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Prefrontal Cognitive Processes: Working Memory and Inhibition in the Antisaccade Task

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Recent research suggests 2 principal processes are assessed in many neuropsychological tests of prefrontal functioning: the ability to keep transient information on-line (working memory) and the ability to inhibit prepotent, but incorrect, responses. The current studies examined the hypothesis that taxing working memory beyond some threshold can result in decreased inhibition, resembling the errors committed by patients with prefrontal dysfunctions. Across 3 studies, 70 nonpatient subjects were tested on the antisaccade (AS) task (D. Guitton, H. A. Buchtel, & R. M. Douglas, 1985)—a task sensitive to inhibitory deficits. Subjects were required to look in the opposite direction of a flashed cue, inhibiting the reflexive tendency to saccade to the cue. Subjects performed concurrent tasks that varied working-memory load. The results indicated that conditions with the highest working-memory load produced inhibitory errors comparable to patients with prefrontal dysfunctions. The findings are discussed in terms of the interaction between working memory and the inhibition of prepotent responses.

For at least 20 years the prefrontal cortex has been thought to be important for a variety of cognitive functions, including planning, impulse control, and attention. The prefrontal cortex also is thought to provide integrative functions for higher cognition, integrations that occur across space and time as well as across component cognitive and perceptual processes (for reviews see Fuster, 1989; Levin, Eisenberg, & Benton, 1991). Recent research with human and infra-human subjects has suggested two principal prefrontal functions: a) the preservation of transient information across short time intervals for organizing upcoming action, often referred to as *working memory,* and b) the inhibition of prepotent but inappropriate responses. Although there is increasing consensus on the centrality of these processes, little is known about whether and how such processes *interact* in the generation of behavior.

The present work is motivated by recent theories and computational models that attempt to provide unified accounts of prefrontal functioning (Cohen & Servan-Schreiber, 1992; Dehaene & Changeux, 1991; Diamond, 1990; Fuster, 1989; Goldman-Rakic, 1987; Kimberg & Farah, 1993; Levine & Prueitt, 1989; Norman & Shallice, 1986). Such models suggest two important ideas that are explored here. First, working memory and the ability to inhibit prepotent responses are intimately related, and a deficient working memory system can increase the difficulty of resisting prepotent actions. Second, there is more of a continuum between normal and abnormal functioning than is often portrayed in the literature, so that many everyday action errors result from a similar process that produces the behavioral "breakdowns" seen in patients with known frontal dysfunctions. To explore these ideas empirically, we examined nonpatient subjects on a task that is sensitive to prefrontal dysfunction—the antisaccade task—in conditions that made varying demands on working memory. The studies allowed us to examine how working memory relates to successful inhibition and whether normal subjects resemble frontally impaired patients under specific high-load conditions. Before describing these studies, we first provide more detail on the framework for characterizing prefrontal cognitive processes from which we are working.

Commonalties Across Tasks that Assess Prefrontal Functioning

The most common analytic technique to assess prefrontal functioning has been to study prefrontal dysfunctioning—breakdowns that occur when some part of the prefrontal cortex is disabled, such as by lesion, disease, or accident. The functions of the prefrontal cortex are inferred from the processes that seem to be changed or missing in the dysfunctioning group as compared with some control. Although there are some difficulties with this analytic strategy (Farah, 1994; Shallice, 1988), it has proved highly successful in documenting a range of behavioral changes associated with frontal insults (for reviews, see Fuster, 1989; Shallice, 1988). In addition, the conclusions about structure–function relations have generally been corroborated and extended by approaches that assess on-line neural processing, such as single-cell recording, evoked po-

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tentials, and positron-emission tomography (PET) scanning (for a review, see Fuster, 1989).

Both kinds of studies use a variety of tasks that appear sensitive to prefrontal functioning, including the Wisconsin Card Sort Task (Milner, 1963), the antisaccade task (Guitton, Buchtel, & Douglas, 1985), the Tower of Hanoi Task (Shallice, 1982), the continuous performance task (Cohen & Servan-Schreiber, 1992), the Stroop Task (Perret, 1974), and prospective-memory tasks (Shimamura, Janowsky, & Squire, 1991). Studies with nonhuman primates have used delayed-response tasks, the A-Not-B task, and visual-search tasks (Diamond & Goldman-Rakic, 1989; Funahashi, Bruce, & Goldman-Rakic, 1990; Fuster, 1991). These and other prefrontally sensitive tasks vary in many of their surface-level characteristics and the relevant behavioral indicators of performance. Such differences have contributed to the wide range of hypothesized prefrontal functions, which are often grouped together into the global category of "executive functions."

Despite the differences across prefrontally sensitive tasks, a remarkable variety of them fit a common structure: They place a subject in a context in which a prepotent response tendency is directly opposed to the activity or activities that lead to correct responding. The prepotent tendency is either built-in or is acquired during an experimental session. To perform correctly, a subject must maintain some information over a short time interval, refrain from performing the habitual or prepotent action, and carry out an alternative action. "Prefrontal" subjects readily fall victim to the prepotent tendency.

Thus, as shown in Table 1, a consistent feature of the prefrontal task is that it puts a prepotent tendency in competition with an alternative response. For example, in the Wisconsin Card Sort Task, subjects sort cards containing figures that vary in form, color, and number. The subject is reinforced consecutively for sorting by one category and is then given feedback indicating that the category is no longer correct. The prepotent tendency is to continue sorting by the previously correct category; the alternative response requires using the feedback to determine a new sorting category. In the antisaccade task, the subject is asked to look in the opposite direction of a peripherally flashed cue. There is a strong reflexive-like pull to look at peripherally flashed stimuli, yet correct responding requires looking in the opposite direction. In the Stroop Task, the subject must name the ink color of color words. The words are color names that are different from the ink colors (e.g., the word *red* is printed in green). The prepotent tendency is to read the word—a highly automatic skill for readers, yet the correct response is to ignore the written word and identify the color of the ink. In the A-Not-B task, a monkey or human infant searches for food (or a toy) in one of two covered wells. After the subject repeatedly finds the food in one location, it is visibly hidden in a new location. The prepotent tendency is to search where the food was found previously, the alternate response is to look in the new location. The delayed alternation task also involves searching for food in one of two covered wells, but in this case the food is always located in the well opposite of where the subject searched on the last trial. The prepotent response is to look where the food was searched for previously; the alternative response is to look in the other well.

Working Memory and Response Inhibition

This prepotent–alternative response analysis may help identify common processing dynamics across a wide range of prefrontal neuropsychological tests. It suggests two minimum requirements for successful responding. First, the subject must keep in mind information that is required to make a correct response and must use that information to guide action appropriately. In many cases, the information changes from trial to trial and must be maintained across a temporal gap (e.g., A-Not-B, Delayed Alternation). In other cases, the subject must maintain a rule or self-instruction that specifies how to act and then must apply the rule to the current circumstances on a particular trial (e.g., Stroop, antisaccade, Wisconsin Card Sort). Keeping transient information in mind and performing explicit computations to guide upcoming action is seen in the cognitive psychological literature as involving working memory (Baddeley, 1986; Carpenter & Just, 1989).

Working memory is assumed to involve both the temporary storage of task-relevant information and a "scratch pad" for on-line computations and their results (Baddeley, 1986; Case, Kurland, & Goldberg, 1982; Daneman &

Table 1
Prepotent Responses, Alternative Responses, and Working Memory Demands for Several Prefrontal Tasks

Task	Prepotent response	Alternative response	Working-memory demand
Wisconsin Card Sort	Sort by previously successful category	Sort by new category	Use feedback to determine possible correct category
Antisaccade	Saccade to flashed cue	Saccade in opposite direction of cue	Keep task instruction active, apply to current context
Stroop	Read the word	Say the ink color	Keep task instruction active, apply to current context
A-Not-B	Search where previously found	Search where hidden	Keep last seen location in mind over a delay
Delayed alternation	Search where previously searched	Search in location opposite to where previously searched	Keep last location reached in mind, apply "opposite" rule

Carpenter, 1980; Pennington, in press). It is assumed to have a limited capacity that is constrained by both the amount of information that can be held simultaneously and the length of time that information can be kept on-line. Unlike longer-term semantic, episodic, and procedural memory, working memory is both transient and of limited capacity, thus resembling the concept of short-term memory. However, the computational and prospective aspects of working memory distinguish it from traditional conceptualizations of short-term memory. Most significantly, working memory is used not only for holding information on line but also for using that information along with contextual specifics to generate upcoming action.

