

# Working memory, fluid intelligence, and science learning

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## Abstract

A review of the history of working memory (WM) studies finds that the concept of WM evolved from short-term memory to a multi-component system. Comparison between contemporary WM models reveals: (1) consensus that the content of WM includes not only task-relevant information, but also task-irrelevant information; (2) consensus that WM consists of phonological and visuospatial components; (3) consensus that short-term memory storage is a function of WM; (4) disagreement as to whether an independent executive control is a necessary WM component; and (5) disagreement as to whether the control function is active or passive. Methods for measuring WM differed across studies with a preponderance of various dual-tasks; little psychometric work has been done on these measures. Correlational studies supported a close relationship between WM and measures of fluid intelligence and science achievement, but we found no experimental studies on the impact of WM training on science achievement. Finally we suggest how WM research findings may be applied to improve fluid intelligence and science achievement.

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Working memory (WM) is responsible for temporarily maintaining and manipulating information during cognitive activity (Baddeley, 2002). It has been found to be closely related to a wide range of high-level cognitive abilities such as reasoning, problem-solving, and learning (Kyllonen & Christal, 1990). In addition, WM is related to academic achievement in the domain of reading (Daneman & Tardif, 1987), writing (Abu-Rabia, 2003), mathematics, and science (De Smedt, Ghesquiere, & Verschaffel, 2004; Gathercole, Pickering, Knight, & Stegmann, 2004). As WM plays an important role in cognitive activity, researchers are exploring ways of applying WM research to improve abilities such as fluid intelligence – the ability to understand complex relationships and solve new problems (Martinez, 2000) – and science achievement. This paper tracks the history of WM studies, synthesizes the definition of WM, contrasts measures of WM, summarizes the relationship between WM and fluid intelligence and science achievement, and discusses how to apply findings from WM research to improve fluid intelligence and facilitate science learning.

## 1. History of WM studies

Studies of WM date back to the 1880s when Ebbinghaus (1885) pioneered the use of nonsense syllables to study learning and forgetting in controlled experiments. Through his research, Ebbinghaus found that he could correctly recall

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seven syllables after just one reading. James (1890) introduced the term “primary memory” to represent the cognitive construct responsible for temporary maintenance of information. He explained that images in primary memory are lost forever unless they are consciously sustained in the mind for a sufficient period of time. More than half a century later, Miller (1956) proposed the term “immediate memory” and described its capacity as  $7 \pm 2$  units or “chunks” of information, which is consistent with Ebbinghaus’ finding on temporary memory capacity.

As cognitive psychology developed, research provided more detailed understandings of memory. Atkinson and Shiffrin (1968) proposed a memory model which included a sensory store, short-term memory (STM), and long-term memory (LTM). According to their model, incoming information was first registered in the sensory store. A limited amount of this information was attended to and passed onto STM; information not attended to was lost. STM was viewed as a capacity-limited, unitary memory store which temporarily kept information for further processing. Information in STM decayed after two seconds if not rehearsed (Miyake & Shah, 1999). Rehearsed information was encoded and saved in LTM, an unlimited store that retained information for long periods. Information relevant to a cognitive task could be retrieved from LTM at a later time.

Memory researchers recognized that theories of STM could not adequately describe the kind of temporary memory that complex cognitive tasks require (Shah & Miyake, 1999). Eventually, memory research gave rise to theories in which STM was seen as one component of a larger system known as WM. Researchers proposed different theories to demystify WM, including models focusing on the structure and function of WM (Baddeley & Hitch, 1974; Cowan, 1999; Engle, Kane, & Tuholski, 1999; Oberauer, Süß, Wilhelm, & Wittmann, 2003), models emphasizing WM processes (Kieras, Meyer, Mueller, & Seymour, 1999; Lovett, Reder, & Lebiere, 1999; Young & Lewis, 1999), and a model stressing the source of content in WM (i.e., the connection between WM and LTM) (Ericsson & Delaney, 1999). These models provided different but complimentary views of WM and contributed to a comprehensive understanding of WM.

## 2. Definitions of working memory

Although studies of WM have a long history, researchers have not reached unanimous agreement as to what WM is (Kyllonen, 2002). Differences in WM models commonly reflect different ideas about the complexity of WM. According to Miyake and Shah (1999), WM models have evolved from a single unitary memory store to a system containing multiple cognitive subsystems responsible for different storage and executive control functions. For example, Miller’s (1956) finding that immediate memory stored only  $7 \pm 2$  “chunks” of information represented the early understanding of WM as a single information store. Baddeley and Hitch’s (1974) model of WM as a multiple-component system consisting of a phonological loop, a visuospatial sketch pad, and a central executive started the age of decomposing WM into different components. The same idea is reflected in other WM models that followed. Although researchers differ in their specifications of WM subsystems, most agree that WM includes multiple subsystems working together to activate task-related information, maintain activation, and manipulate information during the performance of cognitive tasks (Miyake & Shah, 1999). The evolution of WM models shows that ideas about WM have shifted towards a more dynamic and systematic view.

In addition to their different ideas about the complexity of WM, researchers also took different perspectives when they defined WM. Contemporary models define WM from different angles such as content, structure, function, or a combination of these dimensions (Miyake & Shah, 1999). In order to develop a comprehensive understanding of WM, we will compare different perspectives on WM that reflect the aforementioned dimensions.

### 2.1. Content

Most researchers agree that WM stores task-relevant information (Baddeley & Hitch, 1974; Engle, Kane, et al., 1999; Ericsson & Delaney, 1999; Oberauer, Süß, Schulze, Wilhelm, & Wittmann, 2000). Some researchers argue that certain task-irrelevant information is also stored in WM. For example, Lovett et al. (1999) defined the content of WM as a group of activated declarative knowledge nodes, which included both task-relevant and task-irrelevant information. They asserted that some task-irrelevant knowledge nodes were also included in WM because they were highly activated. The inclusion of task-irrelevant information in WM might contradict prior understanding of WM. However, as discussed later, the control function of WM is partially exhibited in inhibiting the influence of task-irrelevant information. Therefore, the inclusion of task-irrelevant information is reasonable and helpful for an accurate understanding of the information content of WM.

