Working Memory Capacity as Executive Attention

Randall W. Engle[1]

School of Psychology, Georgia Institute of Technology, Atlanta, Georgia

Abstract

Performance on measures of working memory (WM) capacity predicts performance on a wide range of real-world cognitive tasks. I review the idea that WM capacity (a) is separable from short-term memory, (b) is an important component of general fluid intelligence, and (c) represents a domain-free limitation in ability to control attention. Studies show that individual differences in WM capacity are reflected in performance on antisaccade, Stroop, and dichotic-listening tasks. WM capacity, or executive attention, is most important under conditions in which interference leads to retrieval of response tendencies that conflict with the current task.

Keywords

working memory capacity; attention

I am an avid baseball fan, and when I am listening to a game on the radio, particularly if the game involves the Atlanta Braves, my wife will occasionally tell me something that she would like for me to do. However, often, and especially in the middle of a tense game, I will not even notice that she is talking to me. Does this ability to block out information have anything to do with working memory? Is there some relationship between the ability to control attention and the amount of information that can be kept temporarily active in memory? Indeed, the idea of such a relationship has been important to attempts to explain cognition for many years.

It is helpful to consider this question in the context of Baddeley and Hitch's (1974) formulation of the *working memory* (WM) system, which consists of temporary memory stores with associated mechanisms for rehearsing stored information and a mechanism of central or executive attention that regulates the contents of the active portion of memory. Performance on measures of WM capacity correlates with performance on a variety of higher-order cognitive tasks involving, for example, reading comprehension, complex learning, and reasoning (Daneman & Carpenter, 1980). What mechanisms are responsible for this correlation?

MEASURES OF WM CAPACITY

A variety of WM tasks are useful in predicting performance on a wide range of cognitive tasks that are more closely related to real-world activities. Further, the tasks apparently reflect a common construct because they account for similar variance and all load on the same factor in a factor analysis. Generally, in each of these tasks the subject receives items to recall and also performs another attention-demanding task that is interleaved between receiving the items for recall. For example, the reading-span task was the first task used to study WM capacity and its relationship with higher-order cognition (Daneman & Carpenter, 1980). My lab uses a version of this task in which subjects read aloud a series of two to seven sentences, each of which is followed by an unrelated word. After the last sentence-word combination is read, subjects try to recall the list of unrelated words. The critical score is the number of words recalled.

The operation-span task is similar in format to the reading-span task (Turner & Engle, 1989). Subjects read aloud a series of operation-word strings such as "Is 4/2 + 3 = 6? (yes or no) DOG." They respond as to whether or not the equation is correct and then read the capitalized word aloud. After a set of two to seven such operation-word strings, we measure the number of words recalled. A third task is the counting-span task, in which subjects see from two to seven displays of targets and distractors and count the number of targets in each display. They then recall the list of digits corresponding to the numbers of targets in the displays, in order. The critical score is the number of digits recalled.

These tasks must involve some fundamental aspect of cognition because performance on them predicts performance on a wide range of higher-order cognitive tasks, including tasks involving reading and listening comprehension, language comprehension, ability to follow directions, vocabulary learning, note taking, writing, reasoning, bridge playing, and learning to write computer programs (Engle, 2001).

WHY DOES PERFORMANCE ON WM TASKS PREDICT PERFORMANCE ON HIGHER-ORDER COGNITIVE TASKS?

Originally, psychologists thought performance on WM-capacity tasks correlated with performance on other cognitive tasks because the processing portion of the WM tasks (e.g., skill in reading the sentences in the reading-span task) was similar to the task being predicted (reading comprehension) (Daneman & Carpenter, 1980). However, individual differences on the processing portion of the WM tasks (reading, doing arithmetic, counting, etc.) are unimportant to the correlation between number of items recalled in the WM tasks and performance on higher-order tasks. The correlation between WM span and reading comprehension, for example, is not reduced in statistical analyses that control for reading or arithmetic expertise (Engle, Cantor, & Carullo, 1992). Moreover, individuals who have equal arithmetic skill still demonstrate differences in the number of words recalled in the operation-span task that correlate with performance in reading comprehension (Conway & Engle, 1996). If domain-specific skills or expertise cannot account for why performance on WM-capacity tasks correlates with performance on higher-order tasks, then what does?