The other requirement of many prefrontal tasks is to avoid or inhibit carrying out a prepotent response. In some cases, the prepotency is high, such as in the Stroop or antisaccade tasks, and even control subjects have difficulty completely inhibiting the prepotency. In other tasks, such as the Delayed alternation or Wisconsin Card Sort, the prepotency is not as strong.

Although there is a growing consensus that prefrontal tasks assess some form of working memory and response inhibition, the relevant underlying processes still are not well understood. One important question concerns the relation between working memory and inhibition (cf. Diamond, 1990; Harnishfeger & Bjorklund, 1993; Hasher & Zacks, 1988). Each might involve separate processes that do not strongly interact. Prefrontal tasks may require that both processes operate effectively for success, although some tasks may pull more for one or the other process. Another possibility is that the ability to inhibit a prepotent response is dependent on, or at least intimately related to, working-memory processes. When working-memory processes are appropriately activated and maintained, then inhibition of other possible actions occurs by default. Stronger incorrect prepotencies require greater working-memory activations to avoid falling prey to the prepotency.

This latter hypothesis is consistent with several current models of performance on prefrontally sensitive tasks. For example, Cohen and Servan-Schreiber (1992) developed connectionist models of schizophrenic and normal performance on the Stroop and the continuous performance tasks. In these models, increasing the activation of units that represented information required for correct responding (working memory) inhibited units that represented prepotent stimulus–response associations, which decreased the probability of incorrect responding. Other connectionist models, by Dehaene and Changeux (1991) and Levine and Prueitt (1989) of the Wisconsin Card Sort task, although different in many respects, simulate an interaction between prepotency strength and the ability to use feedback to determine new sorting categories. Similarly, production-system models developed by Kimberg and Farah (1993) of several prefrontal tasks contain a response-competition dynamic, such that weakening of working-memory associations leads to increased prepotent responding.

From this perspective, task performance and the ability to successfully inhibit are a function of the strength of the prepotency, the current functioning of working-memory processes, and the working-memory demand of the task. Task difficulty can be increased either by increasing prepotency or by increasing working-memory demand (Cohen & Servan-Schreiber, 1992). For example, the antisaccade task involves a highly prepotent action (reflexive-like glance to a peripheral flash) and a relatively low working-memory demand (remember to look to the opposite side of the flash). Because of the strong prepotency, even a slight deficiency in working memory can result in reflexive responding. In contrast, the Wisconsin Card Sort involves a relatively low response prepotency (sort on the previously correct category) but a relatively high working-memory demand (use the feedback to infer which categories might be correct). Difficulties in determining the new category increase the likelihood of a default response, the previously correct category.

The hypothesis that increasing working-memory demand for the alternative response will decrease inhibition is implied in the models of prefrontal functioning but has rarely been examined empirically.[1] Most of the studies that have used prefrontal neuropsychological tasks have examined differences across populations of subjects but have not varied the processing demands of the tasks. One purpose of the present studies was to test the hypothesis that as working-memory load increases, the ability to inhibit prepotent responses decreases.

Computational models suggest various ways that working memory may become chronically dysfunctional in populations with known or suspected prefrontal abnormalities. For example, Cohen and Servan-Schreiber (1992) simulated reduced dopaminergic tone in the prefrontal cortex—a suspected dysfunction in schizophrenia—by lowering a gain parameter of the activation function of working memory units. Kimberg and Farah (1993) weakened the associations among items in working memory. Dehaene and Changeux (1991) and Levine and Prueitt (1989) modified parameters that decreased the system's ability to use feedback to determine alternative responses. All such models have been designed to simulate some type of abnormal prefrontal processing. But less severe and more transient dysfunctioning may also occur, not because of cortical insult or neurochemical abnormality, but because working-memory resources are temporarily overloaded or engaged in other tasks. Such cases of everyday dysfunctioning may share important similarities with more severe forms of frontal dysfunctioning.

Everyday Action Errors

At least since the era of James (1890) and Freud (1901/1966), theorists have viewed the errors we commit in the

[1] Some important exceptions are studies that have varied the length of time information must be maintained in working memory. In studies that have used search tasks with monkeys (Funahashi, Bruce, & Goldman-Rakic, 1993; Fuster, 1973; Goldman-Rakic, 1987) and human infants (Diamond, 1991; Diamond & Goldman-Rakic, 1989), longer delays typically increase the probability of making the prepotent responses.

course of everyday action as providing insight about general cognitive processes. Errors that occur in particular contexts, such as when a system is overloaded, can reveal processes that are invisible under normal circumstances. Recently, some neuropsychologists have commented on the similarity between certain types of everyday action errors and the kinds of difficulties experienced by frontal patients (e.g., Luria, 1966; Shallice, 1988). The most relevant kinds of errors are referred to as *capture errors* (Norman, 1981) or *strong habit intrusions* (Reason, 1979). James (1909/1962) described an often-cited example:

> "Persons in going to their bedroom to dress for dinner have been known to take off one garment after another and finally to get into bed, merely because that was the habitual issue of the first few movements when performed at a later hour." (p. 155)

Additional examples include following an incorrect but habitual route in one's automobile when the intended route deviates from the more traveled one, continuing to dial an old telephone number long after the number has changed, and looking for cookies in the place they were always kept after they have been moved to a new storage location. Such errors are most likely to occur when one is otherwise occupied, such as when listening to the radio or thinking about some other topic.

The working-memory hypothesis suggests that avoiding such errors requires maintaining one's goals and plans online, especially when a strong prepotent or habitual tendency is present. The stronger the prepotency and the more working-memory is otherwise engaged, the greater the probability of error. This view is similar to that of Norman and Shallice (1986), who hypothesized a supervisory attentional system that modulates actions of a lower-level contention scheduling system consisting of automatic-like, condition–action productions. This conception of everyday action errors is also consistent with computational models of prefrontal functioning described earlier and suggests a continuum between more severe forms of working-memory dysfunction in patient populations and the moment-to-moment variations seen in everyday functioning.

We examined this hypothesis in the present study by testing nonpatient subjects on the antisaccade task, a task that has been shown to be sensitive to prefrontal dysfunctioning and that is viewed as requiring a strong inhibitory component. We expected that as the working-memory load of the task increased, the proportion of strong habit or capture errors would also increase, perhaps to the point at which the performance of normal subjects would begin to resemble that of frontal patient populations. Such a finding would support the idea that temporarily overloading working memory can result in functionally similar outcomes as more permanent prefrontal dysfunctions due to lesion or neurochemical abnormalities.

