you maintain the two numbers to be summed, you also need to allocate your attention to different portions of memory to apply relevant rules to mathematical operations. You might first focus your attention on adding “8” and “7” then shift your attention to the “tens” digits (“1” and “6”), while mitigating interference from the other digits (“1” and “3”) and maintaining the partial results of previous operations (e.g., “15” from adding “8” and “7”). While attending to the local part of the problem (e.g., adding the “tens” digits), you also need to maintain the other parts of the problem that are not in the current focus of your attention (e.g., that you now have the digit “5” as a portion of the final answer). All these tasks require what neuroscientists refer to as working memory. In fact, there is hardly a task that can be completed without working memory, making it a critical component of our thoughts and mental processes. This paper will review the current knowledge in the field regarding what working memory is and how it works in the brain to support a variety of cognitive processes and our daily life activities.

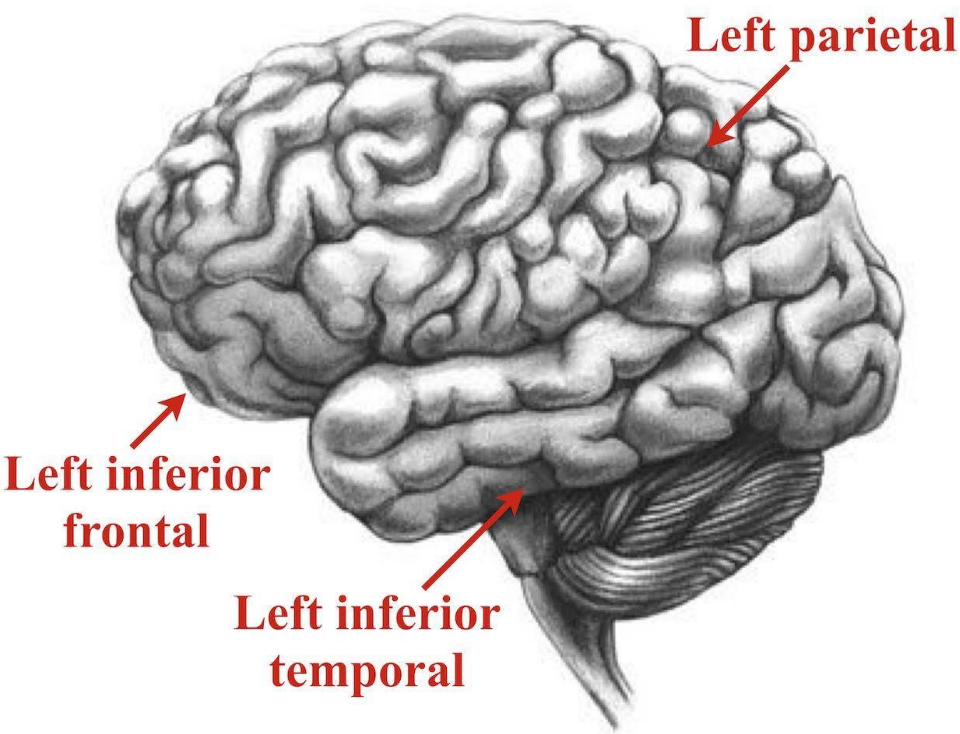
What is the working memory, and how do scientists study it? As somewhat implied in its term, the working memory is the active, thinking part of our memory. The term “short-term memory” can also be used interchangeably because it only lasts about 10-15 seconds without any rehearsal or special aids (Towse, Hitch, & Hutton, 2000). However, some cognitive psychologists differentiate between working memory and short-term memory. They refer to short-term memory as brief storage of information, whereas working memory is considered to be a process that involves both storage and active manipulation of information in a broader concept, to serve the needs of ongoing tasks (as in the math problem example) (Luck and Vogel, 1992), (Baddeley, 1992).

Figure 1



Cognitive psychologists have been testing the function and nature of working memory by using a variety of experimental paradigms in many different task domains. One of the classic ways to test verbal working memory is a verbal list paradigm (Rabin, Barr, & Burton, 2005). In this paradigm, experimenters provide a random list of nouns, words like tulip, hamburger, goat, chair, cook, and shark, and so on. Afterward, a subject is tested to see whether she or he can either recall or recognize some of the words that were present in the list. Figure 1A shows a sample trial of verbal working memory test using a verbal list paradigm. Unlike verbal working memory, testing visual working memory does not involve verbal language. A change detection paradigm is one of the classic ways to measure visual working memory (Figure 1B). In a change detection test, experimenters show a display of multiple objects, followed by a brief delay (e.g., 1 second). After the delay a subject is shown the other image of multiple objects which is sometimes identical to the previous display, but sometimes not. A subject is then asked to judge whether any one of the items in a particular location has changed in its feature such as color (Luck and Vogel, 1997), compared to the previous display. Another example of an experimental paradigm to test visual working memory is a Corsi block task (Corsi, 1972). The Corsi block task (Figure 1C) requires subjects to touch a series of blocks in the same order as the experimenter had done in front of them. For both verbal working memory and visual working memory, experimenters can