As to the source of information in WM, a majority of researchers agree that LTM is a source of information for WM. For instance, Engle, Kane, et al. (1999); Engle, Tuholski, Laughlin, & Conway (1999) contended that WM consisted of LTM traces activated above threshold. Ericsson and Delaney (1999) used the term “long-term working memory” to emphasize the close relationship between WM and LTM. It is reasonable, then, to relate the content of WM to LTM since people draw upon knowledge and prior experience stored in LTM to solve problems. However, as prior studies found, as important as WM is in learning and solving new problems (Kyllonen & Christal, 1990), sensory information from the external world must also be an important part of the content of WM. Thus, both LTM and the external world are sources of WM content.

## 2.2. Structure

Researchers decompose WM into different components, but diverse opinions exist as to what components should be included. Baddeley (2002) proposed that WM was composed of a phonological loop, a visuospatial sketchpad, an episodic buffer, and the central executive. The phonological loop is responsible for temporary storage and manipulation of acoustic and verbal information. The visuospatial sketchpad is used to temporarily store and process visual and spatial information, such as shapes, locations, or movements. The episodic buffer is viewed as an interface which assembles information from WM and LTM. The central executive is responsible for allocating attention and coordinating activities between the three other components.

The ideas of phonological and visuospatial WM are widely supported by other WM models. For instance, Oberauer et al. (2000) used factor analysis on 23 WM measures and found two dimensions among these measures: content and function. The content dimension of WM was further decomposed into acoustic and spatial content. In Barnard's (1999) model, acoustic and visual subsystems were two main sources of information for WM. However, Kieras et al.'s (1999) WM model included WM components not only for auditory and visual information, but also for tactile and kinesthetic information. Even though it is widely accepted that WM stores phonological and visuospatial information, it is worthwhile to investigate the possibility of storing other types of information as well.

Although most researchers agree on the phonological and visuospatial stores in WM, there is clearly a disagreement about the existence of a central executive component in the structure of WM. While some researchers accept its existence, others do not adopt the notion of a unitary control component. For example, Engle, Kane, et al. (1999) argued that controlled attention was responsible for the executive function. In contrast, Barnard (1999) contended that WM involved multiple processing subsystems and that the interaction processes among different subsystems realized the executive control function.

Similarly, Lovett et al. (1999) did not include a separate control component in their WM model, as they argued that control over the activation of information and maintenance of the activation were automatically decided by the relationship among task goal and knowledge nodes and the activation threshold for each specific knowledge node. In their model, the propagation of attention resources from the task goal to related knowledge nodes represents the activation process. The relation between task goal and knowledge nodes determines which knowledge nodes receive what amount of attention resources in this process. The closer a knowledge node is related to the task goal, the more attention resources it receives. In addition, the activation threshold of a specific knowledge node, which represents the minimum amount of attention resources needed to activate that knowledge node, results from a prior retrieval record. The more a knowledge node has been retrieved in the past, the lower its threshold, and the less attention resources are required for it to be activated.

Regarding the maintenance of activation, Lovett et al. (1999) provided a mathematical function of elapsed time. Based on this function, the maintenance time of a specific knowledge node could be estimated using the difference between attention resources received and the activation threshold of the node. Therefore, control of activation and maintenance of activation is jointly determined by the relationship among task goal and knowledge nodes and the activation threshold of each knowledge node. No separate control component is necessary in their model. Both Barnard (1999) and Lovett et al.'s (1999) WM models successfully predicted performance on WM tasks. Thus, it is possible that the control function is realized through internal activities of WM instead of by a separate control component.

In summary, separate components for phonological and visuospatial WM are widely supported in current WM models, while further studies are needed to examine the existence of an independent component for the control function. The decomposition of WM's structure provides a detailed picture of WM and contributes to a better understanding of this complicated system. However, the structural perspective runs the risk of representing WM as a certain fixed

structure somewhere in the brain. Although studies in neuropsychology have demonstrated that certain areas of the cortex are highly activated when individuals engage in WM tasks, it is important to keep in mind that decomposing WM into different components provides only a conceptual picture, not the concrete structure of WM (Miyake & Shah, 1999).

### 2.3. Function

Instead of focusing on the content and structure of WM, many researchers study WM from a functional perspective. Generally, WM is thought to be responsible for storing task-relevant information while performing cognitive tasks, coordinating information processing tasks, and inhibiting interference from activated task-irrelevant information. Researchers divide these functions into two main categories: storage and executive control. They agree that WM has a storage function and use working memory capacity (WMC) to represent the amount of information activated and retained while completing cognitive tasks.

Researchers agree upon the existence of the executive control function, but they provide different descriptions of how to realize the control function. Some researchers state generally that WM has a control function, while others provide detailed explanations of how this function is realized; some argue that the control function is carried out consciously, while others believe that it is affected by different factors or the result of interactions among different subsystems.

For instance, [Baddeley and Hitch \(1974\)](#) asserted that an executive control component in WM was responsible for all control activities, but they did not offer a detailed explanation of how WM realizes its control function. Both [Cowan \(1999\)](#) and [Engle, Tuholski, et al. \(1999\)](#) also supported the idea that controlled attention was responsible for the execution of control function but did not provide detailed descriptions as to how the control function was implemented.

Working from the information-processing perspective, [Kieras et al. \(1999\)](#) specified two stores in WM as the foundation for the executive control function: the control store and the tag store. The former stores items including goals, steps, strategies, and task status information. The latter serves as a catalogue system which holds labeling information for items stored in WM. Additionally, Kieras et al. set up different conditional rules to realize the control function. These rules served as guidelines for clarifying the task goal, selecting task-relevant information, supervising the execution process, and adjusting thinking and behavior to achieve the goal. [Schneider \(1999\)](#) also provided a detailed explanation of how WM realizes its control function. He specified a central executive in his cognitive information process model and summarized its six functions: comparing information, attending to high-priority messages, managing the buffering of information, configuring the information processing network to process a particular task, building new associations, and performing goal-based operations.