The Antisaccade Task and Overview of the Present Study

The antisaccade task was originally developed by Hallett (1978; Hallett & Adams, 1980) to examine the mechanisms responsible for generating automatic and goal-directed saccades. The task was later adapted by Guitton, Buchtel, and Douglas (1982, 1985) to study deficits in inhibitory control in patients with prefrontal lesions and subsequently has been used by others to examine deficits of other populations with suspected prefrontal dysfunctions (e.g., Aman, Roberts, & Pennington, 1994; Fletcher & Sharpe, 1986; Fukushima et al., 1988; Merrill, Paige, Abrams, Jacoby, & Clifford, 1991; Pierrot-Deseilligny, Rivaud, Gaymard, & Agid, 1991; Rothlind, Posner, & Schaughency, 1991). The antisaccade task has a number of desirable characteristics for studying prefrontal cognitive functions. First, it captures a key characteristic of frontal deficits, as summarized by Fuster (1989): "The patient with even minor prefrontal damage tends to show a paucity of deliberate actions . . . The frontal patient, like the frontal animal, tends to perseverate—to repeat old patterns of behavior even in circumstances that demand change" (p. 131). The antisaccade task presents discrete and repeatable instances in which a built-in prepotent tendency must not be acted on in order to produce an appropriate response. In many other tasks the prepotency must be established during testing (e.g., in the Wisconsin Card Sort Task) and therefore may vary in strength and not be as reliably present as often as in the antisaccade task. Another benefit of the task is its relative simplicity and its ability to be used with a wide variety of subjects, including children (Aman et al., 1994). Despite the simplicity in the basic instructions for the task, it is still difficult to perform correctly in a consistent manner, as even control adult subjects do not perform at ceiling.

Guitton et al. (1985) tested patients with discrete unilateral excisions of frontal lobe tissue (for relieving intractable epilepsy) as well as patients with temporal lobe removals and nonpatient controls on the antisaccade and prosaccade tasks. In the antisaccade task a fixation point was displayed for a brief indeterminate time period and was subsequently extinguished when a cue was displayed 12° to its left or its right. Subjects were to look an equal distance to the opposite side of the cue where a target would appear 300–600 ms after the cue's onset. The target, an open square that was missing one of its sides, was displayed for 150 ms before it was masked. Subjects indicated which side of the square was missing by pointing their thumbs in different directions. This procedure was also followed for the prosaccade task, except that the subjects were instructed to make a saccade to the cue, where the target was subsequently displayed. Performance on the prosaccade task did not differ across the groups, suggesting that frontal lesions did not affect the ability to program or execute visually guided saccades. In contrast, there were striking differences in the antisaccade task between the frontal group and the temporal and nonpatient controls (who did not differ from each other). First, the frontal patients made more than twice as many incorrect saccades to the cue (referred to as *reflexive saccades*) than did the other groups (56% vs. 20%). Second, the frontal group's initial antisaccades and corrected antisaccades (after reflexive ones) more often appeared to be reactive to the target onset than in the control groups. The controls were better able to make an anticipatory saccade to the target location before its onset; the frontal group had difficulty initiating a saccade to an empty location. Difficulty in the antisaccade task has been demonstrated in other frontal-lesioned groups (Pierrot-Deseilligny et al., 1991) and in other syndromes with known or suspected prefrontal dysfunctioning, such as schizophrenia (Fukushima et al., 1988; Fukushima, Fukushima, Morita, & Yamashita, 1990), Alzheimer's disease (Fletcher & Sharpe, 1986), and attention deficit hyperactivity disorder (Aman et al., 1994).

The purpose of the present research was to examine the relation between working-memory load and the ability to inhibit prepotent saccades in the antisaccade task. In particular, we tested the hypothesis that as working-memory resources are increasingly taxed, reflexive responding will increase, so that the patterns of errors in nonpatient subjects will begin to resemble the performance of frontal patients. This expectation was based on the interactive framework, presented earlier, that posits the probability of performing various actions is a function of the strength of the prepotency, the available working-memory resources for determining and generating the alternative response, and the working-memory demands of the task. In the presence of a high prepotency, such as in the antisaccade task, a temporary increase in working-memory demand may have a functionally similar effect as a more permanent dysfunction in working-memory processing—a difficulty generating the alternative response, which will result in being "captured" by the default prepotency.

Experiment 1

A well-developed technique for examining the working-memory demand of a task is to add a secondary task whose demand on working memory has already been established. When processes across the tasks share working-memory resources, the decrement in performance in the primary task, secondary task, or both, should be greater than when the tasks share fewer common resources. This strategy has proven effective in a variety of task domains (e.g., Hitch & Baddeley, 1976; Logie, Baddeley, Mane, Donchin, & Sheptak, 1989; Wickens, Kramer, Vanasse, & Donchin, 1983). We adopted this basic methodology here as a means of increasing the overall working-memory demand of the saccade tasks. Put differently, we expected that introducing a secondary working-memory task would decrease the working-memory resources available for the primary saccade tasks.

In the first study, we tested college students on the antisaccade and prosaccade tasks. Each task was performed under two conditions, without a concurrent task and with a concurrent task that involved simple addition problems. The addition problems required a memory component (keeping a changing sum in mind) and a computational component (adding the current sum to a new number). Although we did not expect the concurrent math task to affect performance on the prosaccade task, we did expect it to have a deleterious effect on performance in the antisaccade task. We also tested subjects on an individual-difference measure of working-memory capacity, the sentence span task (Daneman and Carpenter, 1980) to assess whether differences in this task correlated with individual differences in the antisaccade task.

Method

Subjects

Subjects were 21 college students at the University of Denver (8 men, 13 women) who were given course credit for their participation. The subjects ranged in age from 19 years to 28 years (M = 22.1 years; SD = 2.3 years). All subjects participating in the study had normal or corrected-to-normal vision and spoke English as their primary language. Because of problems with the eye movement data collection system, the data from 14 additional subjects could not be used. The data from a subject who misunderstood the instructions also were not used.

Tasks and Apparatus

The subjects were given two eye movement tasks—the prosaccade and antisaccade tasks—in each of two conditions, without a concurrent task and with a mental arithmetic task. The mental arithmetic task was also administered alone. Subjects were also tested on an individual-difference measure of working memory, the sentence span task (Daneman & Carpenter, 1980).

Eye movement tasks. For the prosaccade and antisaccade tasks, stimuli were displayed on a 14-in. (36-cm) VGA color monitor controlled by an IBM compatible 80386 PC. The tasks were programmed using the Micro Experimental Laboratory software package (Schneider, 1988). The program controlled the stimulus presentation and recorded keypress timing and accuracy for target identification. Eye movement data were collected using a corneal reflection eye tracking system. An infrared-sensitive video camera was mounted under the task monitor and focused on the subject's left eye. The eye was illuminated by a near infrared light. The video signal from the camera was fed into an Iscan RK-426 eye tracker that output the x–y positions of the pupil and corneal reflection of the infrared light to a separate 80286 PC at 60 Hz. This computer also collected synchronous data from the task-presenting PC that specified what stimuli were displayed on the task monitor at each 1/60 of a second. For more information on the eye movement hardware and software, see Roberts, Brown, Wiebke, and Haith (1991) and Roberts and Wiebke (1994).

Each trial of the prosaccade (PS) task began with a fixation point at the center of the screen (see Figure 1). At intervals that varied randomly between 1,500 and 3,500 ms the fixation point was extinguished, and a cue consisting of a white square was presented 11.5° to the left or right of the fixation point. Cues of three different sizes were used: small (0.4° square), medium (2.0° square), and large (3.4° square). The different-sized cues allowed us to examine whether cue size affected saccadic direction or response time. The cue was extinguished 400 ms after its onset, and a target was displayed at the cue's location. The target was a 2.0° box containing an arrow pointing left, right, or up. The arrow was displayed for 150 ms before a pattern masked it. The mask was displayed for 1,500 ms or until the subject responded with a keypress. Cue side, cue size, and arrow direction were counterbalanced across 90 experimental trials that were presented in individually determined random orders. There were 12 practice trials.

