

## A Controlled-Attention View of Working-Memory Capacity

By: [Michael J. Kane](#), M. Kathryn Bleckley, Andrew R. A. Conway, Randall W. Engle

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### **Abstract:**

In 2 experiments the authors examined whether individual differences in working-memory (WM) capacity are related to attentional control. Experiment 1 tested high- and low-WM-span (high-span and low-span) participants in a prosaccade task, in which a visual cue appeared in the same location as a subsequent to-be-identified target letter, and in an antisaccade task, in which a target appeared opposite the cued location. Span groups identified targets equally well in the prosaccade task, reflecting equivalence in automatic orienting. However, low-span participants were slower and less accurate than high-span participants in the antisaccade task, reflecting differences in attentional control. Experiment 2 measured eye movements across a long antisaccade session. Low-span participants made slower and more erroneous saccades than did high-span participants. In both experiments, low-span participants performed poorly when task switching from antisaccade to prosaccade blocks. The findings support a controlled-attention view of WM capacity.

### **Article:**

In 1980, Daneman and Carpenter provided the first demonstration of strong correlations among measures of immediate memory and complex cognition. Their working-memory (WM) span tasks, reading span and listening span, required participants to maintain a short list of words in memory while simultaneously reading or hearing sentences that contained the target words. Thus, the critical task—a memory-span test—was embedded within a secondary comprehension task. Daneman and Carpenter found that performance on these span tasks correlated with a global reading comprehension measure (the verbal Scholastic Aptitude Test [SAT]) with  $r$ s ranging from .49 to .59 and with more local comprehension measures (answering factual and pronoun-reference questions about prose passages) with  $r$ s ranging from .42 to .90. These impressive correlations stood in stark contrast to previous failures to correlate language comprehension with traditional short-term memory measures, such as digit span and word span, which placed minimal processing demands on the participant (for reviews see Crowder, 1982; Perfetti & Lesgold, 1977). Attempts to understand the relation between working-memory capacity and higher-order cognition have occupied researchers for the past 20 years and they are the focus of the present investigation.

Daneman and Carpenter (1980, 1983) hypothesized that individual differences in reading efficiency mediated both individual differences in their span task and the correlations between span and comprehension. They assumed that WM capacity was a limited resource that could be allocated to processing functions, storage functions, or both (see Baddeley & Hitch, 1974), and that participants who more efficiently processed the sentences of the span task had more capacity remaining to store the sentence-ending target words. By this view, WM capacity, or the amount of information that can be stored during processing, is tied to the specific processing demands of the concurrent task. Good readers have more storage capacity during reading than do poor readers, but good and poor readers may well have equivalent capacities during other, nonreading tasks. Thus, WM span measures "work," in the sense that they correlate with measures of complex cognition, because they reflect the level of skill in the processing task.

An alternative view proposed by Engle and colleagues (e.g., Tumer & Engle, 1989; Engle, Cantor, & Carullo, 1992) holds that WM capacity is much more general, that it reflects an abiding, domain-free capability that is independent of any one processing task. Consistent with this view, a modification of the reading span task that requires mathematical processing is still an excellent predictor of language comprehension (e.g., Daneman & Merikle, 1996; La Pointe & Engle, 1990). Moreover, when speed of processing during the span task, an index of processing skill, is partialled out of the correlation between span and comprehension, the correlation is not diminished (Engle et al., 1992). Finally, even when the processing task is individually tailored to each participant's skill level, the correlation between span and comprehension is unaffected (Conway & Engle, 1996). As yet another indicator of the generality of WM capacity, span tasks with a variety of processing requirements predict such diverse capabilities as note taking (Kiewra & Benton, 1988), bridge playing (Clarkson-Smith & Hartley, 1990), computer-language learning (Shute, 1991), and novel reasoning (Kyllonen & Christal, 1990).

Clearly, the specific concurrent-processing task has little impact on the predictive validity of WM span measures across a host of higher-order cognitive capabilities. These span tasks must therefore tap a very general—and very important—cognitive primitive. But what is the nature of this primitive? Engle, Tuholski, Laughlin, and Conway (1999) have recently argued that WM span tests "work" because they reflect a general controlled-attention capability. By this view, WM is a hierarchically organized system, in which short-term memory storage components subserve a domain-free, limited-capacity controlled attention (see Baddeley & Hitch, 1974; Cowan, 1995). Moreover, even though individuals may differ on any or all of the components of this hierarchical system, it is the individual differences in the controlled-attention component of WM that are responsible for the correlations among WM span and complex cognition measures.

As a test of this view, Engle, Tuholski, et al. (1999) tested 133 participants on three WM span tests with reading, arithmetic, and counting as the concurrent processing tasks. Participants also completed three traditional short-term memory span (STM) tests without concurrent-processing requirements and two tests of general fluid intelligence (*gF*), the Ravens Progressive Matrices (Raven, Court, & Raven, 1977) and the Candi Culture Fair Test (Institute for Personality and Ability Testing, 1973). Exploratory factor analysis and structural equation modeling were performed on the data. For present purposes, the key findings were twofold. First, the varied WM tests reflected a common factor that was separate from, but strongly related to, the factor for the STM tasks. This finding is consistent with the notion that traditional STM tasks tap only the storage component of the WM system, whereas WM span tasks tap both storage and controlled (executive) attention. Second, in a subsequent structural equation model with STM and WM represented by separate latent variables, the variance common to STM and WM was removed and the correlation between the residual of WM and the *gF* latent variable remained in the .50 range. The STM residual showed no relation to intelligence. Engle, Tuholski, et al. argued that if the shared variance between WM and STM reflects storage, then the residual of WM should reflect controlled attention. Importantly, the controlled-attention component of WM was most strongly correlated with the *gF* latent variable, which was represented by visuospatial reasoning tasks with 'no surface similarity to the span tasks.

A controlled-attention view of WM capacity is consistent with Baddeley's (1986, 1993, 1996) proposal that the central-executive component of WM may be analogous to the Supervisory Attentional System (SAS) described by Shallice and colleagues (Norman & Shallice, 1986; Shallice & Burgess, 1993). The SAS is hypothesized to be a conscious control mechanism that resolves interference between activated action schemas. In particular, when a prepotent action is environmentally triggered but conflicts with the individual's goal state, the SAS biases the action-selection process by providing additional activation to a more appropriate action schema *and by inhibiting the* activation of the inappropriate schema. The SAS thus allows attentional control over action by providing a means with which to override interference from powerful environmental stimuli and habitual responses.

Our view (see also Engle, Kane, & Tuholski, 1999) is that WM capacity, the construct measured by WM span tasks, reflects the general capability to maintain information, such as task goals, in a highly active state.

Although the need for such active maintenance will be minimal in many contexts, it will be particularly important under conditions of interference. Interference slows and impairs memory retrieval and therefore puts a premium on keeping task-relevant information highly active and easily accessible. Thus, individual differences in WM capacity will be most important to higher-order cognition in the face of interference. We also propose that individual differences in WM capacity reflect the degree to which distractors capture attention away from actively maintaining information such as a goal state. Outside of focal attention, the task-relevant information being maintained will return to a base-line activation level. If interference prohibits rapid retrieval of this goal information from long-term memory, then distractors, and not intentions, will guide behavior. Thus, coherent and goal-oriented behavior in interference-rich conditions requires both the active maintenance of relevant information and the blocking or inhibition of irrelevant information. Indeed, we agree with recent proposals that active maintenance may be responsible for the blocking or inhibition of distraction—that is, inhibition is the result of increased activation of goal states (see De Jong, Berendsen, & Cools, 1999; O'Reilly, Braver, & Cohen, 1999; Roberts & Pennington, 1996).

Recent studies have provided evidence that interference differences between high- and low-span participants reflect controlled-attention differences. For example, Rosen and Engle (1997) tested high- and low-span individuals in a category fluency test in which participants were asked to recall as many animal names as they could for 10-15 min. High-span participants generated more animal names than did low-span participants, and the difference between groups increased across the recall period, a finding indicative of span differences in susceptibility to output interference. That is, successful fluency across long intervals requires strategically searching for low dominance exemplars while blocking the reretrieval of high dominance exemplars such as *dog*, *cat*, *cow*, and *horse*. Most important for present purposes, high-span participants' recall superiority was eliminated in a second experiment in which fluency was combined with a secondary digit-tracking task. When high-span participants had attention divided, fluency dropped to the level of low-span participants. Moreover, low-span participants were unaffected by the secondary load. These findings suggest that high-span individuals engage in controlled processing to attain high fluency because their performance dropped under dual-task conditions. In contrast, low-span individuals did not appear to engage in controlled processing during recall (perhaps relying on automatic spreading activation), because their poorer fluency did not differ as a function of load.

Kane and Engle (2000) reached similar conclusions from a proactive interference (PI) task. High- and low-span participants studied and recalled three lists of 10 words each, and all the stimuli were drawn from the same taxonomic category (e.g., *animals*, *occupations*). Recall during such tasks typically drops across each successive list, as the potential for PI from previous lists increases (e.g., Wickens, Bom, & Allen, 1963). All participants showed significant PI, and high- and low-span participants showed equivalent recall on List 1, but low-span participants demonstrated significantly larger PI effects than did high-span participants. High-span participants were better able to block retrieval of prior-list items in recalling later lists. Did this interference resistance require attentional control? Evidence that it did came from divided-attention conditions, in which a secondary finger-tapping task was performed either while encoding or retrieving each list. As in Rosen and Engle (1997), high-span participants under load (at encoding or retrieval) performed similarly to low-span participants under standard conditions—their PI effects increased dramatically, suggesting they normally engaged in controlled processing to limit PI. In contrast, low-span participants were just as vulnerable to PI under load as under no load, suggesting that they did not engage in controlled processing to combat PI.

Together, these individual-differences findings support the notion that WM capacity is related to controlled attention, with higher WM individuals demonstrating better (or more) use of attention to resist interference during encoding and retrieval than do lower WM individuals. However, if WM capacity reflects a relatively low-level, general attentional capability, then span differences in controlled attention should be detectable outside the context of memory-retrieval tasks. High- and low-span individuals should also differ in more "molecular" attention tasks that require minimal storage and no explicit recall from long-term memory. Indeed, the present investigation sought to demonstrate that individual differences in WM capacity correspond to individual differences in attention tasks that bear no resemblance to traditional memory tasks.