measure a subject's working memory capacity, or often called working memory span, by varying the number of items to be remembered in a verbal list or a visual
image display. Figure 1D shows how a subject's accuracy changes with the increasing number of items to be remembered. The working memory span is defined as the number of items that a human observer can remember at once. The converging evidence from various research studies that utilized these working memory test paradigms suggests that working memory has a very limited capacity. Working memory has been found to hold only about three or four items at one time, referred to as "magical number 4" by many experimental psychologists (Luck and Vogel, 1997), (Cowan, 2001), (Sperling, 1960), (Pashler, 1988). **Figure 2**



The advent of different neuroimaging techniques such as functional magnetic resonance imaging (fMRI), event-related potential (ERP), and electroencephalogram (EEG) has allowed scientists to better understand how some of the brain areas work to support the functions of working memory. Brain areas that support functions of verbal working memory and visual working memory seem highly overlap, although there exist some differences as well. Verbal working memory has been found to rely primarily on left inferior frontal and left parietal areas, and visual working memory has also been found to rely on left inferior frontal, left parietal, and left inferior temporal areas [Figure 2]; (Smith and Jonides, 1999), (Wager and Smith, 2003). The difference is that verbal working memory shows a marked left hemisphere dominance, unlike visual working memory, partly because of the overall left hemisphere preference for language processing (Na, Rhyu, & Byun, 2000), (Raja, Dick, & Josse, 2010). Findings from electrophysiological and neuroimaging studies also support the idea of "magical number 4". For example, researchers (Vogel, Machizawa, 2004) recorded event-related potentials (ERPs) from human subjects while they were performing a change detection task for visual working memory measurement. The researchers found ERP recording from parietal and occipital parts of the brain reflected the active involvement of these areas in retention period during the task and the signals from these areas also showed systematic changes depending on the number of items held in working memory. Importantly, however, the ERP signals from these areas reached a plateau and did not change anymore, when more than three or four items had to be remembered. The magnitude of these signals also correlated with each subject's memory capacity. The subjects who showed greater working memory span also showed greater ERP signals from these brain areas. Furthermore, functional magnetic resonance imaging (fMRI) studies have shown that similar brain areas (Todd and Marois, 2004), (Todd and Marois, 2005) were sensitive to the number of items to be held in working memory. These areas also showed different activation patterns when subjects correctly remembered the items vs. when subjects failed to recognize the items correctly. The neuroimaging studies, combined with the behavioral testing paradigms, have been very informative in understanding how the brain works to support working memory.

The three core stages of the working memory system What are the cognitive underpinnings of working memory functions? Some cognitive psychologists (Baddeley, 2003), (Unsworth and Engle, 2007) have proposed a model of working memory. According to their model, new information from the external world is processed, manipulated, and stored through the three core stages: (1) encoding process where perceptual information is transformed into cognitive representation for attentional focus, (2) maintenance process where information in the attentional focus is kept for a while for mental operations, and (3) retrieval process where some cognitive representations are reactivated from the past into the current attentional focus for the mental operations.

The encoding process of information is the initial step for creating efficient working memory and limit our attentional focus only to task-relevant events and information. Researchers have found that brain areas that are actively involved in the encoding stage for working memory include the lateral prefrontal cortex and inferior frontal junction (Postle, 2006). They used images of colors and faces and monitored brain activation patterns while human subjects were encoding these visual items in the functional MRI scanner. They found that the temporal profile of these brain areas was closely associated with the duration of the encoding process. Moreover, these brain areas showed differential durations of activity when subjects spent more time in encoding complex objects (e.g., faces) versus when they rapidly encoded simple features (e.g., colors). It is worth noting that these regions are also previously shown to reflect attentional limitations to conscious perception. Thus, this finding suggests that working memory encoding served by the prefrontal cortex functions is a “rate-limiting” process that controls the rate and the amount of information.

Once some task-relevant information is selected for attentional focus in the encoding stage, what keeps that selected information in our working memory even when it is not currently perceived? Many neuroscientists have sought to address this question to better understand the maintenance processing. How can selected information be stored in mind for future actions after all the perceptual input is actually gone? Recently, there is considerable neurophysiological evidence that both prefrontal and posterior areas of the brain work together for active maintenance of information in working memory. Classic findings showed that some neurons in prefrontal cortex fired selectively during the delay period when a monkey was trying to maintain simple images (Funahashi, Bruce & Goldman-Rakic, 1989), (Fuster, 1973). More recent neuroimaging studies also showed that a brain circuit of frontal and posterior areas plays a vital role in preserving working memory representations (Pasternak and Greenlee, 2005), (Ranganath, 2006).