The term capacity, as used in discussions of short-term memory (STM), often conjures up images of a limited number of items or chunks that can be stored (e.g., 7 ± 2). However, my sense is that WM capacity is not about individual differences in how many items can be stored per se but about differences in the ability to control attention to maintain information in an active, quickly retrievable state. Thus, WM capacity is just as important in retention of a single representation, such as the representation of a goal or of the status of a changing variable, as it is in determining how many representations can be maintained. WM capacity is not directly about memory—it is about using attention to maintain or suppress information. WM capacity is about memory only indirectly. Greater WM capacity does mean that more items can be maintained as active, but this is a result of greater ability to control attention, not a larger memory store. Thus, greater WM capacity also means greater ability to use attention to avoid distraction.

Proactive interference refers to the difficulty people encounter when a new behavior is associated with a context associated with other behaviors. For example, although you probably find your car easily the first time you park in a new mall, after many shopping trips, you may have difficulty recalling where you parked your car because of all the previous places you parked in the mall. Dealing with the effects of proactive interference is one of the primary functions of WM (Kane & Engle, 2000). Without the effects of interference, most of the information people know and need to function in the world could be retrieved from long-term memory sufficiently quickly and accurately for them to perform even complex cognitive functions quite well. It is generally considered a truism that temporarily retained information that is not rehearsed will be lost in 20 s or so. However, Keppel and Underwood (1962) found that retention for a list of three items was nearly perfect after such a delay if there had been no previous lists presented for recall. That is, when interference is relatively absent, there is little decline in the recall of information as delay increases. This finding is quite informative. Effects generally attributed to traditional STM are likely to be observed only when the effects of interference force the individual to maintain information in a verbatim, relatively active state. It is also under those conditions that individual differences in WM capacity become important.

PROACTIVE INTERFERENCE

Kane and I tested this hypothesis with subjects from the upper quartile (high spans) and the lower quartile (low spans) on one of the WM-capacity tasks. The high- and low-WM-capacity subjects completed three trials on which they saw 10 words for later recall, then performed another task for 16 s (this task had the function of preventing rehearsal of the 10 words), and then tried to recall the words (Kane & Engle, 2000). Both groups of subjects recalled about 60% of the words from the first trial. However, subjects with low spans showed more proactive interference over succeeding trials than did people with high spans. That is, low-WM-capacity subjects showed a greater loss of recall with each new list. When the subjects performed a secondary task at the same time (i.e., when they were under what is referred to as an increased cognitive load), the high- and low-span groups performed at about the same level; in other words, high-span subjects' performance decreased under cognitive load, but low-span subjects' performance was unaffected by load. The finding that divided attention increased proactive interference for people with high spans suggests that, under normal conditions, they used attentional control to combat the effects of proactive interference. In contrast, the fact that cognitive load did not affect proactive interference for low-WM-capacity subjects suggests that they do not normally allocate attention to resist interference.

WM, STM, AND GENERAL FLUID INTELLIGENCE

I believe that measures of WM capacity reflect both memory pro-

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cesses and executive attention, whereas traditional measures of STM reflect primarily memory processes such as grouping, chunking, and rehearsal. For example, in the traditional digit-span task, subjects are read or shown a list of digits and asked to recall them in order. Recognition of familiar sequences in the list, such as one's telephone number or address, and the ability to do verbal rehearsal have a large effect on success in this task.

My colleagues and I used a structural equation modeling analysis[2] to test this and the idea that the construct measured by WM-capacity tasks is closely associated with general fluid intelligence[3] (Engle, Tuholski, Laughlin, & Conway, 1999). Although the WM and STM constructs were highly correlated with each other in this analysis, a model with separate constructs for WM and STM fit the data better than a model that combined the two into a single construct. That is, two separate psychological mechanisms were needed to explain the results.