To this end, we tested high- and low-span participants in a visual-orienting task commonly known as the antisaccade task (Hallett, 1978; Hallett & Adams, 1980). This task is simple, nonverbal, and makes minimal memory demands on participants beyond the maintenance of task goals in the face of interference. Very simply, the antisaccade task requires that participants detect an abrupt-onset visual cue in the environment and use that cue to direct their attention and eyes to a spatial location that will subsequently contain a target (for a review, see Everling & Fischer, 1998). Our interest in this task stems from prior demonstrations that its performance under some conditions demands significant attentional control, whereas under other conditions it may rely on relatively automatic orienting responses. For example, when the visual cue predictably signals a location that does not contain the target, participants must either voluntarily move their eyes away from the cue and toward the target location or initially prevent their eyes from being captured by the salient cue altogether. In contrast, when the *cue* predictably appears in the same spatial location as the target, the eyes may be reflexively drawn to the cued location. Although both tasks require the establishment of a goal-oriented task set, only in the former, where the goal conflicts with habit, is it necessary to maintain the goal in an active state for consistently accurate responding.

Roberts, Hager, and Heron (1994) provided compelling evidence that suppressing the orienting response to peripheral cues in the antisaccade task requires controlled attention. Their antisaccade task consisted of two blocked conditions that presented peripheral stimuli at a visual angle that encouraged eye movements. In prosaccade blocks, an abrupt-onset visual cue appeared in the location of the subsequent target; in antisaccade blocks, the cue appeared opposite the location of the target (i.e., if the cue appeared to the right, the target appeared to the left). Thus, optimal performance on antisaccade trials required preventing eye movements to the cue—the reflexive tendency to move eyes to a cue in the periphery had to be blocked or inhibited. Roberts et al. (1994) found that introducing an attention-demanding secondary load task impaired the suppression of reflexive eye movements. When participants in the antisaccade condition had to continuously update the sum of auditorially presented digits, they moved their eyes toward the cue, in error, more than they did under no load. Under load, participants were also slower to direct their eyes to the target and less accurate in identifying the target than under no load. However, the addition of a secondary task had no effect on prosaccade performance, in either eye movements or target identification. Prosaccade orienting thus appeared to be an automatic process, insensitive to goal maintenance, whereas antisaccade orienting appeared to require controlled attention; that is, it was sensitive to active goal maintenance.

Similar to Roberts et al. (1994), our interest in the antisaccade task is in part tied to its recent use in the neuropsychology literature. Performance on the antisaccade, but not the prosaccade, task is particularly impaired in patients with dorsolateral prefrontal cortex (dPFC) damage compared with patients with more posterior damage (Fukushima, Fukushima, Miyasaka, & Yamashita, 1994; Guitton, Buchtel, & Douglas, 1985; Pierrot-Deseilligny, Rivaud, Gaymard, & Agid, 1991). Moreover, an imaging study by Sweeney et al. (1996) found that antisaccade trials increased dPFC activation relative to prosaccade trials, along with increasing activation in some parietal, temporal, and midbrain areas. Our previous empirical work has suggested similarities between patterns of span effects and dPFC effects (Kane & Engle, 2000; Rosen & Engle, 1997), and our theoretical view of WM maintenance and interference resistance is, in part, grounded in work within the dPFC literature (see Engle, Kane, & Tuholsld, 1999; Engle & Oransky, 1999; Kane & Engle, 2001). We therefore had further reason to predict that performance on the antisaccade task, but not the prosaccade task, would discriminate between high- and low-span individuals.

In the present study, then, we tested high- and low-WM-span participants in two experiments with a modified antisaccade task—a nonverbal task that made minimal demands on memory retrieval. We hypothesized that the span groups would perform equivalently on prosaccade trials, because orienting in these trials occurs reflexively and we had no a priori reason to expect span differences in the other processes required by this task, such as response selection. However, given the demand to maintain goal information in the face of interference in the antisaccade task, we predicted that high-span participants would outperform low-span participants. In particular, high-span participants should be better able to prevent orienting toward antisaccade cues than should low-span participants.

## Experiment 1

Experiment I presented high- and low-WM-span participants with an antisaccade task in which an abrupt-onset visual signal predictably cued *the* location of a subsequent target letter. The signal appeared in the same stimulus location as the target in a prosaccade trial block and in the opposite stimulus location as the target on an antisaccade trial block. Participants were instructed to identify the target letter, by means of a key press, as quickly and as accurately as they could. We were not able to measure eye movements in Experiment 1. Instead, we used target-identification latencies and accuracy as more indirect indices of orienting. Although attention and eye movements are not perfectly correlated, we hypothesized that latencies would be shorter, and accuracy higher, for prosaccade trials than for antisaccade trials because in the former, attention was cued to the target location. On antisaccade trials, attention was initially cued away from the target, and so the task put a premium on actively maintaining the task goal in order to prevent (or recover from) reflexively orienting to the abrupt-onset cue. We measured eye movements directly in Experiment 2.

## Method

### *Participant Screening for Working-Memory Capacity*

Participants were screened for WM capacity using the operation-word span task (OSPAN) in which they solved series of simple mathematical operations while attempting to remember a list of unrelated words (for details, see La Pointe & Engle, 1990). A Micro Experimental Laboratory (MEL) 2.0 program presented the task stimuli at the center of a color monitor with a VGA graphics card (set to black and white). Participants were tested individually and sat at the most comfortable viewing distance from the monitor.

Participants saw one operation-word string at a time, and each set of operation-word strings ranged from two to six items in length. For example, a set of three strings might be,

IS  $(9/3) + 2 = 5$  ? drill

IS  $(5 \times 1) - 4 = 2$  ? beach

IS  $(2 \times 2) + 3 = 7$  ? job

The experimenter instructed the participant to begin reading the operation-word pair aloud as soon as it appeared. Pausing was not permitted. After reading the equation aloud, the participant verified whether the provided answer was correct and then read the word aloud. The next operation then immediately appeared. The participant then read the next operation aloud, and the sequence continued until three question marks (???) cued the participant to recall all of the words from that set only. Participants wrote the words on an answer sheet in the order in which they had been presented.

The OSPAN score was the sum of the recalled words for all sets recalled completely and in correct order. Three sets of each length (from two to six operation-word pairs) were tested, and possible scores ranged from 0 to 60. The different set sizes appeared in an unpredictable order, so the number of words to recall was not known until the recall cue appeared.

### *Participants*

Two hundred three undergraduates from Georgia State University and Georgia Institute of Technology participated in Experiment 1, either for extra credit or as partial fulfillment of a course requirement. These participants were identified from a larger pool who had participated in OSPAN: 107 participants were selected from the top quarter of the distribution (high-span participants), and 96 were selected from the bottom quarter (low-span participants). All had correctly solved at least 85% of the OSPAN operations (as typically do 99% of those tested). All participants had normal or corrected-to-normal vision. Participation in the antisaccade task *followed OSPAN by 5 min.*

## *Design*

The design was a 2 X 2 X 2 mixed-model factorial, with task (prosaccade, antisaccade) as a blocked, within-subjects variable and span group (high, low) and task order (prosaccade, antisaccade; antisaccade, prosaccade) as between-subjects variables.

## *Apparatus and Materials*

A MEL 2.0 program presented the stimuli in standard font on a Dell brand (Dell Computer Corp., Austin, TX) color monitor with a VGA graphics card and collected latency and accuracy data from key-press responses. During the antisaccade task, participants sat in a comfortable, but stationary, chair that was positioned (via tape marks on the floor) such that the eyes of a 5 ft 9 in. (1.75 m) person would be approximately 45 cm from the center of the monitor.

## *Procedure*

The basic requirements of the task were to identify the masked target stimulus on each trial and to press the key that corresponded to the target as quickly and accurately as possible. The target on each trial was the capitalized letter *B*, *P*, or *R*. The /, 2, and 3 keys on the number pad of the keyboard were labeled with colored stickers, *B*, *P*, and *R*, respectively. Index, middle, and ring fingers of the right hand were rested on these keys throughout the experiment. The entire experiment consisted of six trial blocks: two "response mapping" practice blocks, a prosaccade practice block, a prosaccade experimental block, an antisaccade practice block, and an antisaccade experimental block, with the order of the prosaccade and antisaccade blocks varying between participants. In all blocks, the target letters *B*, *P*, and *R* occurred an equal number of times.

The experiment started with two response-mapping practice blocks. In each block, 18 trials were presented in which a target letter appeared at central fixation. There were six trials for each target letter, presented in a randomized order for each participant. Each block began with the presentation of a yellow "READY?" signal at the center of the screen against a black background. The ready signal remained on screen until the participant pressed the keyboard's space bar, which was followed by a 400-ms blank screen. A cyan fixation signal ("\*\*\*\*") then appeared at the center of the screen for an interval that varied unpredictably, as is typically done in antisaccade tasks (see Hallett & Adams, 1980; Roberts et al., 1994), here between 200 and 2,200 ms. An equal number of trials had fixation durations of 200, 600, 1,000, 1,400, 1,800, or 2,200 ms. A 100-ms blank screen followed fixation, and then a white target letter appeared in the center of the screen for 100 ms. The target was followed by a succession of backward-masking stimuli: an *H* for 50 ms, and then an 8 that remained until a response key was pressed. A 500-ms tone gave feedback immediately following an incorrect response. The next trial began with a 400-ms blank screen.

In the prosaccade practice block, 18 trials were presented in which the trial sequence proceeded as in the response-mapping practice blocks, except that the target appeared to the right or left of fixation, and the target location was cued by a flashing white "=" symbol. Immediately after the cyan fixation signal disappeared, a 50-ms blank screen was followed by a "=" cue that appeared for 100 ms to the right or left of fixation (with an eccentricity of 11.33° of visual angle), one character space below the horizontal plane of the fixation signal. Then, a second 50-ms blank screen was followed by the second appearance of the cue, which appeared for 100 ms in the same eccentric location. Thus, the cue appeared to briefly flash on and off, and so was a strong attractor of attention. Following another 50-ms blank screen, the target appeared in the character space directly above the one that had been occupied by the cue. Target duration, masking sequence, and error feedback matched those in response-mapping practice. After prosaccade practice, the prosaccade experimental block proceeded in the same way, with 72 trials. Every combination of the three targets, six fixation durations, and two stimulus locations occurred twice across these 72 trials.

The antisaccade practice and experimental blocks were identical to the prosaccade blocks with one exception. In these blocks, the "=" cue always appeared on the opposite side of the screen from the upcoming target stimulus. So if the cue appeared on the left of the screen, the target then appeared on the right of the screen, and vice versa.