The WM models described above convey the idea that WM maintains active control over its functions. Some researchers disagree with this idea and argue that the control function is a passive process, representing the result of interactions between different factors or subsystems. As described in Section 2.2, [Lovett et al. \(1999\)](#) explained the control over activation and maintenance of activation in WM as an interaction between task goals and knowledge nodes and the activation threshold of individual knowledge node. Therefore, there is no conscious control over the propagation and decay of attention resources.

A similar idea is reflected in [Barnard's \(1999\)](#) WM model. Although Barnard did not agree to the existence of a separate control component in WM, he acknowledged that WM played an important control function in performing cognitive tasks. He argued that since there was no central control in WM and the performance of WM was dependent on different subsystems, the realization of the control function occurs through interactions among different cognitive systems rather than by following orders from the "central office."

In sum, researchers endorse the storage and control function of WM, but differ as to how the control function is realized. Further studies should seek to determine whether it is an active or passive process.

### 2.4. Syntheses of WM definitions

From the analysis of the content, structure, and function of WM, one may recognize that a definition based on only one dimension does not provide a full picture of WM. For this reason, some researchers have proposed definitions encompassing multiple dimensions to provide a comprehensive understanding of WM.

Miyake and Shah (1999) analyzed different WM definitions in order to provide a synthesized description of WM. In their definition, WM represents all processes and mechanisms involved in activation of task-relevant knowledge in LTM, activation maintenance, and coordination and regulation of these processes. Information is represented in different formats, and manipulation of information is implemented through interactions among different subsystems. The capacity of WM represents the influence of multiple factors and results from the interaction among subsystems. Like Miyake and Shah's effort to provide a synthesized definition of WM, Oberauer et al. (2000) proposed a hierarchical model of WM based on factor analysis of 23 WM tasks. In their definition, WM was depicted with two higher-order factors—content and function. Verbal and numerical WM and spatial WM were the two subfactors of the content factor. The first subfactor of function is responsible for the storage, transformation, and coordination of information, and the second subfactor combines supervision and processing speed.

These two synthesized definitions of WM provide a more complete picture of WM than those only focusing on one aspect of WM. However, there are still aspects of WM that these synthesized definitions have not addressed, such as how WM combines information from the external world with information from LTM, or whether WM actively or passively controls its activities. Therefore, it is a challenge for future studies to incorporate new findings with what is already known to develop a comprehensive definition of WM.

The trend toward a multidimensional definition of WM highlights both the complexity of WM and the need to understand WM from different angles. These complex definitions deepen our understanding of WM, but they raise big challenges for the measurement of WM. In the next section we review commonly used measures of WM and addresses challenges for measurement of WM in future studies.

### 3. Measurement of WM

From the early use of simple memory span tasks in intelligence tests (Ackerman, Beier, & Boyle, 2005) to the more recent rise in popularity of dual-tasks, great variety exists in the measurement of WM. In this section, we contrast several commonly used measures of WM, including simple memory span, dual-tasks, and other measures used in prior studies. Finally, we discuss challenges for measuring WM in future studies.

#### 3.1. Simple memory span

Simple memory span tasks present the subjects with a series of stimuli, usually letters, words, digits, shapes, or positions, and require them to recall those stimuli in the same or reverse order as they were presented. For example, Masson and Miller (1983) used a simple letter span memory task to measure WM. In the experiment, participants were presented nine series of consonants, each with 4–10 consonants. Every consonant appeared for 1 s on a screen. After the presentation of each series, participants were asked to write down the consonants in the sequence in which they appeared. Kail and Hall (2001) used three types of simple memory span. In their simple letter span task, they presented participants with two letters at a time, asked them to read the letters aloud, at a rate of approximately one letter per second, and then recall the letters in the same sequence. If recall was entirely correct, the procedure was repeated with another two letters. If the participants recalled both trials on level two correctly, the number of letters to be recalled increased by one. This procedure continued until the participant failed on one trial. The final score was the level at which the participant recalled both trials correctly. Their digit and word simple memory span tasks have the same structure as the letter simple span, with the test materials changed to digits 1–9 and nine one-syllable words.

The simple memory span tasks above require the participants to recall the test stimuli in the order they were presented. Other simple memory span tasks ask participants to recall the stimuli in the reverse order, including backward digit span (Ackerman, Beier, & Boyle, 2002; Oberauer et al., 2000), and backward word span (Rosen & Engle, 1997). These simple memory span tasks mainly measure the phonological storage of WM.

Two additional simple memory span tasks have been commonly used to measure the visuospatial storage of WM (Cornoldi & Venville, 2003). In the Corsi Test (Corsi, 1972), the experimenter lays down a series of identical blocks on a board. The participant is required to remember the sequence in which the blocks are laid down and then repeat the sequence—either forwards or backwards (Vecchi & Richardson, 2001). In the Visual Pattern Test (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999), participants are presented with a matrix, in which half of the cells are shaded in black. Then they are given a black matrix, which has the same number of rows and columns as the first one. Participants are supposed to indicate on the black matrix where the black cells were in the original matrix.



Table 1  
Procedural sequence in the reading-span task

	Level 2	Level 3	Level 4	Level 5	Level 6
Set 1	Sentence 1 Sentence 2	Sentence 7 Sentence 8 Sentence 9	Sentence 16 Sentence 17 Sentence 18 Sentence 19	Sentence 28 Sentence 29 Sentence 30 Sentence 31 Sentence 32	Sentence 43 Sentence 44 Sentence 45 Sentence 46 Sentence 47 Sentence 48
	Recall	Recall	Recall	Recall	Recall
Set 2	Sentence 3 Sentence 4	Sentence 10 Sentence 11 Sentence 12	Sentence 20 Sentence 21 Sentence 22 Sentence 23	Sentence 33 Sentence 34 Sentence 35 Sentence 36 Sentence 37	Sentence 49 Sentence 50 Sentence 51 Sentence 52 Sentence 53 Sentence 54
	Recall	Recall	Recall	Recall	Recall
Set 3	Sentence 5 Sentence 6	Sentence 13 Sentence 14 Sentence 15	Sentence 24 Sentence 25 Sentence 26 Sentence 27	Sentence 38 Sentence 39 Sentence 40 Sentence 41 Sentence 42	Sentence 55 Sentence 56 Sentence 57 Sentence 58 Sentence 59 Sentence 60
	Recall	Recall	Recall	Recall	Recall

Although these simple memory span tasks are still used in current studies of WM, most researchers view them as tapping primarily the storage component of WM and not the control function of WM (Conway, Cowan, Bunting, Theriault, & Minkoff, 2002; Engle, Tuholski, et al., 1999). Some researchers believe backward simple memory span tasks require more of the control function of WM than forward simple memory span tasks do. Oberauer et al. (2000) argued that backward digit span is a good measure of “simultaneous storage and transformation” (p. 1025).