When the variance common to WM and STM (presumably due to memory processes common to the two tasks) was statistically removed, WM still correlated with general fluid intelligence. However, the left-over STM variance did not correlate with intelligence. Recall our logic that WM comprises both executive attention and memory processes, whereas STM comprises largely memory processes. Thus, removing the common variance would eliminate the memory processes, and the residual variance in WM would constitute executive attention. Although measures of WM capacity such as operation and reading span are certainly not pure, these results are consistent with the idea that the latent variable resulting from WM tasks reflects a mechanism that one might think of as executive attention, and that it is strongly related to general fluid intelligence. This study provided inferential evidence that performance on WM-capacity tasks is related to performance on other cognitive tasks primarily because of individual differences in executive attention. However, this surmise is based on logic, and, at this point, I have not provided empirical evidence linking individual differences in WM capacity and performance on tasks that psychologists would generally agree are attention tasks. I now describe some new findings that support this contention.

ANTISACCADE TASK

In an attempt to directly measure the relationship between WM capacity and executive attention, my colleagues and I (Kane, Bleckley, Conway, & Engle, 2001) tested individuals with high and low WM capacity on the antisaccade task. In this task, subjects fixate in the middle of a visual display but must respond to target information briefly presented randomly to one side or the other of the display. Just before the target is presented, an attention-attracting cue occurs on the side opposite where the target will appear. The cue always predicts that the target will occur on the opposite side of the display. Optimal performance in the antisaccade task requires that the subject resist the strong tendency to shift attention (as well as eye movements, or saccades) to the attention-capturing cue. Most experiments also include a prosaccade control condition in which the attention-capturing cue occurs on the same side of the display as the subsequent target. Thus, the natural tendency to look at the cue facilitates performance when it occurs in the prosaccade condition but hurts performance in the antisaccade condition.

The performance of subjects with high and low WM spans should not differ in the prosaccade condition. However, if individual differences in WM capacity correspond to differences in executive attention, subjects with low WM spans should be hurt more than subjects with high spans by the need to avoid making the conflicting response in the antisaccade task.

As expected, the two groups of subjects did not differ in time to identify target letters in the prosaccade condition. But, although both groups were slowed in the antisaccade condition, the subjects with low spans were hurt more than the subjects with high spans. In a second study, subjects performed an extended set of antisaccade trials, and again we found that low-span subjects were substantially slower to identify the letters than high-span subjects were. Figure 1 shows the first saccades following the onset of the flashing cue: Low-span subjects were more likely to follow the natural tendency to look in the direction of the cue than were high-span subjects.

The antisaccade results would not be predicted by any account in which WM capacity reflects a limitation in number of items. The results also would not be predicted by any account in which individual differences in WM capacity reflect knowledge specific to the span tasks or in which the pertinent attentional resources are domain specific. The data, however, are consistent with a view that the underlying factor responsible for the relationship between measures of WM capacity and performance on higher-order cognitive tasks is a domain-free executive-attention system. Although individuals possessing different WM capacities will show differences in number of items stored in a variety of memory tasks, this is a result of differing ability to maintain and inhibit information, particularly in the face of distraction and interference.