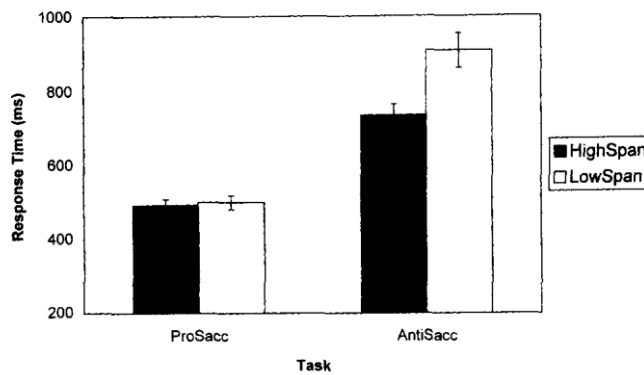


Figure 1. Mean target-identification latencies for high- and low-span participants for participants' first task only in Experiment 1, either prosaccade (ProSacc) or antisaccade (AntiSacc). Error bars depict standard errors of the means. ms = milliseconds.

## Results

### Participants

The mean OSPAN scores for high- and low-span participants, respectively, were 23.65 ( $SD = 6.73$ , range = 18-55) and 6.07 ( $SD = 2.14$ , range = 0-9).

### Response Times

We expected that high- and low-span participants would differ minimally (if at all) in the prosaccade task, where fast and accurate target identification would be aided by a relatively automatic orienting response. In contrast, we expected high-span participants to significantly outperform low-span participants in the antisaccade task, where fast and accurate identification required the active blocking of, or recovery from, an automatic orienting response. For all analyses reported hereafter, the alpha level was set at .05. Also, for all response-time analyses in Experiments 1 and 2, group means were taken across individual participants' median latencies in each condition.

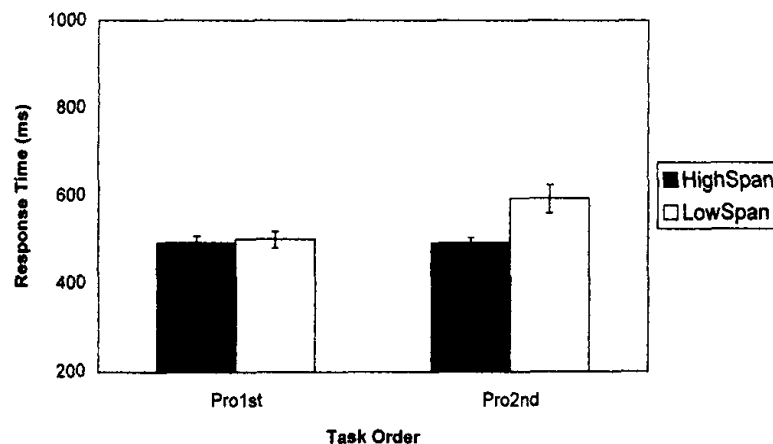
A 2 (span group) x 2 (task) X 2 (task order) mixed-model analysis of variance (ANOVA), with task as a repeated-measures variable, indicated a significant task order effect,  $F(1, 199) = 27.53$ ,  $MSE = 64,846.32$ , as well as a significant Span x Task Order interaction,  $F(1, 199) = 5.39$ ,  $MSE = 64,846.32$ , and Task x Task Order interaction,  $F(1, 199) = 53.76$ ,  $MSE = 14,126.38$ . Therefore, to examine span differences in prosaccade versus antisaccade performance that were independent of order effects, we analyzed response latencies from participants' first task block only, treating task as a between-subjects variable. For the prosaccade task, then, data were analyzed from 52 high-span and 45 low-span participants, and for the antisaccade task, data were analyzed from a different 55 high-span and 51 low-span participants. These data are presented in Figure 1.

The prosaccade task appeared to allow for faster target identification than did the antisaccade task. Most importantly, however, high- and low-span participants performed virtually identically in the prosaccade task ( $M$  difference = 8 ms) and quite differently in the antisaccade task, with high-span participants identifying targets much faster than low-span participants ( $M$  difference = 174 ms). A 2 (span group) X 2 (task) ANOVA indicated that prosaccade identification times were significantly shorter than antisaccade identification times,  $F(1, 199) = 110.79$ ,  $MSE = 48,762.10$ , and although high-span participants identified targets significantly more quickly than did low-span participants,  $F(1, 199) = 8.63$ ,  $MSE = 48,762.10$ , the Span x Task interaction was significant,  $F(1, 199) = 7.12$ ,  $MSE = 48,762.10$ . Of importance, span differences in prosaccade-task latencies were not significant,  $F(1, 95) < 1$ .

The effects of task order on target-identification speeds in prosaccade and antisaccade tasks are depicted in Figures 2 and 3, respectively. For participants who experienced the prosaccade task first, there were no span differences in prosaccade performance, as discussed previously. However, for participants who experienced the prosaccade task second—after completing the antisaccade task—span differences emerged. Here, low-span

participants responded more slowly on prosaccade trials than did high-span participants. A 2 (span) x 2 (task order) ANOVA revealed a significant effect of task order on prosaccade response times,  $F(1, 199) = 4.54$ ,  $MSE = 23,807.66$ , and more importantly, a significant Span x Task Order interaction,  $F(1, 199) = 4.67$ ,  $MSE = 23,807.66$ . Target-identification latencies for low-span participants who completed the prosaccade task after the antisaccade task were significantly longer than those of their high-span counterparts,  $F(1, 104) = 8.86$ ,  $MSE = 31,228.44$ . Moreover, low-span participants who completed the prosaccade task second were significantly slower to identify targets than were those who completed it first,  $F(1, 94) = 5.77$ ,  $MSE = 35,961.98$ . High-span participants showed no such task-order effect,  $F(1, 105) < 1$ . We will hold our interpretation of these findings for the *Discussion* section.

Task order also affected antisaccade performance, but it did so in the opposite direction (see Figure 3). That is, for participants who experienced the antisaccade task first, large span differences were evident, as discussed previously. However, for participants who experienced the antisaccade task second—after completing the prosaccade task—span differences were absent. Moreover, low-span participants' antisaccade performance appeared to benefit more from practice on the prosaccade task than did high-span participants' performance. Indeed, a 2 (span) x 2 (task order) ANOVA on antisaccade latencies indicated a significant effect of task order,  $F(1, 199) = 44.17$ ,  $MSE = 55,165.03$ , as well as a significant Span x Task Order interaction,  $F(1, 199) = 4.58$ ,  $MSE = 55,165.03$ . For participants who completed the antisaccade task second, span differences in target identification latency were not significant,  $F(1, 95) < 1$ . Both span groups who completed the antisaccade task second had shorter response latencies than did those who completed the antisaccade task first: for low spans,  $F(1, 94) = 28.97$ ,  $MSE = 69,613.03$ ; for high spans,  $F(1, 105) = 14.04$ ,  $MSE = 42,230.64$ . However, the significant Span x Task Order interaction indicated that low-span participants' order effect was larger than that of high-span participants.



*Figure 2.* Mean target-identification latencies for high- and low-span participants in the prosaccade task, for those participants who performed the prosaccade task first (Pro1st) versus second (Pro2nd) in Experiment 1. Error bars depict standard errors of the means. ms = milliseconds.



**Table 1**  
**Mean Error Rates in Target Identification by Span Group and Task (Prosaccade vs. Antisaccade) in Experiment 1**

| Span group             | Task       |             |
|------------------------|------------|-------------|
|                        | Prosaccade | Antisaccade |
| High ( <i>n</i> = 107) |            |             |
| <i>M</i>               | .062       | .331        |
| <i>SD</i>              | .079       | .186        |
| Low ( <i>n</i> = 96)   |            |             |
| <i>M</i>               | .081       | .397        |
| <i>SD</i>              | .091       | .178        |

### **Error Rates**

Means of high- and low-span participants' target-identification error rates for prosaccade and antisaccade tasks are presented in Table 1. Overall, high-span participants made fewer errors than did low-span participants, and prosaccade responses were more accurate than antisaccade responses. In addition, span differences in accuracy were smaller in the prosaccade than in the antisaccade task.

These impressions were confirmed by a 2 (span groups) X 2 (tasks) X 2 (task order) mixed-model ANOVA on target-identification error rates, with task as a repeated measures variable. Overall, high-span participants made fewer errors than did low-span participants,  $F(1, 199) = 8.72$ ,  $MSE = 0.02$ , and prosaccade targets were identified more accurately than were antisaccade targets,  $F(1, 199) = 668.60$ ,  $MSE = 0.01$ . The Span X Task interaction approached conventional significance,  $F(1, 199) = 3.73$ ,  $MSE = 0.01$ ,  $p < .06$ , suggesting that span differences in accuracy were slightly greater in the antisaccade than in the prosaccade task. Considering the prosaccade and antisaccade tasks separately, span differences were not significant in the prosaccade task,  $F(1, 199) = 2.76$ ,  $MSE = 0.01$ ,  $p = .10$ , but they were significant in the antisaccade task,  $F(1, 199) = 7.89$ ,  $MSE = 0.03$ .

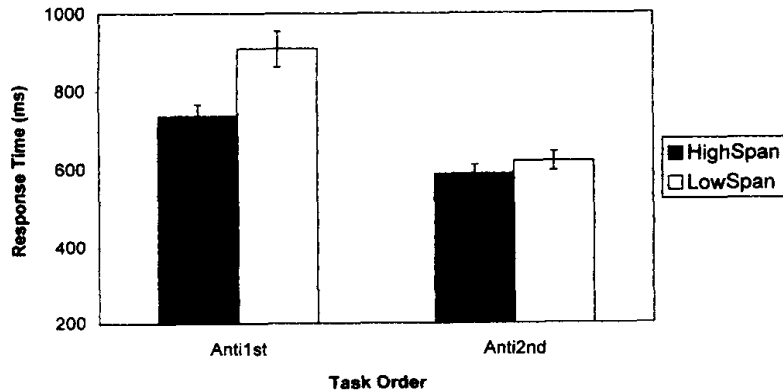
Task-order effects in error rates were also present, but unlike the effects in response times, order affected the span groups equivalently. Task order had a significant effect on overall error rates,  $F(1, 199) = 55.44$ ,  $MSE = 0.02$ , and it interacted with task,  $F(1, 199) = 48.91$ ,  $MSE = 0.01$ , such that order effects were larger for the antisaccade task than for the prosaccade task. Both tasks did show significant order effects, however. Participants who completed the prosaccade task first made significantly fewer prosaccade errors than did those who completed it second ( $M_s = .057$  and  $.084$ , respectively),  $F(1, 199) = 4.78$ ,  $MSE = 0.01$ . In contrast, participants who completed the antisaccade task first made significantly more antisaccade errors than did those who completed it second ( $M_s = .449$  and  $.267$ , respectively),  $F(1, 199) = 66.33$ ,  $MSE = 0.03$ .