3.2. Dual-tasks

Daneman and co-workers (Daneman & Carpenter, 1980; Daneman & Tardif, 1987) developed a series of dual-tasks according to Baddeley and Hitch’s (1974) definition of WM, which required simultaneous processing and storage of information. These dual-tasks consist of a processing task and a memory task. Participants’ performances on the memory task were used as measures of their WMC.

The processing task for reading-span dual-tasks is to read a series of sentences, while the memory task is to recall the last word in each sentence. The reading-span dual-tasks involved 60 unrelated sentences, 13–16 words in length which ended with different words. For example, one sentence was “The taxi turned up Michigan Avenue where they had a clear view of the lake” (Daneman & Carpenter, 1980). These sentences were divided into 15 sets, each containing *N* sentences ( $2 \leq N \leq 6$ ) (Table 1). After participants finished reading the sentences in each set, they were required to recall the last word of each sentence in the order that the sentences were presented. The sequence of sentences in the reading-span task started from set 1 of level 2 (a set of two sentences, see Table 1). After the participant finished all three sets on one level, he or she moved on to set 1 of the next level. The test stopped at the level at which the participant failed all three sets. The level at which the participant succeeded in two of the three sets was recorded as the WMC of that participant.

The format of mathematics-span dual-tasks and spatial-span dual-tasks are the same as that of reading-span dual-tasks. The difference exists in the processing task and the content of the memory task. For the mathematics-span dual-tasks, the processing task is to select two out of three numbers to make a new number which could be evenly divided by 3. The memory task is to recall the new number generated after a certain number of tasks. For example,

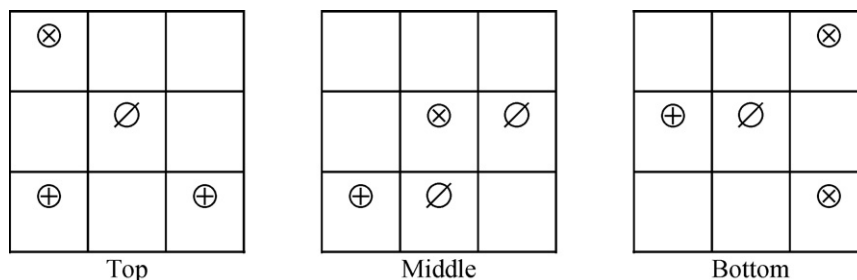


Fig. 1. Example of spatial span task for working memory. Note: (⊗), (∅), and (⊕) represent different tokens. Tokens used in the real task may be different from these symbols.

given the series 26-9-72, a participant would need to select 9 and 72 to come up with the new number 972. After several processing task trials, the participant recalls the numbers he/she generated.

Spatial-span dual-tasks present participants with cards having three  $3 \times 3$  tic-tac-toe grids such as those shown in Fig. 1. There are tokens in some of the cells. Participants are instructed to imagine the grids as the top, middle, and bottom layers of a three-dimensional tic-tac-toe game (the line through the cells containing the ⊗ tokens). The processing task is to identify the winning line by pointing out those tokens on the card, while the memory task is to recall the line (Daneman & Tardif, 1987).

### 3.3. Dual-task modifications

Daneman and co-workers pioneered the use of dual-tasks in the measurement of WM. Modifications have appeared in subsequent studies, but the basic dual-task structure has remained the same. To examine whether WM is task-dependent, Turner and Engle (1989) developed several dual-tasks in which the processing and memory tasks focus on different types of information. They used operation-word, operation-digit, sentence-digit, and sentence-word dual-tasks to measure WMC. The operation-word task required subjects to do an arithmetic calculation, judge whether the answer provided was correct, and then remember a word. The operation-digit task was similar except that subjects remembered a number instead of a word. The sentence-digit task required participants to read a sentence out aloud, judge whether it made sense, and finally remember a digit. The sentence-word task had a similar structure, but subjects remembered a word rather than a number after reading the sentence. The number of trials in each set, and the number of sets on each level followed the same pattern as that in Daneman and Carpenter's (1980) study (Table 1).

In addition to the content of the tasks and how they are combined, Turner and Engle's (1989) dual-tasks have also increased the difficulty of the processing tasks involved in measures of WM. The dual-tasks used in Daneman and Carpenter's (1980) study asked participants to read a sentence out aloud. The dual-tasks used in Turner and Engle's (1989) study added the requirement of determining whether the sentence made sense. Many subsequent studies have used the more challenging tasks in their measures of WMC (Cantor, Engle, & Hamilton, 1991; Engle, Nations, & Cantor, 1990; Hambrick & Engle, 2001).

The dual-tasks mentioned above – and those used in early studies of WM – focused far more on performance on the memory task than on the processing task. Studies in the late 1990s began to include criteria for performance on the processing task. For example, Engle, Kane, et al. (1999); Engle, Tuholski, et al. (1999) required that only those subjects who answered more than 85% of the processing tasks correctly could be used in the final data analysis. They believed this ensured that those included in the data analysis tried their best on the processing task while they concurrently memorized the accompanying words or digits. Subsequent studies adopted this strategy to guarantee the quality of performance on the processing task (Conway et al., 2002).

Dual-tasks played a critical role in the development of WM measurements and have become a standard. Daneman and Tardif (1987) asserted that the dual-tasks measure both the storage and the control function of WM and viewed them as a more valid WM measurement tool than simple memory span tasks. Studies also found dual-tasks have higher and more consistent correlations with higher-order cognitive abilities than have simple memory span tasks (Engle, Tuholski, et al., 1999; Unsworth & Engle, 2006). Additionally, modifications of dual-tasks further expanded the areas measured by dual-tasks and increased the weight of performance on the processing task in measuring WMC.