Subjects were instructed to look at the fixation point until the cue was presented, at which point they were to make an eye

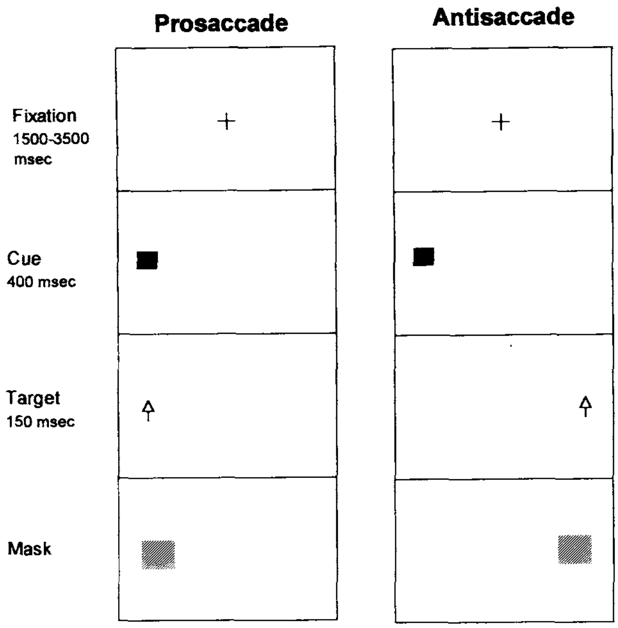

Figure 1. Sequence of events for the prosaccade and antisaccade tasks. Each frame represents what was displayed on the computer monitor for the period of time shown on the left of the figure.

movement to the cue to determine the direction of the target arrow. They indicated their response by pushing one of the corresponding arrow keys (left, up, right) on a computer keyboard.

The occurrence, timing, direction, and amplitude of saccades were scored by an automatic scoring system developed by Roberts and Wiebke (1994; Roberts et al., 1991). The system uses a hierarchical set of algorithms to disambiguate saccadic movements from background noise. Briefly, when the difference between two successive moving averages crosses a threshold, the program assumes a saccade has occurred within a specific time window. Each pair of successive looking locations is then compared within the window to make a best guess about the exact moment the saccade was initiated. The program's performance is highly reliable with skilled human scorers (Roberts & Wiebke, 1994). In addition, a skilled observer reviewed all of the program's judgments and corrected the few that seemed inaccurate.

The dependent measures of interest were the direction of the eye movement, the latency of the initiation of the saccade to the cue, and the correctness of target identification.

The antisaccade (AS) task was identical to the PS task, except the target was always presented on the side opposite the cue (see Figure 1). Subjects were instructed to look in the direction opposite the cue to see the target. It was stressed that an eye movement to the cue was considered incorrect and would diminish the speed and accuracy of target identification. Eye movements were scored in the same fashion as described for the PS task. The dependent measures were the proportion of incorrect initial saccades to the cue (called *reflexive*), the latency of the first eye movement (reflexive or antisaccade), the timing of corrective saccades after reflexive ones, and the correctness of target identification.

The AS and PS tasks were each performed under two conditions, with and without a concurrent task. In the no-load condition, the tasks were administered as just described. In the arithmetic condition, the experimenter orally presented random sequences of numbers ranging from 1 to 9 as the subjects performed the eye movement tasks. Subjects were required to add the first two numbers in the sequence and verbalize the answer. The third number was immediately presented, and the subject was instructed to add the previous sum to the new number and verbalize the answer. This continued through the fifth number in the sequence, after which a new sequence was started. The experimenter said "new" to inform the subject when a new sequence began. Before subjects performed the PS or AS task in the arithmetic condition, they performed 10 sets of the arithmetic problems alone as a baseline (after 2 practice sets). In all conditions, subjects were instructed to answer problems as quickly as they could with a high degree of accuracy. The experimenter presented a new problem immediately after an answer was given. When performing the eye movement tasks, subjects were also instructed to try to do as well as they could on both tasks. The goal of this procedure was to have subjects maintain high accuracy on arithmetic problems at a relatively constant pace. The procedure appeared to be effective: The proportion of correct answers was high in both the baseline (M = 0.95, SD = 0.05) and eye movement (M = 0.94, SD = 0.05) tasks, and there were no differences between performances in the AS or PS tasks, $t(20) < 1$, $p > .3$. The average time per problem was slightly shorter in the baseline tasks (M = 2.4 s, SD = 0.6 s) than in the eye movement tasks (M = 2.9 s, SD = 0.8 s), $t(20) = 6.9$, $p < .01$, and there were no differences in time per problem across the two eye movement tasks, $t(20) = 1.0$, $p > .2$.

Sentence span task. A version of the sentence span task developed by Daneman and Carpenter (1980) was used as a separate individual-difference measure of working-memory capacity. Subjects read single sentences aloud at their own pace and were instructed to remember the last word of each sentence. After a set of sentences had been read, each subject was asked to recall all of the last words for all sentences in the set. Sentences were selected from a total of 65 unrelated sentences, each of which was displayed individually on an 8-in. × 5-in. (20-cm × 13-cm) card. Sentences were 13–16 words long, and each ended with a noun. The sentences were presented one at a time, in set sizes ranging from 2 to 6 sentences. Subjects performed three sets at each set size in increasing order, starting at a set size of 2, until they failed to accurately recall all the words in all three sets of a particular set size. There were two practice trials (with a set size of 2) before testing. The dependent measure of interest was the largest set size for which the subject correctly remembered two out of the three sets.

Procedure

Subjects were tested individually on 2 separate days with a mean delay of 6.8 days (SD = 6) between testing sessions. Subjects were assigned randomly to one of two task orders with the constraint that there were equal numbers in each order. Because some subjects' data could not be analyzed because of equipment problems, there were unequal numbers in the two orders. Twelve subjects received the PS tasks in the first session and the AS tasks in the second, and 9 subjects received the tasks in the reverse order. In each session, subjects first performed the eye movement task without the concurrent arithmetic problems, then the baseline arithmetic problems, and finally the eye movement task with the arithmetic problems. Pilot work indicated that this ordering maximized subjects' ability to perform well on the concurrent-load version of the eye movement task. At the end of the second session, all subjects were tested on the sentence span task.

The eye movement tasks were administered in a dark room relatively free of distractions. Subjects' heads were steadied with a forehead rest and were positioned 42 cm from the computer monitor. Before the eye movement tasks, calibration data were collected as the subject looked at particular locations on the screen. We used the calibration data to linearize the eye movement data and to map looking locations onto the coordinate space of the task monitor (for details, see Roberts et al., 1991; Roberts & Wiebke, 1994).

Results

Eye Movements

Saccade direction. The dependent variable of primary interest was saccade direction. A reflexive saccade to the cue was the correct response on the PS tasks but was the incorrect response on the AS tasks. As shown in Figure 2(a), subjects made reflexive saccades close to 100% of the time in the PS tasks; we therefore did not analyze these accuracy data further.

We hypothesized that reflexive responding in the AS task would increase when subjects performed the concurrent addition problems. To examine this hypothesis as well as other potential influences on performance, we analyzed the proportion of reflexive saccades in the AS tasks in a mixed analysis of variance (ANOVA) with order (AS or PS tasks performed first) as a between-subjects variable and concurrent load (arithmetic or none), cue size (large, medium, or small), and cue side (left or right) as within-subject variables. As expected, subjects made more reflexive saccades when solving the simple addition problems (M = 51%, SD = 22%) than when not performing a concurrent task (M = 31%, SD = 22%), $F(1, 19) = 26.5$, $p < .001$, also see Figure 2(a).