The Span X Task Order interaction in error rate was not significant,  $F(1, 199) < 1$ , nor was the Span X Task X Task Order interaction,  $F(1, 199) = 1.04$ ,  $MSE = 0.01$ ,  $p > .30$ . Span did not interact with task order when considering error rates only from prosaccade trials,  $F(1, 199) < 1$ , nor when considering error rates only from antisaccade trials,  $F(1, 199) < 1$ .

### **Discussion**

Participants with high and low WM spans differed in an attention-demanding visual-orienting task, but not in a relatively automatic version of the task. The antisaccade task predictably required attention (and probably eyes, given the visual angle) to be moved away from a salient, abrupt-onset cue and so demanded attentional control. That is, the task required active maintenance of goal information in the face of competition from external stimuli. Here, high-span participants were able to identify targets more quickly and accurately than were low-span participants. High-span participants were better able to resist having attention captured by the cue, and/or they were faster than low-span participants to disengage attention from the cue and toward the target location. The prosaccade task predictably required participants to move attention (and probably eyes) toward an abrupt-onset cue and so allowed responding based, in part, on relatively automatic orienting. Here, high- and low-span

participants performed equivalently; at least this was true when we controlled for task-order effects. When we examined only those participants who completed the prosaccade task first, high- and low-span participants' response times were virtually identical. When attention was cued exogenously by an environmental stimulus, high- and low-span participants were equally able to shift attention quickly and accurately (and were equally able to perform the choice reaction time [RT] task, which made significant perceptual, response-selection, and speed demands on participants). Thus, it was only when attention had to be shifted in opposition to a powerful cue that high-span participants performed better than did low-span participants.



*Figure 3.* Mean target-identification latencies for high- and low-span participants in the antisaccade task, for those participants who performed the antisaccade task first (Anti1st) versus second (Anti2nd) in Experiment 1. Error bars depict standard errors of the means. ms = milliseconds.

The order effects we found were unexpected, and although they are interesting and suggestive, we cannot yet draw strong conclusions from them. However, we speculate that the prosaccade-task-order effects may reflect the relative flexibility of high-span individuals' attentional control. Whereas high- and low-span participants were equally fast in the prosaccade task when it was the first task of the experiment, low-span participants were significantly slower when it followed the antisaccade task. Furthermore, only the low-span participants were slowed on the prosaccade task as a second task compared with as a first task; high-span participants' latencies were unaffected by task order (although both groups were affected in accuracy).

Why should low-span participants have responded more slowly on prosaccade trials following the antisaccade task? A possibility is that once low-span participants had repeatedly attempted the controlled task of looking away from the cue, they had more difficulty than high-span participants in abandoning that task set in favor of the more automatic task set allowed by prosaccade trials. Low-span participants may have perseverated more than high-span participants on the antisaccade requirement of trying to look away from the cue when the task changed to allow looking toward the cue. Of course, this speculative interpretation is consistent with our view that low-span individuals are less able to control attention than are high-span individuals. The findings are fascinating, in any case, and we replicate them in Experiment 2.

An interesting contrast to the prosaccade order effects was seen in the antisaccade task. Both high- and low-span participants were faster when antisaccade was their second task of the experiment (i.e., when it followed the prosaccade task) than when it was their first task. Moreover, this "task-two" benefit was actually larger for low-span than for high-span participants, and when the antisaccade task was presented second it eliminated span differences in target identification times. Because this finding suggests that span differences in antisaccade performance may be eliminated with minimal practice, Experiment 2 further explored the effect of practice on the antisaccade task.

## Experiment 2

In Experiment 2, high- and low-WM-span participants performed the target identification task from Experiment 1, while we monitored eye movements. We also presented 10 separate blocks of 36 antisaccade trials in order to examine practice effects on span differences in suppressing eye movements. The final trial

block was a prosaccade block that tested the effects of extended antisaccade practice on prosaccade performance.

## Method

The OSPAN and target-identification-task methods for Experiment 2 were identical to those of Experiment 1 with the following exceptions.

### Participants

We tested 40 undergraduates (20 high span, 20 low span) from Georgia State University and Georgia Institute of Technology, who *received* \$20 each. All had normal or corrected-to-normal vision. Participants were identified from a larger pool that had participated in OSPAN; this pool, and these specific participants, were different from those tested in Experiment 1. Participation in the antisaccade task may have followed OSPAN by as little as 1 day and as much as 90 days. Because of problems with the eye-movement data-collection system, data from 7 participants were discarded, leaving 16 high-span and 17 low-span individuals in the analyses.

### Design

The design was a 2 X 11 mixed-model factorial, with span group (high, low) as a between-subjects variable, and trial block (1-11) manipulated within subjects. In addition, a within-subjects task variable (antisaccade, prosaccade) was perfectly confounded with block, with Blocks 1-10 presenting antisaccade trials and Block 11 presenting prosaccade trials.

### Apparatus and Materials

The target-identification task program and hardware were similar to those in Experiment 1.

Eye-movement data were collected using an E-5000 eye tracker and pupilometer (Applied Science Laboratories, Bedford, MA). This is an infrared-based, corneal-reflectance system that records the  $x$ - and  $y$ -coordinates of the pupil and corneal reflectance at 60 Hz, allowing saccade latencies to be calculated with a temporal accuracy of 16.667 ms. Spatial error of the apparatus (difference between actual point of gaze and calculated point of gaze) was less than  $1^\circ$ . A magnetic head tracking (MHT) system (Flock of Birds; Ascension Technology Corp., Burlington, VT) was used to coordinate head movements and camera focus on the eye. Measurements were taken on the left eye. The apparatus allowed for the detection of eye movements greater than  $0.5^\circ$ . Software provided by ASL was used to calculate point of gaze, fixation, fixation duration, and interfixation interval. Point of gaze was calculated using the angular disparity between pupil reflectance and maximum corneal reflectance. A fixation was said to have occurred if the mean  $x$ - and  $y$ -coordinates of eye position did not move more than  $1^\circ$  for a period of at least 100 ms. Fixation and fixation duration were said to have terminated if three successive samples exceeded criterion. The interfixation interval was the time in milliseconds from the last sample included in the previous fixation until a new fixation was established. The MEL 2.0 program sent data to the eye-tracker computer as events occurred in the task.

### Procedure

After informed *consent* was obtained, participants put on the MHT headband, and point of gaze was calibrated. Participants began with one response-mapping practice block of 36 trials, in which the target letters *B*, *P*, or *R* appeared at fixation and were pattern masked. Trials followed the same timing sequence as in Experiment 1. Participants then practiced the antisaccade task for only 6 trials and then began the 10 experimental blocks of 36 antisaccade trials each. After they completed the antisaccade trial blocks, participants practiced the prosaccade task for 6 trials and then began the 1 experimental block of 36 prosaccade trials. At the beginning of each experimental block, gaze was checked for proper calibration and recalibrated as necessary.

## Results

### Participants

The mean OSPAN scores for high- and low-span participants, respectively, were 26.94 ( $SD = 10.96$ , range = 19-60) and 5.94 ( $SD = 2.49$ , range = 0-9).

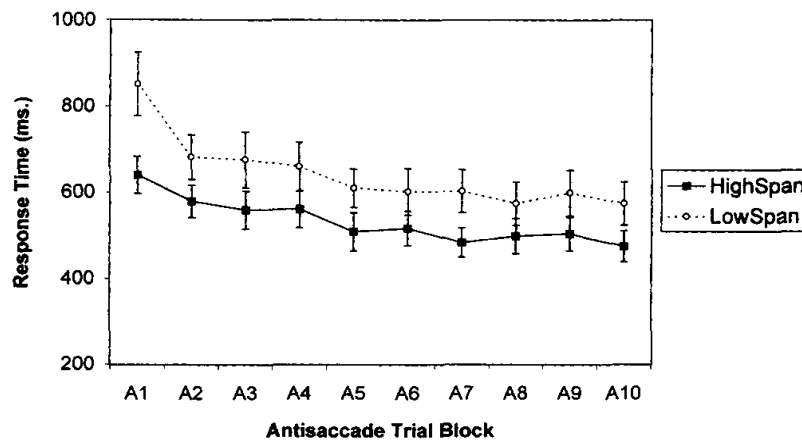


Figure 4. Mean target-identification latencies for high- and low-span participants across 10 antisaccade trial blocks (A1–A10) in Experiment 2. Error bars depict standard errors of the means. ms = milliseconds.

### Target Identification Task

In parallel with Experiment 1, we first present the response-time and error-rate data from the target-identification task, followed thereafter by the eye-movement data.

**Response times.** High- and low-span participants' mean target-identification latencies for Blocks 1-10 of the antisaccade task are presented in Figure 4. What is immediately clear is that high-span participants responded faster than did low-span participants across all antisaccade blocks. Indeed, a 2 (span groups) X 10 (blocks) mixed-model ANOVA indicated that high-span participants responded faster than low-span participants ( $M_s = 533$  and  $641$  ms, respectively),  $F(1, 31) = 6.08$ ,  $MSE = 159,276.61$ , and that responses became faster across blocks,  $F(9, 279) = 15.95$ ,  $MSE = 8,447.54$ . Finally, even though span differences appeared larger in Block 1 than in subsequent blocks, the Span X Block interaction did not approach significance,  $F(9, 279) = 1.00$ ,  $MSE = 8,447.54$ ,  $p = .44$ . Thus, in contrast to Experiment 1, in which significant prosaccade practice eliminated span differences in subsequent antisaccade performance, here span differences persisted across several hundred trials of antisaccade practice.

On the final block, Block 11, which presented prosaccade trials, high-span participants identified targets significantly faster than did low-span participants ( $M_s = 460$  and  $551$  ms, respectively),  $F(1, 31) = 6.18$ ,  $MSE = 11,101.92$ . Thus, as in Experiment 1, significant antisaccade practice was followed by substantial span differences in prosaccade task performance, with low-span participants taking much longer to identify a target even when their eyes should have been reflexively drawn to its subsequent location.