The final stage of working memory is the retrieval process. Unlike the maintenance stage, not much research has been done yet. It is assumed that working memory retrieval of information is a rapid and parallel process in which information outside of attentional focus is brought back to the current attentional focus for active mental operations. For the information outside of attentional focus to be retrieved into the current working memory processing, it should be stored somewhere else, which is suggested to be “long-term memory." Experimental psychologists test the working memory retrieval process by showing subjects memory sets consisting of a sequence of verbal items (e.g., letters or digits). Then they ask a human subject to identify whether the probe item was a member of the memory set (Oztekin, McElree & Staresina, 2009). More future research needs to be done to better understand how information stored in the long-term memory is retrieved for further mental operations of working memory.

An ongoing controversy: Is working memory qualitatively different from long-term memory?

Working memory is a critical ability in the present moment to maintain and utilize any useful information in our mind, but not necessarily in a year from now on. As reviewed above, working memory is characterized by a very short retention duration and severely limited capacity. On the other hand, we also have more durable and stable information stored in our long-term memory. For example, we can remember certain events such as where you were during 9/11(if you were alive at the time), and we can also recall motor skills we learned years ago such as roller-skating. Such type of information is stored in long-term memory, which can be retrieved into working memory to be used again when it is needed. Neuroscientists have suggested that there is no capacity limit in long-term memory. Due to such differences between working memory and long-term memory in their storage and timing, neuroscientists have been trying to examine whether they are completely distinct brain systems, or whether they rely on the same mechanisms.

Some neuroscientists suggest that working memory and long-term memory rely on completely different subsets of brain areas for the retrieval process. They suggest that working memory seems to rely on the hippocampus area of the brain, whereas long-term memory is stored throughout the cortex of the brain (Frankland and Bontempi, 2005), (McClelland, McNaughton & O'Reilly, 1995). The two different brain systems in the hippocampus and cortical areas might explain how our memories and experiences are so different. Classic examples come from studies of patients with impaired working memory. Some patients have shown grossly impaired working memory span, combined with relatively intact long-term memory storage (Vallar, Papagno, Baddely, Kopelmen & Wilson, 2002), (Shallice and Warrington, 1970). The opposite pattern has also been reported. Some other patients with severe damage in their medial temporal areas of the brain have shown impaired long-term memory but preserved working memory (Baddeley and Warrington, 1970). Researchers have also reported neuroimaging data from healthy human subjects and showed some sub-regions in the medial temporal and frontal areas selective for each memory system (Cabeza, Dolcos, Grahm & Nyberg, 2002), (Talmi, Grady, Goshen-Gottstein & Moscovitch, 2005). Moreover, there has been a report that the brain activity of hippocampus showed sensitivity to the human subject's recognition accuracy during working memory span tests (Squire, 1992). Based on such evidence, they have proposed that working memory and long-term memory are separable brain systems.

On the other hand, some other groups of researchers have reported their discoveries suggesting that retrieval processes of working memory and long-term memory rely on the same mechanism. They argue that working memory is simply a temporary activation of some portion of long term memory storage (Cowan, 2001), (Jonides, Lewis, Lustig, Berman & Moore 2008). According to their view, working memory is a subset of long-term memory, which belongs to one large storage system. Much evidence from neuroimaging studies has been reported to support this view. For example, substantial overlaps in the brain areas during working memory and long-term memory retrieval have been reported, including lateral prefrontal regions and medial temporal regions of the brain (Cabeza and Nyberg, 2000), (Fletcher and Henson, 2001).

Since the controversy is still ongoing, future research would need to pursue better measurements with multimodal neuroimaging techniques for higher spatial and temporal resolution and reliable computational approaches.

Conclusion

This paper reviewed the current literature on the characteristics and structure of working memory and some exciting discoveries on brain functions that support working memory from recent neuroimaging studies. Working memory is an essential part of our mental processes and our daily routines and behaviors. Although working memory plays a vital role in shaping our ability to learn and function in the world around us, it is severely limited in terms of both duration and capacity. The recent emergence of computing tools and technologies will allow future neuroscience research to make meaningful progress in the field, by characterizing how different brain areas work in concert in real-time to help humans (and potentially robots as well) select something important for the current goal (e.g., encoding), keep it during mental operations (e.g., maintenance), and bring some old memories back to the current workplace of working memory (e.g., retrieval). Such understanding will also be also valuable for developing artificial intelligence and designing medical devices for patients who experience difficulties with their working and long-term memories.

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