However, there are several main issues that researchers need to consider in future studies when using dual-tasks to measure WM. First, researchers need to carefully select testing materials according to the difficulty of stimuli and subjects' age and education level. Turner and Engle (1989) found the correlation between WMC and reading comprehension was highest when they chose sentences with medium level difficulty to measure WMC. This finding indicates that researchers need to carefully select materials for WM tasks and use multiple tools to ensure accurate measurement. Appropriate test materials would differ according to participants' age and educational background. Second, although adopting 85% as the criterion for the performance on the processing task prevents participants from only focusing on the memory task, it is possible that students who put forward their best effort did not achieve the 85% correct threshold. Thus, devising methods for inducing and detecting participants' optimal performance in dual-tasks remains a challenge for future studies.

### 3.4. Other WM measures

In addition to simple memory span tasks and dual-tasks, other measures are occasionally used in WM studies. For instance, Kyllonen and Christal (1990) used ABCD Grammatical Reasoning, ABC Numerical Assignment, Mental Arithmetic, and Alphabet Recoding tasks to measure WM. In the ABCD Grammatical Reasoning task, participants observed three sentences presented successively on a screen. These sentences described the logical relationship between letters A, B, C, and D. Participants were required to answer a question about the logical relationship while following the rules (1) letters A and B are defined as Set 1, and letters C and D as Set 2 and (2) letters in the same set must be adjacent in the final answer. For example, if the three sentences presented on the screen were: "A precedes B", "D is not preceded by C", and "Set 1 is preceded by Set 2", the answer to the question "Which order is correct? (1) ABCD; (2) ABDC; (3) BACD; (4) BADC; (5) CDAB; (6) CDBA; (7) DCAB; (8) DCBA" would be (7) DCAB. Participants had enough time to study each sentence, but could not go back to review previous screens.

The ABC Numerical Assignment task was very similar to the ABCD Grammatical Reasoning task, except participants were required to reason about the mathematical relationship between letters that represented numbers. For example, participants might be shown the three screens " $A = B/2$ "; " $B = C - 4$ "; " $C = 8$ " and be asked to give the values of A, B, and C.

The mental arithmetic task presented participants with an arithmetic formula. They were required to do calculations in their heads and select the correct answer from five options provided on a screen.

The alphabet recoding task asked participants to reason about a sequence of letters. For example, the first screen showing "GNB" was followed by a second screen with "+2". The participant was expected to answer "IPD".

All of Kyllonen and Christal's (1990) tasks imposed a high information workload on participants and were more difficult than those used in earlier studies. Two aspects of their measurement of WMC deserve special attention. First, previous tasks separated processing and memorizing activities, while Kyllonen and Christal's methods combined these two processes, making every task a problem solving exercise. Thus, results from previous dual-tasks reflected WMC, whereas Kyllonen and Christal's measurements of WMC actually reflected the participants' performance on problem-solving tasks. Second, Kyllonen and Christal provided feedback after each task and each section of the test, while other studies did not give feedback to participants during testing. As there is evidence that feedback contributes to a decrease errors in performing spatial tasks (Lohmann & Nichols, 1990), researchers must consider how feedback affects measurement and whether feedback should be a part of the assessment of WM in future studies.

### 3.5. Summary

In studies of WM, a wide variety of tools are used to measure WM. The diversity of WM measurements has both positive and negative influences on the study of WM. The positive side is that multiple measures of WM might help reveal different aspects of WM. Different simple memory span tasks could be used to measure phonological and visuospatial storage of WM. A composite score from several WM measures might provide a more accurate estimate of WM. For instance, Fry and Hale (1996) used four tasks to measure WM and calculated the average score as their estimate of WMC.



However, there are several challenges for the measurement of WM in future studies of WM. First, the lack of a standard WM measurement also brings the danger that results might differ substantially from one study to another because different tasks or test materials are used. Results from simple memory span tasks, dual-tasks, and measures more similar to problem-solving (such as those used in Kyllonen and Christal's (1990) study) might differ because they have dissimilar requirements on cognitive resources. Additionally, even for the same type of task (e.g., dual-tasks), varying levels of difficulty of testing materials might introduce unstable measurement results.

Second, reliability is another consideration in evaluating different tools for measuring WM. However, only a few studies reported the reliability of their WM measurements (Hambrick & Engle, 2001; Oberauer et al., 2000, 2003). Huge differences existed, as internal-consistency ("Cronbach's  $\alpha$ ") coefficients ranged from 0.41 to 0.94 (Oberauer et al., 2000). The fact that some of the coefficients are so low casts doubts on the quality of these measurements, so further research is warranted to examine the reliability of WM measurements and explore factors affecting it.

In summary, researchers need to cautiously select WM measures to suit their measurement goal, and at the same time carefully choose test type and materials to fit the age and education of participants. Kyllonen (2002) contended that good measures of WM should: (1) invoke simultaneous processing and storage, (2) not involve learning, and (3) require knowledge that all subjects are presumed to have. These criteria might serve as a baseline for the development and selection of WM measurements.

### 3.6. WM and fluid intelligence

Fluid intelligence is defined as the ability to understand complex relationships and solve novel problems (Martinez, 2000). It is the closest second-level factor to general intelligence in Carroll's (1993) hierarchical model of intelligence. Martinez argued that it should be viewed as a "close cousin" of general intelligence (p. 19). Cognitive tests that do not rely on acquired knowledge are viewed as good measures of fluid intelligence, such as Raven's Progressive Matrices (Raven, 1998) and Cattell's Culture Fair Test (Cattell, 1973). Researchers have been studying the relationship between WM and fluid intelligence for more than a decade but still have not reached agreement on the precise relationship between working memory and fluid intelligence. Some have argued that WM is so highly correlated with fluid intelligence that they could be deemed isomorphic (Engle, 2002; Jensen, 1998; Kyllonen, 2002; Stauffer, Ree, & Carretta, 1996), some have stated that these two constructs are barely linked to each other (Deary, 2000; Kline, 2000), while most have claimed that WM and fluid intelligence are closely related but not identical (Ackerman et al., 2005; Beier & Ackerman, 2005; Kane, Hambrick, & Conway, 2005).