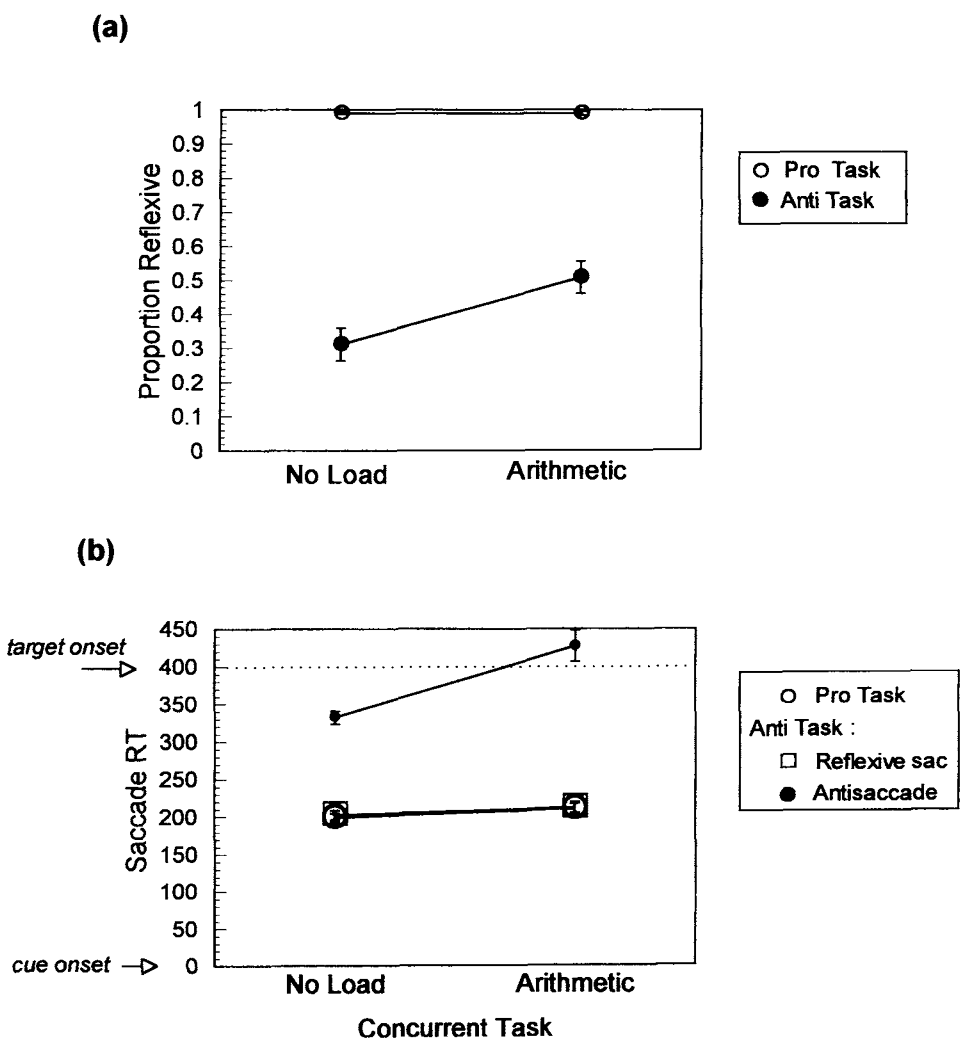

Figure 2. Panel (a): Proportion of reflexive saccades in the prosaccade (Pro) and antisaccade (Anti) tasks as a function of concurrent-load condition in Experiment 1. Panel (b): Saccade response times (RT; in msec) for reflexive saccades in the prosaccade task and reflexive and anti-saccades in the antisaccade task as a function of concurrent load in Experiment 1.

We also found main effects for cue size and task order: Performance improved slightly (fewer reflexive saccades) as cue size increased, (proportion reflexive for small, medium, and large cues: *M*s = 44%, 41%, 37%; *SD*s = 19%, 22%, 33%; respectively), $F(2, 38) = 10.0$, $p < .001$. The improvement fit a linear trend, $F(1, 19) = 17.1$, $p < .005$. Thus, increasing the cue size moderately increased the subjects' ability to make an antisaccade away from the cue. The proportion of reflexive saccades in the AS tasks also was lower when the AS tasks were performed before the PS tasks ($M = 31\%$, $SD = 14\%$) than when they were performed after the PS tasks ($M = 48\%$, $SD = 22\%$), $F(1, 19) = 4.2$, $p = .05$. Presumably, the prior experience of making 180 reflexive saccades in the PS tasks further strengthened the prepotent tendency to make a saccade to a peripherally flashed cue in the AS tasks. Interestingly, this carryover effect spanned the several days between the two testing sessions. The only other significant effect was an interaction between the side of the cue and the presence or absence of the concurrent load, $F(1, 19) = 6.0$, $p < .05$. Post hoc contrasts indicated that the proportions of reflexive saccades did not differ between left and right cues when there was no concurrent load (left: $M = 30\%$, $SD = 24\%$; right: $M = 32\%$, $SD = 22\%$), $F(1, 20) = 0.3$, *ns*, but did differ in the arithmetic concurrent-load condition, with more reflexive responding when the cue was on the left side (left: $M = 55\%$, $SD = 22\%$; right: $M = 46\%$, $SD = 26\%$), $F(1, 20) = 3.07$, $p < .07$.

Saccade response time. Saccades toward a peripherally flashed cue are presumably generated by a relatively automatic process (cf. Funahashi, Bruce, & Goldman-Rakic, 1993; Guitton et al., 1985; Pierrot-Deseilligny et al., 1991); thus, we expected the latencies for reflexive saccades to be fast and to not be significantly affected by task or concurrent load. In contrast, antisaccades should result from a more deliberate and effortful process involving working memory and should therefore be relatively slow overall and further slowed by the presence of the concurrent working-memory load. To examine these expectations, we calculated saccadic reaction time (RT) from the onset of the cue to the initiation of the eye movement. Median RTs were computed separately for reflexive saccades (on the PS tasks and AS tasks) and antisaccades (AS tasks only).

We first analyzed the reflexive RTs in a mixed ANOVA with task order (PS task or AS task first) as a between-subjects variable and task (PS task or AS task) and concurrent load (arithmetic or none) as within-subject variables.[2] As shown in Figure 2(b), RTs for reflexive saccades remained at about 200 ms regardless of task or concurrent load (overall $M = 198$ ms, $SD = 30$ ms), all $ps > .18$. The only significant effect was an interaction between task and order, $F(1, 19) = 5.8$, $p < .05$. Although no post hoc contrasts were individually significant, the interaction reflected relatively faster RTs in the PS task when it came before the AS task ($M = 193$ ms, $SD = 20$ ms) than when it came after the AS task ($M = 209$ ms, $SD = 29$ ms) in comparison to the RTs in the AS task, where there were smaller differences across the two orders (PS task first: $M = 197$ ms, $SD = 26$ ms; AS task first: $M = 193$ ms; $SD = 27$ ms).

We separately examined all RTs on the AS tasks as a function of type of response (reflexive or antisaccade), concurrent load (no-load or arithmetic), and task order. As shown in Figure 2(b), there was a large main effect for type of response, $F(1, 19) = 340.1$, $p < .001$, with much slower RTs for antisaccades ($M = 333$ ms, $SD = 28$ ms) than for incorrect reflexive saccades ($M = 196$ ms, $SD = 41$ ms). There was also a main effect for concurrent load, $F(1, 19) = 14.5$, $p < .005$, with slower responding with the arithmetic concurrent load than without the load. A significant interaction between response type and concurrent load, $F(1, 19) = 15.1$, $p < .005$, indicated that the additional requirement of performing the arithmetic problems slowed antisaccades (arithmetic: $M = 425$ ms, $SD = 100$ ms; no-load: $M = 333$ ms, $SD = 41$ ms), $F(2, 19) = 8.1$, $p < .005$, but did not have a significant impact on reflexive saccades (arithmetic: $M = 197$ ms, $SD = 34$ ms; no-load: $M = 194$ ms, $SD = 29$ ms), $F(2, 19) < 1$, *ns* (see Figure 2). Thus, performing the addition problems slowed antisaccades but did not affect the timing of reflexive saccades.