**Error rates.** Table 2 presents high- and low-span participants' target-identification mean error rates across the 10 anti-saccade blocks. Overall, low-span participants made more errors than did high-span participants ( $M_s = .26$  and  $.18$ , respectively),  $F(1, 31) = 4.12$ ,  $MSE = 4.20$ , and errors became less frequent across practice,  $F(9, 279) = 7.92$ ,  $MSE = 0.24$ . The span difference in antisaccade errors persisted across all of practice, with the Span Group x Block interaction not approaching significance,  $F(9, 279) < 1$ .

On the prosaccade block (Block 11), low-span participants' error rate ( $M = .123$ ) was double that of high-span participants ( $M = .062$ ),  $F(1, 31) = 4.64$ ,  $MSE = 0.01$ , a significant difference that again is consistent with the proposal that low-span participants had more difficulty than high-span participants shifting set from the antisaccade to the prosaccade task.

## Eye Movements

Here we report our analyses of participants' eye-movement data concerning the directional accuracy and speed of initial saccades on each trial. For these analyses, the display screen was divided into four areas of interest, three of which comprised a central band of approximately  $5^\circ$  of vertical visual angle extending horizontally from the left edge of the screen to the right. The fourth area contained the rest of the display screen. A center fixation area extended  $1.3^\circ$  to either side of the fixation point. For each trial, the first fixation following the onset of the cue was examined. Fixations occurring in the fourth area were not included in the analyses; those falling to either the right or the left of the center area were. *If the saccade was made* in the direction of the cue, the saccade was considered "reflexive." If it was made away from the cue, it was considered "controlled." A correct saccade was defined by the instructions for that condition. Trials in which either the corneal or pupil reflectance was lost, a key press was made before the initial saccade, or no saccade was made at all were excluded from analyses. These criteria eliminated 19% of the high-span participants' data and 15% of the low-span participants' data, figures not out of line with previous investigations using such an apparatus (e.g., Butler, Zacks, & Henderson, 1999).

For each trial the saccade accuracy and latency were calculated from the eye movement data. The initial saccade following the presentation of the cue was defined by three consecutive 17-ms eye movement samples that occurred in the same horizontal direction and whose durations summed to at least 100 ms. Saccade-initiation latencies were calculated from the onset of the flashing cue until the beginning of the first of the three 17-ms samples.

**Saccade directional accuracy.** Figure 5 displays the proportions of high- and low-span participants' initial saccades on anti-saccade trials that were reflexively drawn to the cue, in opposition to task instructions. Clearly, low-span participants were more likely than high-span participants to initially move their eyes toward the abrupt-onset cue, which reliably appeared in a location that would not contain the target. Indeed, as in the target-identification data, the span difference persisted across practice on hundreds of antisaccade trials.

These observations were confirmed by a 2 (span groups)  $\times$  10 (blocks) mixed-model ANOVA, indicating that low-span participants showed a higher proportion of reflexive saccades than did high-span participants ( $M_s = .371$  and  $.280$ , respectively),  $F(1, 31) = 4.19$ ,  $MSE = 12.11$ . Overall proportions of reflexive saccades did not decrease significantly over blocks,  $F(9, 279) = 1.52$ ,  $MSE = 0.22$ ,  $p = .14$ , nor did span differences in reflexive responding decrease,  $F(9, 279) = 1.49$ ,  $MSE = 0.22$ ,  $p = .15$ .

Moreover, on those trials on which a reflexive saccade occurred, span differences emerged in the time taken to recover. For each saccade-error trial, we summed the fixation and interfixation times from the initial reflexive eye movement until the eye moved out of the incorrect-side region of interest. Low-span participants maintained fixations on the incorrect side of the screen over 150 ms longer than did high-span participants (overall  $M_s = 674$  and  $512$  ms, respectively),  $F(1, 31) = 4.38$ ,  $MSE = 0.81$ . Thus, compared with high-span participants, low-span participants not only made more saccade errors, but after committing an error, they also took much longer to correct it.

Table 2  
Mean Error Rates in Antisaccade Target Identification by Span Group  
and Trial Block in Experiment 2

| Span group        | Trial block |      |      |      |      |      |      |      |      |      |
|-------------------|-------------|------|------|------|------|------|------|------|------|------|
|                   | 1           | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
| High ( $n = 16$ ) |             |      |      |      |      |      |      |      |      |      |
| <i>M</i>          | .257        | .208 | .203 | .179 | .174 | .148 | .142 | .174 | .135 | .144 |
| <i>SD</i>         | .441        | .408 | .406 | .388 | .384 | .354 | .358 | .386 | .349 | .351 |
| Low ( $n = 17$ )  |             |      |      |      |      |      |      |      |      |      |
| <i>M</i>          | .388        | .268 | .263 | .239 | .248 | .260 | .239 | .221 | .229 | .216 |
| <i>SD</i>         | .487        | .445 | .441 | .426 | .434 | .437 | .425 | .413 | .418 | .407 |



In Block 11, the prosaccade block, low-span participants also made more saccade errors than did high-span participants. Here, however, saccade errors reflect looking away from the cue instead of reflexively attending to the cue. These are nonreflexive saccade errors. Thus, the higher saccade error rate for low-span participants, ( $M = .281$ ) compared with high-span participants ( $M = .202$ ), indicates that low-span participants were significantly more likely to look away from a "valid," prosaccade cue,  $F(1, 31) = 9.85$ ,  $MSE = 0.18$ . Low-span participants appeared to have more difficulty than did high-span participants in abandoning the task set from the previous antisaccade blocks and shifting set to the prosaccade task requirements, a difficulty that was also reflected in the target-identification data from this experiment and from Experiment 1.

**Latency of initial saccades.** Figure 6 presents mean latency for initiating saccades across antisaccade trial blocks, collapsed across correct controlled eye movements (i.e., toward the direction opposite the cue) and incorrect reflexive eye movements (i.e., toward the same direction as the cue). Overall, low-span participants initiated their eye movements more slowly following the cue than did high-span participants across the entire session.

A 2 (spans) x 10 (blocks) X 2 (saccade type: controlled vs. reflexive) mixed-model ANOVA indicated that the saccade latencies for low-span participants ( $M = 284$  ms) were significantly longer than those for high-span participants ( $M = 236$  ms),  $F(1, 31) = 4.63$ ,  $MSE = 61,085.36$ , and that saccade latencies remained relatively stable across blocks,  $F(9, 279) = 1.03$ ,  $MSE = 13,208.93$ ,  $p > .40$ . The Span x Block interaction was not significant,  $F(9, 572) = 1.49$ ,  $MSE = 13,208.93$ , indicating stable span differences across blocks. Finally, although controlled, correct saccades were initiated more slowly than were reflexive, incorrect saccades,  $F(1, 572) = 58.30$ ,  $MSE = 13,208.93$ , saccade type did not interact with span,  $F(1, 572) < 1$ , or with block,  $F(9, 572) = 1.62$ ,  $MSE = 13,208.93$ ,  $p > .55$ . Thus, eye movements that were reflexively drawn to the cue in error were initiated more quickly for both high- and low-span participants ( $M_s = 215$  and  $269$  ms, respectively) than were eye movements correctly directed away from the cue ( $M_s = 287$  and  $322$  ms, respectively). However, of central interest here is that high-span participants were not only more likely than low-span participants to move their eyes in the correct direction on antisaccade trials, but they also initiated those saccades more quickly.

On prosaccade trials (Block 11), low-span participants' saccades were initiated significantly more slowly ( $M = 286$  ms) than were high-span participants' saccades ( $M = 203$  ms),  $F(1, 31) = 5.54$ ,  $MSE = 7,660.51$ . Correct reflexive saccades were generated some-what more quickly than were incorrect controlled saccades,  $F(1, 31) = 3.61$ ,  $MSE = 7,660.51$ ,  $p < .07$ , but the Span X Saccade Type interaction did not approach significance,  $F(1, 31) = 1.22$ ,  $MSE = 7,660.51$ ,  $p = .27$ .

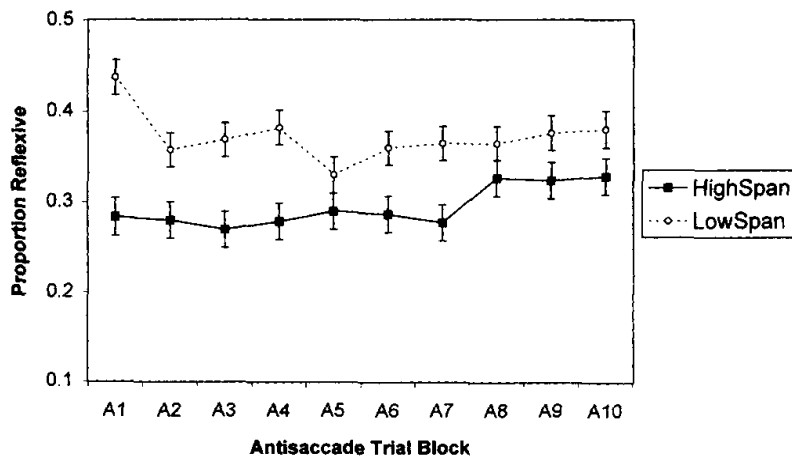


Figure 5. Mean proportion of reflexive eye movements, made in error, across 10 antisaccade trial blocks (A1–A10) for high- and low-span participants in Experiment 2. Error bars depict standard errors of the means.

Thus, not only did low-span participants tend to make eye movement errors on prosaccade trials following extended antisaccade practice, but also the saccade latencies were quite long. These long latencies might suggest that low-span participants were making controlled saccades on many prosaccade trials (note that low-span participants' mean saccade latency in the prosaccade task, at 286 ms, was nearly identical to that for the antisaccade task, at 284 ms). Following antisaccade practice, then, low-span participants appeared to persist, more than high-span participants, in making controlled eye movements when no longer required.

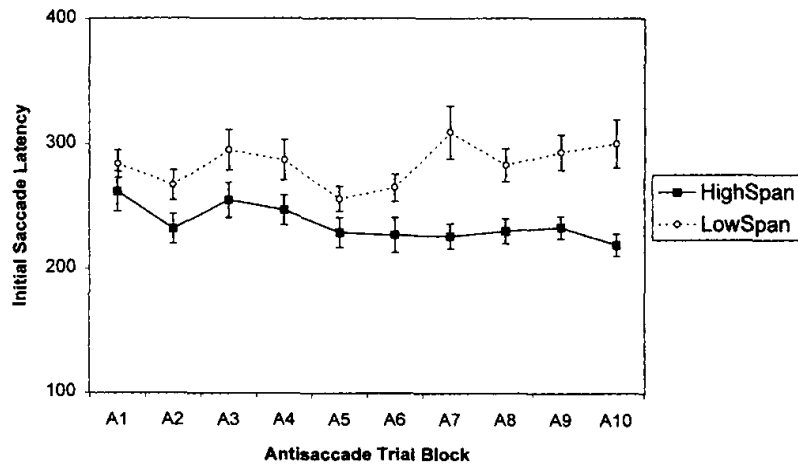


Figure 6. Mean saccade-initiation latencies for high- and low-span participants across 10 antisaccade trial blocks (A1–A10) in Experiment 2. Error bars depict standard errors of the means.