Review of the literature revealed that in addition to the on-going uncertainty about the measurement of WM, measures of fluid intelligence varied. Moreover, different terms for fluid intelligence were used interchangeably, such as "nonverbal intelligence", "reasoning ability", "g", "general fluid intelligence", and "intelligence". In addition, different statistical methods were used to examine the relationship between WM and fluid intelligence. This variation in measurement, terminology, and statistical methods might have contributed to reaching different or even conflicting conclusions about the relationship between WM and fluid intelligence.

For example, instead of subdividing intelligence into fluid intelligence and crystallized intelligence (i.e., acquired knowledge), Jurden (1995) split intelligence into verbal and non-verbal intelligence. He used the Block Design subtest from the WAIS-R (Wechsler, 1981), the cube comparison task from the Educational Testing Service (ETS) kit (Ekstrom, French, & Harman, 1976), and Raven's Advanced Progressive Matrices (Raven, 1958) to measure non-verbal intelligence. WM measures used in his study included Reading Span (Daneman & Carpenter, 1980) and Computational Span Task (Salthouse & Babcock, 1990). The correlations between WM measures and Raven's Advanced Progressive Matrices were 0.20 and 0.43. The correlations between scores on non-verbal intelligence and WM ranged from  $-0.08$  to 0.45.

Fry and Hale's (1996) research on processing speed, WM, and fluid intelligence used the Raven's Standard Progressive Matrices (Court & Raven, 1982) to measure fluid intelligence and four modified simple memory span tasks to assess WM. These tasks required participants to recall digits or positions and the color of these stimuli in the same or reverse order. Fry and Hale (1996) found the impact of WM on fluid intelligence was statistically significant even after the influences of age and processing speed had been statistically controlled for in their path analysis. The coefficient of the causal path from WM to fluid intelligence was 0.38.

Kyllonen and Christal's (1990) study was cited in many of the aforementioned studies of WM and fluid intelligence (Engle, Kane, et al., 1999; Kane & Hambrick, 2004). They used the term "reasoning ability" in their study and described

it as “at or near the core of what is ordinarily meant by intelligence” (p. 390) (Kyllonen & Christal, 1990) and equated it to general fluid intelligence. They used 15 reasoning tests to measure reasoning ability, some of which required mathematical or grammatical skills and word knowledge. The correlation between these reasoning tests and Kyllonen and Christal’s WM measures ranged from 0.80 to 0.90. Twelve years later, Kyllonen (2002) reexamined this topic using the term “*g*” and defining it as the general mental ability, a concept bigger than “reasoning ability”, “fluid intelligence”, and “general fluid intelligence”. He summarized studies on human abilities from different perspectives and concluded that *g* is equal to working memory capacity.

In Colom, Flores-Mendoza, and Rebollo’s (2003) study on the relationship between WM and intelligence, the intelligence tests they used were Raven’s Standard Progressive Matrices (Centro editor de psicología aplicada, 1993), and the Letter Series test from the Primary Mental Abilities Test (Thurstone, 1938), which asks participants to choose a letter among several letters based on some inductive relationships among them. WM was assessed with simple letter span and digit span tasks, as well as tasks used in Kyllonen and Christal’s (1990) study. The correlation between WM scores and the letter and digit span scores were 0.69 and 0.71, respectively.

Engle, Tuholski, et al. (1999) conducted latent variable analysis on the relationship among WM, STM, and general fluid intelligence. Conway et al. (2002) studied the relationship among the aforementioned variables and processing speed. Both studies used Raven’s Standard Progressive Matrices (Raven, Court, & Raven, 1977) and Cattell’s Culture Fair Test (Cattell, 1973). Operation span, reading span, and counting span dual-tasks were used in both studies to assess WM. Engle, Kane, et al. (1999) and Engle, Tuholski, et al. (1999) found WM correlated with general fluid intelligence 0.49 after STM was statistically controlled for. Conway et al. (2002) found that with both STM and processing speed controlled for, WM still correlated with general fluid intelligence 0.60.

Two other studies indirectly provided evidence about the relationship between WM and fluid intelligence. Stauffer et al. (1996) used confirmatory factor analysis on 10 traditional paper-and-pencil aptitude tests from the Armed Services Vocational Aptitude Battery (U.S. Department of Defense, 1984) and 25 cognitive-components-based tests (including tests on basic cognitive ability, WM, processing speed, declarative knowledge, and procedural knowledge). The results indicated a general intelligence factor and a WM factor for each test battery. The correlation between these two factors was 0.99. In addition, Kane et al. (2004) used structural equation modeling on tests of STM, WM, verbal reasoning, spatial reasoning, and fluid intelligence and found WM significantly correlated with fluid intelligence at 0.52 after the influence of STM was controlled for.

Although some of the studies reported above did not use the term “fluid intelligence”, they did use measures of fluid intelligence. Others equated the construct measured to fluid intelligence, but the tests used might have been influenced by participants’ acquired knowledge. The variability in definitions of fluid intelligence, usage of terms, the diversity in test tools, and the verified statistical methods used yielded a wide range of correlation coefficients between WM and fluid intelligence from 0.20 to 0.90.

Although this wide range of correlation coefficients has led to conflicting ideas about the nature of the relationship between WM and fluid intelligence, it is widely accepted that WM is a strong predictor of fluid intelligence (Engle, Tuholski, et al., 1999; Kane, Hambrick, & Conway, 2005), but not identical to it. Conway et al. (2002) contended that WM might be the most important among many factors that influence fluid intelligence.

### 3.7. WM and science learning

While there have been extensive studies of WM’s relationship with reading and mathematics achievement (Alloway, 2006; Reuhkala, 2001; Swanson & Howell, 2003), less emphasis has been given to the connection between WM and science learning. Due to the importance of science education in the current education agenda of many countries (Hass, 2005), we next review the relationship between WM and science learning. (Although studies speak of learning as a relatively permanent change over time, universally a static achievement measure is used.)