Guitton et al. (1985) found that the antisaccades of frontal patients, as compared with those of controls, had longer latencies and that many more antisaccades occurred only after the onset of the target (referred to as *visually triggered saccades*). In contrast, Guitton's control subjects more often began the saccade toward the target before it came on the screen (there were 400 ms between the cue and target onsets). A conservative estimate of saccadic RT is 200 ms, so saccades occurring 200 ms after the onset of the target could be considered visually triggered. Guitton et al. (1985), however, found visually triggered antisaccades occurring at 100 ms after target onset and argued that the faster-than-usual RTs resulted from an already programmed saccadic movement that lacked an internal trigger (also see Fischer & Weber, 1993). This proposition was supported by the finding that the profile of antisaccade RTs was similar at various cue–target stimulus onset asynchronies (SOAs). In the present case, subjects in the arithmetic condition made more visually triggered antisaccades than they did in the no-load condition. With the 200-ms criterion, subjects made visually triggered saccades 11% ($SD = 8\%$) of the time in the arithmetic condition and 2% ($SD = 3\%$) of the time in the no-load condition, $F(1, 19) = 18.0$, $p < .001$. With the 100-ms criterion, subjects made 40% ($SD = 21\%$) visually triggered saccades in the arithmetic condition and 13% ($SD = 8\%$) in the no-load condition, $F(1, 19) = 29.4$, $p < .001$.

After subjects made an incorrect reflexive saccade in the AS tasks, they typically made a corrective antisaccade.

[2] Because there were varying proportions of reflexive and antisaccades on the AS tasks, we did not analyze for all possible within-subject effects, because the cell sizes for RTs were too small (less than 5 subjects) in the full design. Thus, we focused our analyses on the primary variables of interest (task and concurrent load), which maintained cell sizes > 10.

Frontal patients' corrective saccades are typically slower and more often visually triggered by the target than are the corrective saccades of controls (Guitton et al., 1982, 1985). In the present case, subjects were slightly slower at making corrective saccades (as measured from the cue onset) in the arithmetic condition (M = 475 ms, SD = 50 ms) than in the no-load condition (M = 450 ms, SD = 46 ms), $F(1, 19) = 6.9$, $p < .05$. The percentage of visually triggered corrective saccades did not differ between the conditions using the 200-ms criterion (M = 10%, SD = 10%; M = 6%, SD = 10%; for arithmetic and no-load, respectively), $F(1, 19) = 2.7$, $p = .11$. Using the 100-ms criterion, corrective saccades in the arithmetic condition were more often visually triggered (M = 48%, SD = 20%) than in the no-load condition (M = 33%, SD = 19%), $F(1, 19) = 14.6$, $p < .005$.

To summarize the eye movement findings, the extra demand of performing simple addition problems increased the likelihood of making reflexive saccades and increased the latencies of antisaccades in the AS task. In contrast, the additional demand did not affect the timing of reflexive saccades in either the AS or PS tasks.

Target Identification

The target consisted of an arrow facing in one of three directions, and subjects pressed one of three buttons to indicate which target was displayed before the mask. Accuracy of target identification generally mirrored the eye movement findings, which is to be expected given that the direction and timing of eye movements often determined the length of time a subject had to view the target. Proportions of correct keypresses were analyzed in a mixed ANOVA with task order as a between-subjects variable and task (PS and AS), concurrent load, cue size, and cue side as within-subject variables. As shown in Table 2, subjects correctly identified more targets in the PS task (93%) than in the AS task (68.7%), $F(1, 19) = 116.6$, $p < .001$, and performed better without the arithmetic concurrent load (87.7%) than with the additional load (73.9%), $F(1, 19) = 54.2$, $p < .001$. A significant interaction between task and load condition, $F(1, 19) = 25.8$, $p < .001$, indicated a larger decrement in performance due to the arithmetic load in the AS task (20.4%) than in the PS task (7.2%), although both decrements were statistically reliable, $ps < .01$. As found with eye movements, performance was slightly better with the larger-sized cues (large: M = 83.3, SD = 10.2; medium: M = 81.8, SD = 9.8; small: M = 77.4, SD = 9.8), $F(2, 38) = 20.2$, $p < .001$. Post hoc contrasts revealed a significant difference between the small and medium sizes ($p < .05$), but not between medium and large sizes (*ns*). Size also interacted with task, $F(2, 38) = 8.6$, $p < .005$, reflecting greater differences due to size in the AS versus the PS task. There were no other significant effects.

Table 2
Target Identification as a Function of Task and Concurrent-Load Condition in Experiment 1

	Task			
	Prosaccade		Antisaccade	
Concurrent load	No-load	Arithmetic	No-load	Arithmetic
Percent correct[a]				
M	96.6	89.4	78.9	58.5
SD	4.2	7.7	11.8	17.3

[a] Significant effects for task, concurrent load, and Task × Concurrent Load, $p < .001$.

To summarize, difficulty in correctly identifying targets generally paralleled the eye movement findings: Accuracy worsened with the additional load of the math problems, and the decrement was more severe in the AS task than in the PS task.

Individual Differences and Working Memory

The Daneman and Carpenter (1983) working-memory sentence task provided an independent measure of working-memory capacity. We correlated performance on this task with the proportion of reflexive responses, the median latency for antisaccades, and the number of correct target identifications on the AS task with and without the concurrent arithmetic load, as well as with the degree of individual decrement on these measures in the arithmetic version as compared with the no-load version. None of the correlations was statistically reliable, $ps > .5$. The lack of reliable relations cannot be attributed to a restricted range in any of the variables. For example, percentage reflexive responding on the AS task without the arithmetic concurrent load ranged from 9% to 92% (SD = 22%), and working-memory scores on the sentences task ranged from 5 to 12 (SD = 2.1). Another potential assessment of individual differences in working memory was the rate of performance on the baseline arithmetic problems before the concurrent arithmetic conditions of the PS and AS tasks. We averaged the time taken to answer the arithmetic problems correctly on both assessments. This measure also did not correlate with any measures from the AS task.

Discussion

Taken as a whole, the findings support the hypothesis that increasing the working-memory demand of the AS task increases the difficulty of inhibiting the prepotent tendency to glance at a peripherally flashed cue when attempting to generate a saccade to the opposite direction. In several respects, the pattern of performance decrements associated with adding the concurrent task resembles the deficits shown by frontal patients and other patient populations with suspected prefrontal dysfunctioning. "Frontal" subjects do not differ from controls in the timing or accuracy of prosaccades, but they make many more incorrect reflexive saccades in the AS task. In addition, frontal subjects consistently take longer to initiate antisaccades and corrective saccades, with higher proportions of these eye movements appearing to be visually triggered by the onset of the target (e.g., Guitton et al., 1985; Pierrot-Deseilligny et al., 1991). This pattern of differences was the same pattern found between the no-load and arithmetic-load concurrent conditions in the present study.

The findings support the idea that reflexive saccades are generated by a relatively automatic process. Reflexive saccades, whether as correct responses in the PS task or incorrect responses in the AS task, occurred about 190 ms after the onset of the cue. Adding the concurrent load in either task did not alter this timing. In contrast, antisaccades took about 150 ms longer to initiate and were further slowed by the arithmetic concurrent load. These findings support the idea that the generation of the antisaccade involves working memory and that increasing the load on working memory decreases the resources available to generate the antisaccade, allowing the reflexive saccade to more often "win" the competition.

The size and the side of the cue also affected performance. We expected that larger-sized cues might increase the prepotency of looking at the cue. Instead, larger-sized cues were slightly easier to look away from in the AS tasks, which presumably resulted in somewhat improved target identifications. A possible explanation for this result is that larger cues are noticed more easily and quickly, allowing deliberate processes of working memory more opportunity to program an antisaccade. Cues on the left side caused slightly more reflexive saccades than did cues on the right, although this difference occurred only in the arithmetic concurrent-load version of the AS task. This effect may be due to the concurrent arithmetic task recruiting disproportionate processing in the left and right cerebral hemispheres. The subtle extent of the effect, however, requires replication before further hypothesizing is warranted.