### Discussion

Our findings from Experiment 2 replicate and extend the key findings from Experiment 1. First, high- and low-WM-span participants differed significantly in identifying visual targets that were signaled by antisaccade cues. That is, on trials in which a flashing cue predictably appeared in the opposite location as the upcoming target, low-span participants were slower and more error prone in identifying targets. Moreover, Experiment 2 demonstrated that this substantial span difference was maintained across a total of 360 trials, with little sign of diminution over practice. These findings suggest that low-span individuals are less able to block reflexive eye movements to abrupt-onset cues that conflict with task goals and that low-span individuals' difficulties are not limited to novel situations that involve minimal practice.

In addition, with respect to the target-identification task, Experiment 2 replicated the unexpected finding from Experiment 1 that prosaccade performance for low-span participants was particularly disturbed by prior practice on antisaccade trials. Compared with high-span participants, low-span participants were significantly slower (by more than 150 ms) and less accurate in their responding on the block of prosaccade trials, which followed 10 blocks of antisaccade practice. Low-span individuals may be less able to shift intentional set between tasks than are high-span individuals.

The eye-movement data collected in Experiment 2 nicely reinforce the target-identification findings from both experiments. Specifically, on antisaccade trials, low-span participants were considerably more likely to make reflexive saccades toward the cue than were high-span participants. This difference in the ability to suppress saccades, although especially large in the first trial block, persisted over substantial practice. Moreover, once an error was committed, low-span participants took much longer than high-span participants to recover and move their eyes to the correct side of the screen. The same was true for initial saccade latency: Antisaccades were initiated more slowly by low-span participants than by high-span participants over the entire session.

Moreover, with respect to the prosaccade task, the eye-movement data suggested that low-span individuals' difficulties following antisaccade practice are at least in part due to a perseveration on the antisaccade task goal. Low-span participants were more likely than high-span participants to look away from the prosaccade cue, and they were slower to initiate saccades in this condition. Even though the cue consistently appeared in the same



location as the target, low-span participants appear to have been less able than high-span participants to reconfigure their task set to allow less controlled, more automatic responding.

The data from Experiment 2 also constrain further hypotheses regarding the other task-order effect from Experiment 1, namely that *prosaccade practice eliminated* span differences in antisaccade performance. Clearly, the findings from Experiment 2 discount the possibility that simply any kind of visual-orienting task practice will eliminate span differences in the antisaccade task, because span differences in target identification, saccade accuracy, and saccade latency remained significant across 10 blocks of antisaccade practice. Either the Experiment 1 effect was spurious, or something specific about prosaccade practice led low-span participants to improve in the antisaccade task. Further experiments will be required to determine which of these is correct.

## General Discussion

In two experiments in which participants with high- and low-WM-span capacity were tested on an analogue of the antisaccade task (Hallett, 1978), high-span participants demonstrated better control over visual orienting. In antisaccade trial blocks, in which eyes and attention were to be moved away from an abrupt-onset visual cue, optimal performance required that reflexive orienting responses be suppressed. Here, in accord with task demands, high-span participants were less likely than low-span participants to move their eyes toward the flashing cue (Experiment 2), and high-span participants were faster to correct their saccade errors (Experiment 2). High-span participants were also faster and more accurate in identifying visual targets that appeared in the opposite location as the cue (Experiments 1 and 2). In contrast, in prosaccade trial blocks, in which participants' reflexive responses did not conflict with task goals, high- and low-span participants performed similarly when the prosaccade task was performed first.

Thus, of primary interest here is that high-span individuals outperformed low-span individuals in a task demanding significant attention control but not a significant memory load. In a task requiring no complex mathematical processing or retention of random word lists (as in the OSPAN task), substantial differences were seen between individuals of high- and low-WM-span capacity. At least, span differences were seen in the antisaccade task, a task that not only required participants to orient their eyes to a discrete location on cue but also required them to actively maintain the task goals in the face of powerful interference from the environment. When such controlled processing was unnecessary for successful performance, that is, on prosaccade trials, high- and low-span individuals performed equivalently. Note, however, that prosaccade performance did demand more than simple reflexes, as heavily masked stimuli were to be rapidly identified by means of a choice RT task. WM capacity thus appears to be related to the controlled processing required in responding to interference. WM capacity, as measured by OSPAN and other complex WM tasks, predicts performance even on very simple, low-level tasks that require little in the way of complex higher-order processing, as long as successful performance depends on active maintenance in interference-rich conditions.

But do we know that the processing components shared by OSPAN, a complex multidetermined task, and the antisaccade task, also a multidetermined task, are the same ones shared by OSPAN and higher-order cognitive tasks? Do we know that a unitary, general attention control capability underlies both OSPAN, antisaccade, and even *gF* test performance? Or might several individual factors contribute in different ways to different processes required by these tasks? Clearly, the present study alone cannot answer such questions. Indeed, a large-scale, structural-equation-modeling study might be very useful in this regard.

However, on the basis of the extant literature, we see substantial converging evidence for the general-attention view. For example, it is clear that with respect to the OSPAN task, mathematical ability does not contribute to the correlation between working memory and reading comprehension (Conway & Engle, 1996), nor does processing time on the equations (Conway & Engle, 1996; Engle et al., 1992), nor does study time on the words (Engle et al., 1992). It is also clear that a latent WM variable representing the shared variance among the OSPAN, the reading-span task, and the counting-span task, is very strongly linked to a *gF* latent variable, whereas a latent variable of STM storage tasks is not (Engle, Tuholski, et al., 1999). Thus, neither math skill,

reading skill, counting skill, processing speed, study time, nor simple storage capability is critical to the relation between WM span and measures of higher-order cognition.

Moreover, it has been demonstrated that individual differences in OSPAN correspond to individual differences in interference-resistance and dual-task effects across a variety of memory tasks (Conway & Engle, 1994; Kane & Engle, 2000; Rosen & Engle, 1997, 1998). And Roberts et al. (1994) demonstrated that dividing participants' attention in the antisaccade task leads to performance that is similar to our low-span participants' performance. The lack of such a dual-task effect on prosaccade performance also corresponds nicely to our finding of no span differences in prosaccade performance. In the present study, we have obviously not manipulated all relevant variables at once. However, we find the converging evidence across many studies to provide strong support for the idea that OSPAN taps a very general cognitive primitive, closely linked to a form of attentional control that is critical to performance of the antisaccade task—and to many other tasks as well.

Despite all these consistencies, our findings are at odds with one surprising aspect of the Roberts et al. (1994) results. Roberts et al. found that a secondary attentional-load task impaired the suppression of antisaccades, suggesting that such suppression is a controlled process, but they found no span effects in their data. Roberts et al. tested participants in a reading span task (Experiments 1, 2, 3) and a counting span task (Experiments 2, 3), and found essentially no significant correlations among span and various antisaccade measures. Roberts et al. hypothesized that span and antisaccade performance may reflect different components of a multidimensional WM or executive system. Such a hypothesis (and data) certainly conflicts with our view of the generality of WM and span tasks and is not consistent with our findings here. We are not sure why Roberts et al. did not detect span effects, as there are many ways to obtain null results.' It is possible, however, that our experiments tested a wider *range of WM* capacities or at least a greater number of participants at the ends of the distribution. The possibility that Roberts et al. did not test many participants who we would characterize as low-span individuals is suggested by the task-switching findings discussed below. We found large task-order effects, with low-span individuals performing much more slowly on the prosaccade task when it came second, but weaker task-order effects for high-span individuals. Roberts et al. (Experiment 1) found only a small order effect. Their small effect suggests that their sample may have included relatively few low-span individuals, as we have defined them.

### ***Working Memory, Controlled Attention, and Task Switching***

The task-order effects observed here, particularly with respect to the prosaccade task, are intriguing. Performance on prosaccade tasks, unlike antisaccade tasks, is typically unaffected by the imposition of a memory load (Roberts et al., 1994), by advancing age (Butler et al., 1999), or by injury to prefrontal cortex (e.g., Fukushima et al., 1994). And here, in Experiment 1, we found that for unpracticed participants, prosaccade-task performance was not related to WM capacity, either. Together these findings indicate that the prosaccade task may be performed with little involvement of controlled processing. However, our findings also demonstrate that this "automatic" task may be disrupted by the prior performance of a similar, but attention-demanding, task. Particularly for low-span individuals, switching instructional set from the antisaccade task to the prosaccade task appeared to be quite difficult. Following practice on the antisaccade task, low-span participants made more antisaccade-type eye movements than did high-span participants on the prosaccade task (Experiment 2), and low-span participants were slower and less accurate than high-span participants in the prosaccade target-identification task (Experiments 1 and 2). However, even high-span participants showed some evidence of perseveration, with an increase in identification errors in Experiment 1, and with a nonnegligible number of "anti" saccades in the final, prosaccade task block in Experiment 2.

Our findings are partially consistent with a demonstration by Weber (1995) that participants performed worse on both prosaccade and antisaccade tasks when the task demands switched randomly between trials compared with when the tasks were predictably blocked. For most participants, saccades were slower and less accurate when there was little or no warning about what kind of trial would be next. However, much of the switching cost on prosaccade trials was eliminated when a task cue appeared at least 100 ms before the location cue, suggesting that a prosaccade task set could be implemented with minimal warning following an antisaccade

trial. We have found, in contrast, that a preceding antisaccade block can disrupt performance over an entire, predict-able block of prosaccade trials. As discussed above, Roberts et al. (1994) also found a similar, but smaller, switching effect in their Experiment 1. Perhaps antisaccade-to-prosaccade switching costs require more momentum in set than can be created from just one trial to the next, or perhaps Weber did not test many low-span participants in his study.