A review of available studies on the relationship between WM and science learning (or science achievement) revealed that they are positively correlated. For instance, Gathercole et al. (2004) found a strong relationship between WMC and science achievement for 14-year-old students. WM was measured by forward and backward digit/letter span tasks and reading dual-tasks. Schools supplied the science achievement levels of each student. The correlation coefficients between WM measures and science achievement ranged from 0.32 (with forward digit span task) to 0.50 (with reading dual-tasks). Danili and Reid (2004) found that 15- and 16-year-old students with high and low WMC (measured by Backward Digit Span) differed significantly in their performance on chemistry tests. Tsaparlis (2005) examined the

correlation between WMC (measured by backward digit span) and performance on chemistry problem-solving tests through nine independent studies of first-year undergraduate chemistry students. The correlations ranged between 0.28 and 0.74.

Studies on the association between limited WMC and information load in problem-solving in science also provided support for the positive relationship between WM and science achievement. Because WMC limits the amount of information which can be concurrently processed, performance on science problem-solving tasks is expected to drop when the information load exceeds students' WMC (Johnstone & El-Banna, 1986). Johnstone and El-Banna's and Opdenacker et al.'s (1990) studies reported that middle-school students and undergraduates gradually decreased their chemistry problem-solving performances when the amount of information to be processed exceeded their WMC (assessed by backward digit span and a figure intersection test). This phenomena is also consistent with Sweller's (1994) cognitive overload theory, which posits that learning processes will be negatively affected if the cognitive load exceeds the limit of WMC.

Although most prior research has confirmed the positive relationship between WMC and science achievement, there is also research which does not support this connection. For instance, Staver and Jacks (1988) used the reading-span task to measure WM and did not find a correlation with students' performance in balancing chemical equations. However, a non-significant relationship between WMC and performance in balancing chemical equations does not necessarily negate the relationship between WMC and science achievement. It may be that different components of WM play different roles in learning science. There is some support for this idea in studies of the relationship between WMC and mathematics achievement. For example, De Smedt et al. (2004) found that phonological WMC measured by two short-term memory measures (Non-word Repetition Test and Forward Digit Span) was significantly correlated with mathematics achievement in both first and fifth grade, while visuospatial WMC assessed by Corsi Span and Visual Pattern Span was correlated with mathematics achievement only in first grade. Therefore, further studies of the relationship between WM and science achievement should measure different components of WM in different aged student populations in order to examine the relationship in detail.

The weight of the evidence from prior research, then, points to a strong connection between WM and science achievement (Niaz & Logie, 1993). Thus, we now turn our attention to ways in which research findings on WM are being applied to facilitate science learning.

#### 4. Applications of WM research to facilitate science learning

Prior studies indicated that WMC limits students' performance in science learning (Danili & Reid, 2004; Johnstone & Al-Naeme, 1991; Sweller, 1994). Researchers have taken two main approaches to deal with the limit of WMC to help students learn science. One is to decrease the information load in science learning materials, and the other is to increase students' WMC through specialized training programs.

##### 4.1. Decreasing cognitive load

According to Sweller's (1994) cognitive load theory, WMC imposes a limit to the amount of information individuals can process in cognitive activities. When the cognitive load exceeds the limit of WMC, learning processes will be affected. Two factors contributing to the amount of cognitive load are the presentation of materials (external cognitive load) and the complexity of learning materials provided to students (internal cognitive load). Thus, to decrease cognitive load, one could decrease external cognitive load by presenting the materials in a way that is easy to understand or by lessening internal cognitive load through reducing the interactivity among elements in the materials.

Strategies developed based on Sweller's (1994) cognitive load theory have been experimentally tested and found to be effective in reducing external cognitive load in learning science. Giving students goal-free problems to avoid means-ends analysis is one such strategy. Means-ends analysis is a common method in problem-solving. However, it was found to be a very WM-consuming process because it required students to mentally maintain the goal state, the problem state, and all needed problem-solving steps. By providing goal-free problems to students, Sweller, van Merriënboer and Paas (1998) argued that students only had to maintain the problem state and any problem-solving step applicable to that state and thus reduced the cognitive load.

Providing worked examples was shown to be another effective way to decrease extraneous cognitive load (Sweller et al., 1998). Schemas are thought of as general, structured knowledge representations in the mind that encapsulate

information related to a certain topic and could be used together in problem-solving. Worked examples with annotations about their crucial features were found to be helpful for students in applying schemas in problem-solving instead of using means-ends analysis (Cooper & Sweller, 1987; Sweller & Cooper, 1985).

Furthermore, redesigning learning materials that split students' attention, for instance from a text paragraph and a separate diagram to an integrated diagram, helped reduce external cognitive load (Sweller & Chandler, 1994). Presenting learning materials under audio/visual conditions has reduced extraneous cognitive load more than in visual/visual conditions, especially when the internal cognitive load is high (Sweller et al., 1998).

Studies showed that strategies reducing both external and internal cognitive load of learning materials effectively improved students' science learning. For instance, Danili and Reid (2004) redesigned teaching materials to reduce the amount of information students had to deal with simultaneously based on their finding that WMC affects students' performance in chemistry. Strategies to reduce internal cognitive load included presenting the materials in a more stepwise fashion, changing the presentation order of the materials, and relating learning materials to prior knowledge. Measures to decrease external cognitive load were using dialogue boxes, pictures, diagrams, and models to help students focus on the main messages and deepen their understanding through multiple coding channels. The new teaching materials also allowed students to spend less time taking notes and focus more on understanding the material. Four middle-school chemistry teachers from four schools participated in their quasi-experimental study. Each teacher taught an experimental class using the redesigned materials and a control class using the original materials. The results showed that although the teacher effect was significant, the difference in the average improvement between the experimental students ( $n=99$ ) and the control students ( $n=112$ ) was also statistically significant ( $p<0.01$ ). Students in the experimental group, on average, scored higher on an achievement test based on the content than did the control group.

#### 4.2. Improving WMC

Although redesigning learning materials and presentation methods to reduce WM demands appears to have improved student learning, it is unrealistic to redesign all instructional materials and presentation methods. Moreover, this approach does not provide students with the capacity to deal with complicated tasks or problems that are not carefully scaffolded either in or out of school. Thus, a second approach to deal with WMC limitations is to improve WMC so that students have more information-processing capability to cope with complex cognitive tasks.