Individual differences on the Daneman and Carpenter (1980) sentence span task did not correlate with performance on the AS tasks. There are several possible reasons for the lack of a relation. First, variability between individuals in a normal population on the antisaccade task may not be due primarily to differences in working-memory capacity (as they might in a frontally impaired group). Another possibility is that the two tasks tap different types or characteristics of working memory. It still seems to be the case, however, that externally increasing the working-memory load has an overall detrimental effect on AS performance (arithmetic condition). In the next two experiments we further explored these hypotheses by varying the hypothesized working-memory load of concurrent tasks and by examining another individual difference measure of working memory.

Experiment 2

Our explanation for why the arithmetic concurrent load had a large adverse effect on performance in the AS task is that performing addition problems taxed limited working-memory resources that are required for inhibiting the reflexive response and generating an antisaccade. It is possible, however, that many concurrent tasks would have a detrimental impact on performance regardless of their demand on working-memory resources. Performing any other task may divert attention or share other limited resources that affect the difficulty of generating antisaccades. In the present case, listening to the experimenter present numbers, vocalizing a response, or both, may have worsened performance—not the hypothesized working-memory component of adding numbers and keeping in mind the current sum. To examine this hypothesis we tested subjects in another concurrent-load condition, the shadowing condition. In the shadowing condition, the subjects listened to numbers presented at approximately the same rate as in the arithmetic condition and were required to vocalize the number they had just heard. The input and output requirements of the task were identical to those of the arithmetic condition, but the shadowing task lacks the additional requirement to add the number and keep in mind the previous sum while a new number is presented. Thus, the shadowing condition allowed us to examine whether it was the working memory demand associated with the arithmetic task, and not the requirement to perform two tasks simultaneously, that interfered with performance on the AS task in Experiment 1. We expected that the ability to inhibit reflexive saccades and initiate antisaccades would be significantly better in the shadowing condition than they had been in the arithmetic condition. To examine this hypothesis, we tested subjects on the AS task without a concurrent load, with the arithmetic load, and with a shadowing load. In addition, we added another individual difference measure of working memory, the counting span task, to examine whether performance on this task related to performance on the AS tasks.

Method

Subjects

Subjects were 23 college students (6 men, 17 women) who were given course credit for their participation. The subjects ranged in age from 19 years to 27 years (M = 20.6 years; SD = 10 months). All subjects participating in the study had normal or corrected-to-normal vision and spoke English as their primary language. Four additional subjects were tested but were not included in the data analyses: 1 subject's eye movement data contained too much noise to be reliably scored, 1 subject failed to complete a second testing session, and 2 subjects performed several tasks incorrectly.

Tasks

Subjects performed the AS task in three concurrent-load conditions: no-load, arithmetic, and shadowing. The hardware and software used to present the tasks and to collect, calibrate, and score eye movements were the same as those used in Experiment 1. Subjects performed two individual difference tests of working memory: Daneman and Carpenter's (1980) sentence span task, which was used in Experiment 1, and a counting span task (Case et al., 1982).

Eye movement tasks. The AS task was the same as that described in Experiment 1, except that each condition contained 60 experimental trials rather than 90 and used only medium-sized cues. Procedures for the arithmetic condition and the no-load condition were the same as those described in Experiment 1. As in the first experiment, subjects performed well on the addition problems when they were administered alone (M = 95% correct, SD = 5%) and during the AS task (M = 94% correct, SD = 4%), $t(22) = 0.6$, *ns*. The average time per problem was slightly slower when performed during the AS task (M = 2.8 s, SD = 0.4 s) than when performed alone (M = 2.4 s, SD = 0.5 s), $t(22) = 4.9$, $p < .01$.

In the shadowing concurrent-load condition, randomly chosen digits (1–9) were presented on an audiotape at the rate of 1 every 2 s, which was faster than the average time taken per digit in the arithmetic problems in Experiment 1 (1 per 2.9 s). Subjects were instructed to repeat each digit out loud during the brief interval. Subjects practiced repeating the digits for 1 min before the experimental trials began.

Sentence span task. This task was the same as described in Experiment 1.

Counting span task. This task was based on the task used by Case et al. (1982). Subjects were instructed to count yellow dots shown on 8-½-in. × 11-in. (22-cm × 28-cm) white cards on which both blue and yellow dots appeared. The dots were arranged in scrambled irregular patterns. Subjects were instructed to count the yellow dots, ignore the blue dots, and remember the number of yellow dots on each card. When subjects were shown a blank card, they were instructed to recall the number of yellow dots on the previous cards. Cards came in set sizes from two to six cards, and there were three different sets for each size. There were two practice sets, each containing two cards. Subjects performed the sets in increasing order, from a set size of two to six. When a subject failed all three sets at a particular level, the testing was discontinued. The dependent measure was the largest set size in which the subject correctly remembered at least two of the three sets.

Procedure

Subjects were tested individually on 2 separate days with a mean delay of 6.9 days between testing sessions (SD = 3.7 days). All subjects performed the no-load AS task on the first day of testing, followed by either the arithmetic or shadowing concurrent-load versions. (Pilot work indicated that giving the no-load condition first aided performance on the concurrent-load versions of the task.) Half of the subjects received the arithmetic condition on the first day and the shadowing condition on the second day, and half received the tasks in the reverse order. Because of the 4 subjects whose data were not analyzed, the number of subjects in each order was not equal: 10 subjects received the arithmetic version first, and 13 subjects received the shadowing version first. Subjects performed one of the working-memory individual difference tasks at the end of each testing session.

The testing conditions and general procedures were the same as in the first experiment.

Results and Discussion

Eye Movements

Saccade direction. We expected that repeating single digits (shadowing condition) would put less demand on working memory than would adding digits to a running total (arithmetic condition). Consequently, subjects were expected to make fewer reflexive saccades to the cue in the shadowing version of the AS task than in the arithmetic version of the task. To examine this hypothesis, we submitted the proportion of reflexive saccades to a mixed ANOVA with task order (arithmetic or shadowing version first) as a between-subjects variable and concurrent load (no-load, shadowing, arithmetic) and cue side (left, right) as within-subject variables. As seen in Figure 3(a), there was a significant main effect for concurrent load, $F(2, 42) = 17.9$, $p < .001$. Post hoc contrasts indicated that there was significantly more reflexive responding in the arithmetic condition (M = 52%, SD = 20%) than there was in the shadowing condition (M = 37%, SD = 24%) and that there was more reflexive responding in the shadowing condition than in the no-load condition (M = 25%, SD = 14%), all $ps < .005$. The only other significant effect was a Cue Side × Concurrent Load interaction, $F(2, 42) = 7.7$, $p < .005$. Post hoc contrasts indicated no differences between left and right cues in the no-load or shadowing conditions, $ps > .3$, but indicated a marginally significant decrement in performance for left-side cues (M = 59%, SD = 23%) relative to right-side cues (M = 46%, SD = 24%), $p < .06$ in the arithmetic condition.

Saccade response time. Although we did not expect the timing of reflexive saccades to be sensitive to the concurrent-load manipulation, we did expect antisaccades to show longer latencies as the working-memory load of the concurrent task increased. To examine this expectation we submitted median saccade response times (from the cue onset) to a mixed ANOVA with task order as a between-subjects variable and response type (anti- or reflexive saccade) and concurrent load as within-subject variables. As shown in Figure 3(b), the pattern of saccade latencies supported our expectations. A large main effect for response type, $F(1, 21) = 279.7$, $p < .001$, was due to the considerably shorter latencies for reflexive saccades (M = 180 ms, SD = 19 ms) than for antisaccades (M = 352 ms, SD = 60.4 ms). There was also a main effect for concurrent load, $F(2, 42) = 21.4$, $p < .001$, which resulted from differences in the antisaccade RTs across load type. Antisaccade latencies in the arithmetic condition (M = 430 ms, SD = 90 ms) were significantly longer than in the shadowing condition (M = 318, SD = 65), $F(2, 21) = 18.3$, $p < .001$. RTs in the shadowing condition did not differ from those in the no-load condition, $F(2, 21) < 2.0$, $p > .18$. There were no differences in the latencies of reflexive saccades across the three load conditions, $ps > .3$.