Interestingly, our results resemble those from Allport, Styles, and Hsieh (1994; see also Harvey, 1984), who examined task switching in a series of experiments using various Stroop-like tasks, including the traditional color-word task (Stroop, 1935). In their Experiment 5, they found substantial set-shifting costs when naming the color of a color-word on one trial (high interference) was followed by reading the word of a color-word on the next trial (low interference). Thus, shifting set from a controlled task to an automatic task was markedly difficult, even though the tasks alternated predictably and occurred as much as 1,100 ms apart. The converse effect was not found, however, in that shifting set from reading words to naming colors produced no cost whatsoever. In a similar vein, but outside the Stroop-task context, Meuter and Allport (1999) recently demonstrated switching asymmetries in bilingual participants who switched between their dominant and nondominant language in naming digits: Switch costs were larger from the nondominant language into the dominant language than vice versa. Much like our data from Experiment 1, then, these findings demonstrate that switching from a more automatic task to a more controlled task causes minimal difficulty compared with switching from a controlled to an automatic task. Allport et al. (1994) discuss their findings in terms of *task-set inertia*, a kind of PI in which a nondominant response mapping imposes a stronger set that is more difficult to overcome than is the set for a dominant response. Given our prior findings of WM-span differences in PI (Kane & Engle, 2000), we recommend further exploration of the relations among WM, controlled attention, and task switching.

### ***"Controlled Attention" or Attentional Inhibition?***

Here and elsewhere (Engle, Kane, et al., 1999; Engle, Tuholski, et al., 1999) we have argued that individual differences in WM capacity reflect rather fundamental differences in controlled attention. By "controlled attention" we generally mean an executive control capability; that is, an ability to effectively maintain stimulus, goal, or context information in an active, easily accessible state in the face of interference, to effectively inhibit goal-irrelevant stimuli or responses, or both (for related views, see Cohen & Servan-Schreiber, 1992; Dempster, 1991, 1992; Duncan, 1995; Hasher & Zacks, 1988). Thus, in WM-span tasks, high-span individuals are able to actively maintain information in memory while simultaneously turning attention toward a secondary-processing task. In the antisaccade task, we suggest, high-span individuals are better able to maintain the goal of the task, *"look away from the cue,"* active in memory despite the strong interference presented by the abrupt-onset cue. *In our view, then, this attentional control capability allows flexibility in response to environmental demands, whether those demands involve keeping many representations active in some contexts, keeping only one simple goal active in other contexts, or keeping irrelevant representations or responses at bay through inhibition.*

But do we really have much evidence for such a flexible control difference between high- and low-WM-span individuals? In fact, almost all of the research linking WM and attention has used selection tasks that require participants to ignore some nontarget information in attending to some target. For example, high- and low-span individuals differed in the negative priming task, in which to-be-named target letters appeared amidst to-be-ignored distractor letters (Conway, Tuholski, Shisler, & Engle, 1999). High-span individuals showed negative priming but low-span individuals did not. That is, only high-span individuals were differentially *slowed when the to-be-ignored* letter from one trial became the to-be-named letter on the next trial, a finding some theorists suggest reflects prior inhibition of the distractor (e.g., Houghton & Tipper, 1994; but see Milliken, Joordens, Merikle, & Seiffert, 1998).

As another example, Conway, Cowan, and Bunting (in press) recently tested high- and low-span individuals in the dichotic-listening "cocktail party" task (Cherry, 1953), in which participants repeat aloud an auditory message played in one ear and ignore a message played in the other ear. Participants typically learn to manage the task quite well, and although they are able to detect the physical characteristics of the ignored message (e.g.,

pitch, volume), they can report little of its content. Conway et al. followed up Moray's (1959) discovery that when the participants' names were played in the distractor ear, approximately 33% of participants reported detecting it. Conway et al. found, however, that high- and low-span individuals had dramatically different "hit" rates: Whereas a full 65% of low-span individuals reported hearing their name, only 20% of high-span individuals did. These findings suggest that when the task goal is to ignore or block a stimulus source, high-span individuals do so better than low-span individuals.

In line with the antisaccade findings reported here, then, the current evidence certainly points to WM capacity being related to attentional inhibition, or the ability to suppress interference from distractor stimuli or prepotent responses in the service of task goals. Indeed, largely on the basis of evidence from memory-interference studies, Engle (1996; Conway & Engle, 1994) suggested that inhibitory capabilities may be the primary determinant of WM span differences, a similar proposal to that made earlier by Hasher, Zacks, and their colleagues (e.g., Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999; Zacks & Hasher, 1994). Hasher and Zacks have proposed that age (and other) differences in WM and language comprehension are driven by an inhibitory deficit. For example, older adults show compromised WM capabilities not because they have smaller capacity but rather because their attentional inhibitory mechanisms fail to regulate the contents of WM. With inhibitory failure comes an increased cluttering of WM, where relevant and irrelevant information compete for retrieval access and action control. In the Hasher and Zacks view, then, attentional inhibition is the primitive ability that drives WM capacity. In contrast, we have proposed that WM capacity, or controlled attention capability, is the primitive that drives inhibition, as well as maintenance and other attention-demanding functions (see also De Jong et al., 1999; O'Reilly et al., 1999; Roberts & Pennington, 1996).

How can we resolve this theoretical "chicken—egg" dilemma? There appears to be evidence supporting both positions. For example, May, Hasher, and Kane (1999) demonstrated that vulnerability to PI may determine WM span scores, thus implicating inhibition as an important determinant of WM capacity. May et al. presented older and younger adults with different versions of the Daneman and Carpenter (1980) reading span task and the backward digit span task. Some memory sets proceeded from small sets of two upward to large sets of six, in "ascending" order, as is often done in research and in clinical testing. Others were presented in a "descending" order from large to small sets. The logic was that PI may build rapidly across memory sets (à la Keppel & Underwood, 1962), and typical ascending versions of span tasks maximize the potential for PI effects because the larger sets of four, five, or six items are attempted after numerous other sets are completed. In contrast, on descending versions of the task, PI susceptibility will have less impact on scores because large sets may be attempted before much PI has built up. Indeed, May et al. found substantial age differences in span on ascending versions of the task, where PI potential was high, consistent with prior demonstrations of age differences in interference (for a review, see Kane & Hasher, 1995). However, age differences were eliminated on descending versions of the task, where PI was minimal. May et al. interpreted their findings to suggest that a WM score, *and* thus the differentiation of high- and low-span participants, is influenced by PI susceptibility, which in turn is driven by attentional inhibition.

Other evidence suggests, however, that inhibition is the result of controlled processing that relies on WM capacity. Specifically, studies of divided attention and interference suggest that high- and low-span participants, who normally differ in interference susceptibility, become equivalently interference prone when required to perform a secondary task. As discussed in the introduction to this article, Rosen and Engle (1997) in a fluency task and Kane and Engle (2000) in a PI build-up task demonstrated that in the absence of interference, both high- and low-span participants were quite able to retrieve information from long-term memory. However, when the potential for PI was increased, low-span participants proved to be much more vulnerable to interference than were high-span participants. These findings are perfectly consistent with May et al. (1999).

In our view, however, the inhibition-as-primitive hypothesis runs into difficulty in light of divided-attention, or "load" effects, on interference susceptibility. In both the Rosen and Engle (1997) and Kane and Engle (2000) studies, some participants were tested under an attentional load, such as monitoring auditory digits or tapping fingers in a complex pattern. These secondary tasks bore no surface similarity to the primary memory tasks'

stimuli or modality. Nonetheless, in both studies, high- and low-span participants performing under load were equivalently vulnerable to interference; load equalized the span groups. That is, high-span participants became more vulnerable to interference under load, whereas low-span participants remained equivalently susceptible to interference under load and no load. These data not only suggest that high- and low-span participants allocate attention differently when faced with interference-rich situations but also that inhibitory capabilities of high-span participants can be manipulated by the task demands. High-span participants are adept at resisting interference under normal conditions; however, their ability to resist interference is significantly hampered by the imposition of a secondary task.

If inhibition were the primitive capability that drove WM capacity and controlled attention, then an attentional load should not be effective in disrupting inhibition. Indeed, the Roberts et al. (1994) findings in the antisaccade task also suggest that the suppression of reflexive saccade requires controlled attention: Adding a secondary auditory—verbal summation task, bearing no similarity to the antisaccade task, impaired participants' ability to look away from the antisaccade cue. If suppression can be affected by dual-task conditions, it suggests to us that a more general attentional capability is responsible for successful inhibition and inhibitory differences. We suggest that the general controlled ability to actively maintain information in the face of interference is central to individual differences in WM capacity and therefore is central to the range of complex cognitive behaviors that WM-span tests predict.

## **Conclusion**

In two experiments, individuals of high- and low-WM-span capabilities were tested in an analogue of the antisaccade task, a task previously found to be reliant on controlled processing and sensitive to dPFC functioning. In both experiments, high-span participants were faster and more accurate in identifying visual targets signaled by antisaccade cues; that is, when the location of the cue indicated that the upcoming target would appear in the opposite screen location, high-span participants were better able to direct their eyes in opposition to the cue. However, high- and low-span participants performed equivalently following prosaccade cues that indicated a target would appear in the same location as the cue. Here, where performance could rely in part on reflexive, automatic orienting responses, no span differences were seen. At least, no span differences were seen in the prosaccade task when it was the first task encountered by participants. High-span participants were equally fast in the prosaccade task regardless of task order, but low-span participants experienced more difficulty in switching from the antisaccade task to the prosaccade task. Here, low-span participants were slower to identify prosaccade targets, suggesting that they perseverated on the antisaccade task demands and failed to reflexively attend to the cue.

In Experiment 2, eye movements were monitored across a substantial number of practice trials with the antisaccade task. Low-span participants were more likely than high-span participants to reflexively move their eyes to the cue, even though their goal was to suppress these reflexive saccades in favor of moving the eyes away from the cue. And, as in Experiment 1, low-span participants were slower and less accurate in identifying these antisaccade targets than were high-span participants. Moreover, the span differences in reflexive saccades and target identification remained stable and substantial throughout the 360 trials of practice.

These findings are consistent with the idea that WM capacity, as defined by complex span measures, is a valid predictor of attentional control. In a simple attention task involving minimal memory demands, no complex cognitive skill, and no surface similarity to a span task, but significant attention and dPFC involvement, high-WM-span individuals consistently outperformed low-WM-span individuals. WM capacity may therefore reflect a basic attentional control capability, reliant on dPFC circuits, that is critical across a wide range of cognitive contexts involving interference, from long-term memory retrieval, to language comprehension, to reasoning.