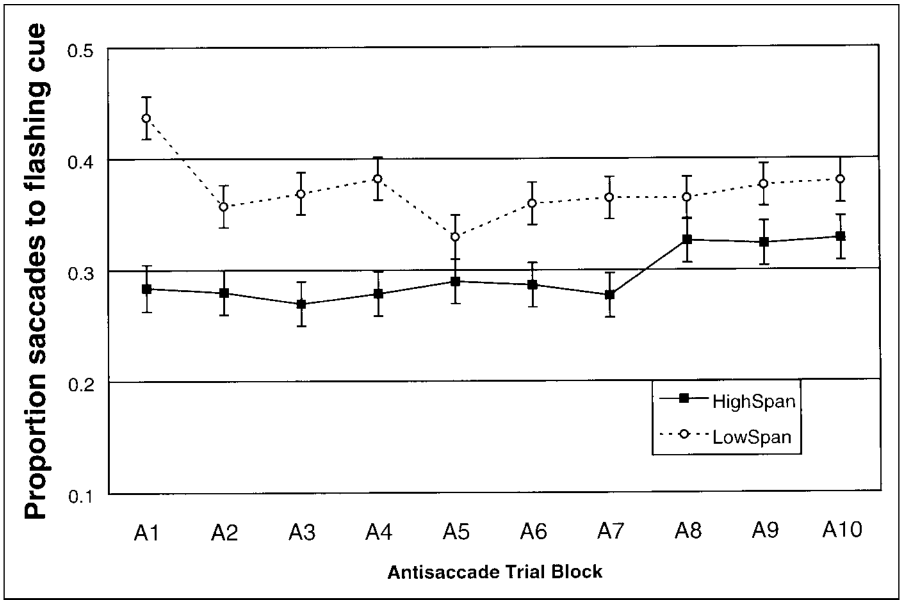

Fig. 1. Proportion of initial eye movements to the misleading cue in the antisaccade condition as a function of working memory span (high vs. low) and block of trials. Adapted from "A Controlled-Attention View of WM Capacity," by M.J. Kane, M.K. Bleckley, A.R.A. Conway, & R.W. Engle, 2001, *Journal of Experimental Psychology: General*, *130*, p. 176. Copyright 2001 by the American Psychological Association. Adapted with permission of the author.

STROOP TASK

The Stroop task, like the antisaccade task, also requires maintenance of a single crucial goal in WM. In this task, subjects are shown color words and are required to name the color of the ink in which each word is printed. The word and ink color can be congruent or incongruent. For example, the word "red" can be printed in blue ink (incongruent) or in red ink (congruent). If the word and ink color are incongruent, there is a strong predisposition to make a response inappropriate to the task, that is, to say the word, rather than to say the color of the ink in which the word is printed. Performance on the Stroop task should rely on executive attention to maintain the goal of naming the color of the letters even when the word elicits a stronger response tendency to say the word.

Kane and I (2001) conducted a study in which the percentage of trials on which the ink color and the word name were congruent was 0%, 50%, or 75%. Goal maintenance should be easiest in the 0% condition because no trials present matching ink color and words. Goal maintenance should be hardest in the 75%-congruent condition because the word name can be used to respond correctly on the vast majority of trials. We found that performance on incongruent trials differed substantially for high- and low-WM subjects and also depended on the proportion of congruent trials. Although both groups made more errors on incongruent trials as the proportion of congruent trials increased (see Fig. 2), the percentage of errors did not differ for high- and low-WM subjects in the 0%- or 50%-congruent conditions. When 75% of the trials were congruent, however, people with low spans made almost twice as many errors as people with high spans. Thus, differences between people with high and low spans are not overall differences in inhibition in all situations; rather, only when the context makes it difficult to maintain the appropriate task goal do people with high WM spans perform better than people with low WM spans.

DICHOTIC-LISTENING TASK

Yet another attention task in which WM capacity has been shown to be important is the venerable dichotic-listening task, which measures a person's ability to repeat aloud words presented to one ear while ignoring information presented to the other ear. Conway, Cowan, and Bunting (2001) had subjects shadow words in one ear while ignoring words spoken to the other ear. At some point, each subject's first name was spoken as a word in the ignored message, and the question was whether, at the end of the study, the subject would report hearing his or her name. High-WM subjects should be better than low-WM subjects at ignoring distracting information, so they should be less likely to report hearing their name under these conditions. And although only 20% of high-span subjects reported hearing their name, 65% of low-span subjects reported hearing their name. Again, the conclusion is that people with low WM spans are less capable than people with high WM spans of doing the mental work necessary to block distracting information.