There have been extensive studies on how to improve memory capacity, especially for senior people (Ericsson, 2003; Floyd & Scogin, 1997; Klingberg et al., 2005; Yohman, Schaeffer, & Parsons, 1988). These studies vary in the target construct they tried to improve and the way the participants were trained. Some studies examined how to improve general memory in daily life by teaching memory strategies such as rehearsal, information chunking, visual imagery, and verbal mediation strategies (Turley-Ames & Whitfield, 2003; Yohman et al., 1988). Ericsson and co-workers demonstrated that extensive practice on memorizing and training on the use of memory strategies could substantially improve ordinary people's memory, however, the improvement was limited to the special type of information used in the training (Chase & Ericsson, 1982; Ericsson & Delaney, 1999; Ericsson & Kintsch, 1995).

Although these studies found that extensive practice and memory strategies contributed to the improvement of memory, most of them focused on how to efficiently organize information and establish associations so that the needed information could be retrieved effectively. For science learning, according to Sweller's (1994) cognitive load theory, students encounter difficulty in studying the material when the cognitive load exceeds their WMC. Therefore, only improving memory skills, especially memory of a specific type of information, might not be useful in facilitating science learning. A study conducted by Klingberg et al. (2005) trained children with attention-deficit/hyperactivity disorder (ADHD) on both STM and attention control and successfully improved their WMC and fluid intelligence through computerized cognitive training (CCT). This study falls into the category of training on WM and might provide insight about how to facilitate science learning by increasing WMC. Therefore, we review this study in detail below.

Klingberg et al. (2005) used a program called RoboMemo<sup>®</sup> (2005, Cogmed Cognitive Medical Systems AB, Stockholm, Sweden) to train WM in a randomized controlled experiment. The program is composed of ten exercises, which include visuospatial, numerical, and verbal tasks. A robot guides program users through all tasks and reads letters or digits during the exercises. Subjects respond to the program by clicking on the screen with a mouse. The program automatically adjusts the difficulty level to match the WMC of a particular subject (Klingberg et al., 2005). In Klingberg et al.'s study, the training was conducted at home or in school with a coach (usually the child's parent).



Children trained for about 40 min each day, 5 days a week, for 5 weeks. The average total training time was 26.6 days. The Span-Board Task from the WAIS-RNI test battery (Wechsler, 1981) and Digit-Span from the WISC-III test battery were used to measure WMC before and after training (Klingberg et al., 2005). The Stroop Interference Task (Lezak, 1995) was used to assess children's attention control, and Raven's Coloured Progressive Matrices (Raven, 1995) was administered to measure fluid intelligence. Their results showed that children with ADHD significantly increased WMC, improved reasoning ability, and reduced ADHD symptoms through the training.

Klingberg et al. (2005) demonstrated the possibility of improving WMC and fluid intelligence through CCT for children with ADHD. As WMC limits one's information-processing ability in learning science and fluid intelligence plays a critical role in problem-solving, we might infer that increased WMC could lead to improvement in science achievement. Moreover, if CCT also works on children without ADHD, it may not only increase students' WMC and fluid intelligence, but also result in a positive impact on students' academic achievement and their lifelong learning. However, because the children in Klingberg et al.'s study represented a narrow, special population and the study was implemented in a clinical setting, the results cannot be extended to a larger population or a school setting. Therefore, further studies should examine the impact of CCT on WM, fluid intelligence, and science achievement for regular students in a school setting. If found to be effective in facilitating regular students' science learning in a school setting, CCT might become a viable approach to improving school science achievement.

In summary, WM plays an important role in learning science. Improving WMC holds the promise of providing students with more cognitive resources for both knowledge acquisition and application. It may not only improve students' current science achievement, but more importantly, also enhance their lifelong learning and problem-solving ability. Alternatively, it may, as Ericsson (2003) found, only improve capacity on a narrow range of tasks and not have the salutary effect hoped for. Clearly, WM research should focus on this critical issue.

## 5. Conclusions and future research

WM plays a critical role in completing cognitive tasks. A clear and comprehensive understanding of WM today should contribute to further research on WM and successful application of WM study findings to education. Through examining different models of WM, we found differences in the role of content, structure, and function. These models provided diverse but complimentary views of WM. To develop a full picture of WM, we provided two synthesized definitions of WM and appealed to future studies to incorporate new findings into our current understanding of WM in order to develop a comprehensive picture.

Regarding the measurement of WM, we found great variability among current measures. This variety provided methods to measure WM from different perspectives, but also created inconsistency and led to difficulty in comparing studies of the relationship between WM and other constructs like fluid intelligence and science achievement. Hence, establishing a standard for WM measures, or at least identifying benchmark measures that researchers would agree to use, seems like a worthwhile goal for the field. When doing this, we need to consider some specific characteristics of the measurement tools, such as the selection of task materials, the difficulty of tasks, whether tasks provide feedback to participants, and whether to set a criterion (e.g., 85%) for performance on the processing task. Furthermore, as a few studies reported a wide range of reliability coefficients, further psychometric study of WM measures is warranted.

Research demonstrated the close relationship among WM, fluid intelligence, and science achievement. Due to the importance of WM in cognitive activities, performance on cognitive tasks will be affected when the information load exceeds individuals' WMC. Empirical evidence confirmed that students' performance in science decreases with the increase of cognitive load. Prior studies provided two methods to help students deal with this situation: decreasing cognitive load by redesigning presentation methods and learning materials or increasing WMC through training. Although studies showed decreasing cognitive load through redesigning presentation methods and learning materials effectively improved students' learning, the generality and practicality of this redesign approach to learning materials and instruction is limited at present. Moreover, such an approach does not provide students with cognitive capacities across different domains and situations. Increasing WMC through CCT or other training programs might improve students' cognitive capacities in ways that are applicable to learning activities in all areas. The finding that CCT effectively increased WM and fluid intelligence of children with ADHD indicates the plasticity of WM and the promise of facilitating science learning through improving WMC. Hence, it seems worthwhile to verify whether CCT could increase the WM of children without ADHD and what influence WMC changes have on fluid intelligence and science achievement. If CCT effectively improves regular students' WM and positively influences fluid intelli-



gence and science achievement, it would provide a useful tool for promoting students' cognitive development and learning.

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