## **Notes:**

1 Larson and Perry (1999) recently reported another failure to detect a significant correlation between a WM measure and antisaccade performance. However, we note the following difficulties in interpreting their findings: (a) The sample was limited to 31 participants, not prescreened for their WM capacity; (b) the working-



memory measure ("Mental Counters Test") was not a span task per se, and so it may or may not have tapped the same construct as WM span tasks (see Engle, Tuohlski, et al., 1999); and (c) they tested all participants in the prosaccade task first, followed by the antisaccade task. In our Experiment 1, we found that span differences in antisaccade performance were eliminated by prior practice with the pro-saccade task.

## References

- Allport, A. A., Styles, E. A., & Hsieh, S. (1994). Shifting attentional set: Exploring the dynamic control of tasks. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance XV* (pp. 421-452). Hillsdale, NJ: Erlbaum.
- Baddeley, A. D. (1986). *Working memory*. London/New York: Oxford University Press.
- Baddeley, A. D. (1993). Working memory or working attention? In A. Baddeley & L. Weiskrantz (Eds.), *Attention: Selection, awareness, and control: A tribute to Donald Broadbent* (pp. 152-170). Oxford, England: Clarendon Press.
- Baddeley, A. D. (1996). Exploring the central executive. *Quarterly Journal of Experimental Psychology*, 49A, 5-28.
- Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. A. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47-89). New York: Academic Press.
- Butler, K. M., Zacks, R. T., & Henderson, J. M. (1999). Suppression of reflexive saccades in younger and older adults: Age comparisons on an antisaccade task. *Memory and Cognition*, 27, 584-591.
- Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. *Journal of the Acoustical Society of America*, 25, 975-979.
- Clarkson-Smith, L., & Hartley, A. A. (1990). The game of bridge as an exercise in working memory and reasoning. *Journal of Gerontology*, 45, P233-P238.
- Cohen, J. D., & Servan-Schreiber, D. (1992). Context, cortex, and dopamine: A connectionist approach to behavior and biology in schizophrenia. *Psychological Review*, 99, 45-77.
- Conway, A. R. A., Cowan, N., & Bunting, M. F. (in press). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulletin & Review*.
- Conway, A. R. A., & Engle, R. W. (1994). Working memory and retrieval: A resource-dependent inhibition model. *Journal of Experimental Psychology: General*, 123, 354-373.
- Conway, A. R. A., & Engle, R. W. (1996). Individual differences in working memory capacity: More evidence for a general capacity theory. *Memory*, 4, 577-590.
- Conway, A. R. A., Tuohlski, S. W., Shisler, R. J., & Engle, R. W. (1999). The effect of memory load on negative priming: An individual differences investigation. *Memory & Cognition*, 27, 1042-1050.
- Cowan, N. (1995). *Attention and memory: An integrated framework*. Oxford, England: Oxford University Press.
- Crowder, R. G. (1982). The demise of short-term memory. *Acta Psychologica*, 50, 291-323.
- Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, 19, 450-466.
- Daneman, M., & Carpenter, P. A. (1983). Individual differences in integrating information between and within sentences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 9, 561-584.
- Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: A meta-analysis. *Psychonomic Bulletin and Review*, 3, 422-433.
- De Jong, R. D., Berendsen, E., & Cools, R. (1999). Goal neglect and inhibitory limitations: Dissociable causes of interference effects in conflict situations. *Acta Psychologica*, 101, 379-394.
- Dempster, F. N. (1991). Inhibitory processes: A neglected dimension in intelligence. *Intelligence*, 15, 157-173.
- Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review*, 12, 45-75.
- Duncan, J. (1995). Attention, intelligence, and the frontal lobes. In M. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 721-733). Cambridge, MA: MIT Press.
- Engle, R. W. (1996). Working memory and retrieval: An inhibition-resource approach. In J. T. E. Richardson, R. W. Engle, L. Hasher, R. H. Logie, E. R. Stoltzfus, & R. T. Zacks, *Working memory and human cognition*. New York: Oxford University Press.
- Engle, R. W., Cantor, J., & Candi°, J. J. (1992). Individual differences in working memory and comprehension: A test of four hypotheses. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 18,

972-992.

- Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102-134). New York: Cambridge University Press.
- Engle, R. W., & Oransky, N. (1999). The evolution from short-term to working memory: Multi-store to dynamic models of temporary storage. In R. J. Sternberg (Ed.), *The nature of cognition* (pp. 515-555). Cambridge, MA: MIT Press.
- Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent variable approach. *Journal of Experimental Psychology: General*, *128*, 309-331.
- Everling, S., & Fischer, B. (1998). The antisaccade: A review of basic research and clinical findings. *Neuropsychologia*, *36*, 885-899.
- Fukushima, J., Fukushima, K., Miyasaka, K., & Yamashita, I. (1994). Voluntary control of saccadic eye movement in patients with frontal cortical lesions and Parkinsonian patients in comparison with that in schizophrenics. *Biological Psychiatry*, *36*, 21-30.
- Guittou, D., Buchtel, H. A., & Douglas, R. M. (1985). Frontal lobe lesions in man cause difficulties in suppressing reflexive glances and in generating goal-directed saccades. *Experimental Brain Research*, *58*, 455-472.
- Hallett, P. E. (1978). Primary and secondary saccades to goals defined by instructions. *Vision Research*, *18*, 1279-1296.
- Hallett, P. E., & Adams, B. D. (1980). The predictability of saccadic latency in a novel voluntary oculomotor task. *Vision Research*, *20*, 329-339.
- Harvey, N. (1984). The Stroop effect: Failure to focus attention or failure to maintain focusing? *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *36*, 89-115.
- Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 22, pp. 193-225). San Diego, CA: Academic Press.
- Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In A. Koriat & D. Gopher (Eds.), *Attention and performance XVII* (pp. 653-675). Cambridge, MA: MIT Press.
- Houghton, G., & Tipper, S. P. (1994). A model of inhibitory mechanisms in selective attention. In D. Dagenbach & T. Carr (Eds.), *Inhibitory processes in attention, memory, and language* (pp. 53-112). San Diego, CA: Academic Press.
- Institute for Personality and Ability Testing. (1973). *Measuring intelligence with Culture Fair Tests*. Champaign, IL: Author.
- Kane, M. J., & Engle, R. W. (2001). *The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence*. Manuscript submitted for publication.
- Kane, M. J., & Engle, R. W. (2000). Working memory capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 336-358.
- Kane, M. J., & Hasher, L. (1995). Interference. In G. Maddox (Ed.), *Encyclopedia of aging* (2nd ed.; pp. 514-516). New York: Springer-Verlag.
- Keppel, G., & Underwood, B. J. (1962). Proactive inhibition in short-term retention of single items. *Journal of Verbal Learning and Verbal Behavior*, *1*, 153-161.
- Kiewra, K. A., & Benton, S. L. (1988). The relationship between information processing ability and note-taking. *Contemporary Educational Psychology*, *13*, 33-44.
- Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity?! *Intelligence*, *14*, 389-433.
- La Pointe, L. B., & Engle, R. W. (1990). Simple and complex word spans as measures of working memory capacity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*, 1118-1133.
- Larson, G. E., & Perry, Z. A. (1999). Visual capture and human error. *Applied Cognitive Psychology*, *13*, 227-236.



- May, C. P., Hasher, L., & Kane, M. J. (1999). The role of interference in memory span. *Memory & Cognition*, 27, 759-767.
- Meuter, R. F. I., & Allport, A. (1999). Bilingual language switching in naming: Asymmetrical costs of language selection. *Journal of Memory and Language*, 40, 25-40.
- Milliken, B., Joordens, S., Merikle, P. M., & Seiffert, A. E. (1998). Selective attention: A reevaluation of the implications of negative priming. *Psychological Review*, 105, 203-229.
- Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *Quarterly Journal of Experimental Psychology*, 11, 56-60.
- Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation: Advances in research and theory* (Vol. 4, pp. 1-18). New York: Plenum Press.
- O'Reilly, R. C., Braver, T. S., & Cohen, J. D. (1999). A biologically-based computational model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 375-411). New York: Cambridge University Press.
- Perfetti, C. A., & Lesgold, A. M. (1977). Discourse comprehension and sources of individual differences. In M. A. Just & P. A. Carpenter (Eds.), *Cognitive processes in comprehension*. Hillsdale, NJ: Erlbaum.
- Pierrot-Deseilligny, C., Rivaud, S., Gaymard, B., & Agid, Y. (1991). Cortical control of reflexive visually-guided saccades. *Brain*, 114, 1473-1485.
- Raven, J. C., Court, J. H., & Raven, J. (1977). *Raven's Progressive Matrices and Vocabulary Scales*. New York: Psychological Corporation.
- Roberts, R. J., Jr., Hager, L. D., & Heron, C. (1994). Prefrontal cognitive processes: Working memory and inhibition in the antisaccade task. *Journal of Experimental Psychology: General*, 123, 374-393.
- Roberts, R. J., Jr., & Pennington, B. F. (1996). An interactive framework for examining prefrontal cognitive processes. *Developmental Neuropsychology*, 12, 105-126.
- Rosen, V. M., & Engle, R. W. (1997). The role of working memory capacity in retrieval. *Journal of Experimental Psychology: General*, 126, 211-227.
- Rosen, V. M., & Engle, R. W. (1998). Working memory capacity and suppression. *Journal of Memory and Language*, 39, 418-436.
- Shallice, T., & Burgess, P. W. (1993). Supervisory control of action and thought selection. In A. Baddeley & L. Weiskrantz (Eds.), *Attention: Selection, awareness, and control: A tribute to Donald Broadbent* (pp. 171-187). Oxford, England: Clarendon Press.
- Shute, V. J. (1991). Who is likely to acquire programming skills? *Journal of Educational Computing Research*, 7, 1-24.
- Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, 18, 643-662.
- Sweeney, J. A., Mintun, M. A., Kwee, S., Wiseman, M. B., Brown, D. L., Rosenberg, D. R., & Carl, J. R. (1996). Positron emission tomography study of voluntary saccadic eye movements and spatial working memory. *Journal of Neurophysiology*, 75, 454-468.
- Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, 28, 127-154.
- Weber, H. (1995). Presaccadic processes in the generation of pro and anti saccades in human subjects-A reaction-time study. *Perception*, 24, 1265-1280.
- Wickens, D. D., Bom, D. G., & Allen, C. K. (1963). Proactive inhibition and item similarity in short-term memory. *Journal of Verbal Learning and Verbal Behavior*, 2, 440-445.
- Zacks, R. T., & Hasher, L. (1994). Directed ignoring: Inhibitory regulation of working memory. In D. Dagenbach & T. H. Carr (Eds.), *Inhibitory processes in attention, memory, and language* (pp. 241-264). New York: Academic Press.