CONCLUSIONS

WM-capacity tasks measure a construct fundamentally important to higher-order cognition. That construct is distinguishable from STM and is at least related to, maybe isomorphic to, general fluid intelligence and executive attention. One crucial function of the

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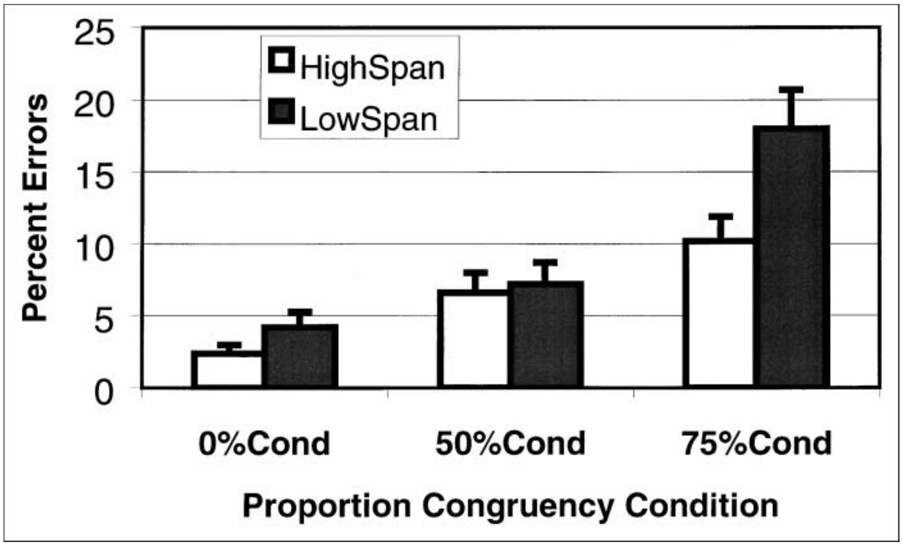

Fig. 2. Percentage of errors on incongruent trials in the Stroop task as a function of working memory span (high vs. low) and percentage of trials that were congruent (Kane & Engle, 2001). Cond = condition.

WM system is keeping information quickly retrievable when the task context provides interfering information that would lead to an inappropriate response.

These conclusions raise some intriguing questions for future research. Do individual differences in WM capacity–executive attention reflect a central domain-free attention mechanism or domain-specific components? How do these differences map onto the main brain structures associated with executive attention? The prefrontal cortex appears to be important in maintaining information in an active state, and the anterior cingulate is an important structure in detecting or dealing with conflict of the type that would occur in the antisaccade and Stroop tasks. Other brain structures (e.g., the locus coeruleus) appear to be important to adjusting the level of mental effort expended on a task. It remains to be seen whether the differences in executive attention I have described here reflect differences in a unified central system or are specific to particular components of the brain. Also, because WM capacity (executive attention) appears to be an important mechanism underlying fluid intelligence, an important question is how differences in executive attention are manifest in what is viewed as intelligent behavior.

Recommended Reading

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Notes

1. Address correspondence to Randall W. Engle, School of Psychology, Georgia Institute of Technology, 274 5th St. NW, Atlanta, GA 30332-0170; e-mail: randall.engle@psych.gatech.edu.

2. Structural equation modeling (SEM) is a method of statistical analysis by which correlations among a large number of tests are analyzed. A model is first defined, and if the model is able to reproduce the correlations that were observed, the model is thought to be valid. If the model is unable to reproduce the correlations that were observed, then the model is rejected and alternative models are then tested. SEM is better than standard correlation and regression procedures for two main reasons. First, *latent* variables are constructed from multiple tests that purportedly measure the same construct. Thus, a construct is defined in terms of common variance alone, free of measurement error. Second, causal relations among latent variables can be tested by fitting a model to observed data.

3. General intelligence, or *g*, can be thought to consist of two types of intelligence: general crystallized intelligence, which is culturally derived knowledge, and general fluid intelligence, which is the ability to reason and to solve novel problems.

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