The antisaccade could be initiated before or after the target was presented. The proportion of antisaccades that could be considered visually triggered from the target onset reflected the same pattern of findings just described, with the arithmetic load causing more visually triggered antisaccades than the other two conditions. With the criterion of 200 ms or more after target onset, 13% (SD = 14%) of the antisaccades in the arithmetic condition were visually triggered, whereas 1% (SD = 3%) and 2% (SD = 3%) were visually triggered in the no-load and shadowing conditions, respectively, $F(2, 42) = 11.0$, $p < .005$. With the 100-ms criterion, 36% (SD = 19%) of the antisaccades in the arithmetic condition were visually triggered, as compared with 8% (SD = 10%) for the no-load condition and 10%

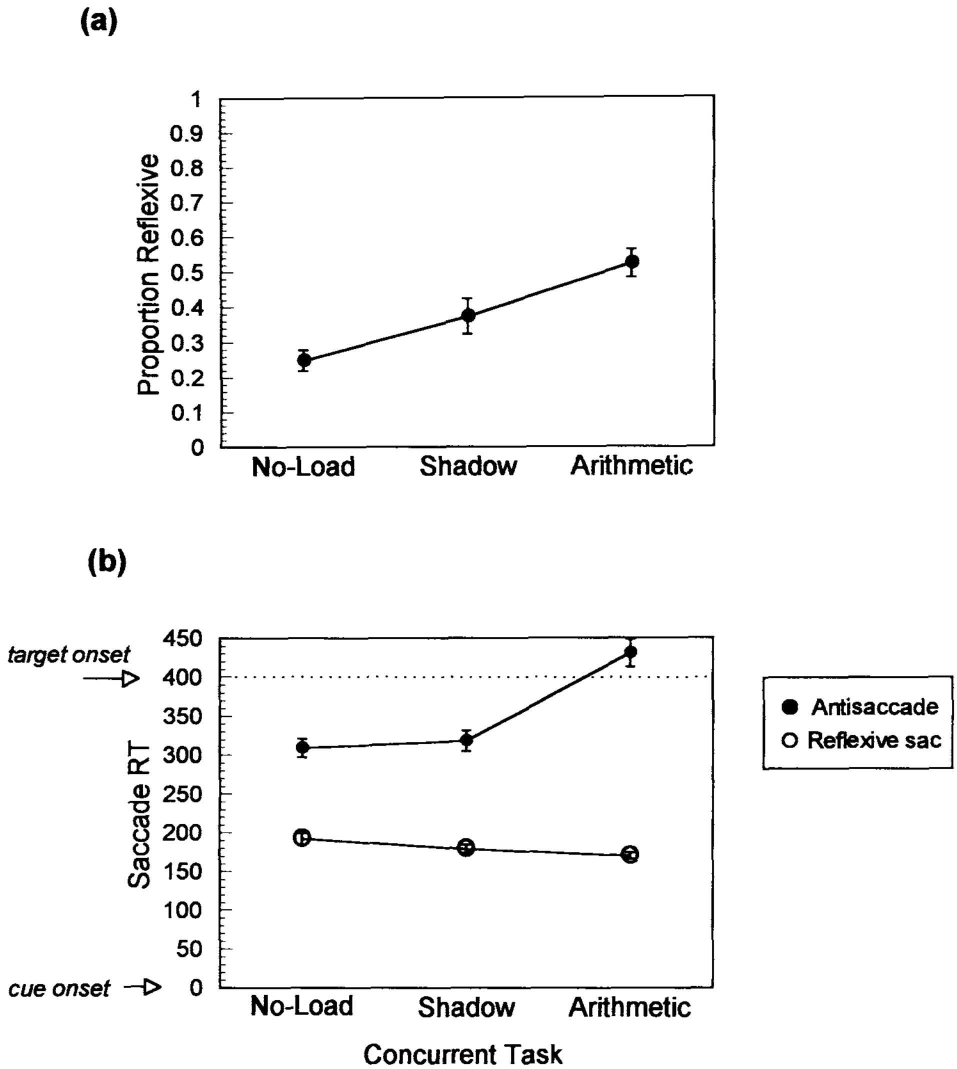

Figure 3. Panel (a): Proportion of reflexive saccades for each of the concurrent-load conditions during the antisaccade task in Experiment 2. Panel (b): Saccade response times (RT; in msec) for reflexive and antisaccades in each of the concurrent-load conditions in the antisaccade task in Experiment 2.

(SD = 13%) for the shadowing condition, $F(2, 42) = 39.9$, $p < .001$.

The latency to make a corrective saccade to the target (after a reflexive one) also differed as a function of concurrent-load condition, $F(2, 44) = 8.6$, $p < .005$. Post hoc contrasts indicated that the arithmetic condition produced longer latencies (M = 432 ms, SD = 58 ms) than either the shadowing condition (M = 389 ms, SD = 63 ms) or the no-load condition (M = 395 ms, SD = 57 ms), $p < .005$. The latter two conditions were not significantly different from each other. The proportion of visually triggered corrective saccades did not differ across load condition with the 200-ms criterion (overall M = 4%, SD = 3%), $F(2, 42) = 0.5$, $p > .6$. With the 100-ms criterion, subjects made more visually triggered corrective saccades in the arithmetic condition (M = 30%, SD = 20%) than in the no-load (M = 18%, SD = 18%) or shadowing (M = 19%, SD = 20) conditions, $F(2, 42) = 3.5$, $p < .05$.

Target Identification

Consistent with the eye movement findings, correct target identification was most difficult in the arithmetic condition (see Table 3). The proportion of correct judgments was analyzed in a mixed ANOVA with task order as a between-subjects variable and concurrent load and cue side as within-subject variables. A significant concurrent-load effect, $F(2, 42) = 31.6$, $p < .001$, was due to less accurate identification in the arithmetic condition (M = 68%) than in the shadowing condition (M = 87%) or no-load (M = 88%) condition, $p < .001$, which were not significantly different

Table 3
Target Identification as a Function of Concurrent-Load Condition in Experiments 2 and 3

Percentage correct	Concurrent load			
	No-load	Repeat	Shadow	Arithmetic
Experiment 2[a]				
M	87.8	—	86.6	68.0
SD	12.8	—	13.1	17.7
Experiment 3[b]				
M	81.9	82.5	85.8	—
SD	15.4	11.7	13.9	—

Note. Dashes indicate no data.
[a] The arithmetic condition significantly differs from the other two conditions, $p < .001$. [b] There is no significant difference between the conditions.

from each other, $p > .4$. There were no other main effects or interactions.

Individual Differences and Working Memory

The two independent measures of working-memory capacity (sentence span and counting span tasks) and the time taken to answer the baseline arithmetic problems were correlated with the response measures on each of the three versions of the AS task. These measures were the proportion of reflexive saccades, the median response latencies for antisaccades, the number of correct target identifications, and the degree of decrement in these measures in the arithmetic version as compared with the no-load version. The vast majority of correlations were not statistically reliable at the .05 level. The only significant correlations were between the counting span task and the antisaccade latencies on two versions of the AS task, (no-load version: $r = -.44$, $p < .05$; arithmetic version: $r = -.42$, $p < .05$). There were also marginally significant relations between correctness of target identification and performance on the counting span task for the three conditions, *r*s from .36–.41, *p*s $\leq .08$. Although these correlations were in the correct direction, suggesting that higher scores on the counting span working-memory measure related to better performance on the AS tasks, the low significance levels given the large number of correlations prompts caution in interpretation.

Summary

To summarize, the pattern of performance on the no-load and arithmetic conditions of the AS tasks replicated the findings of Experiment 1: Adding the arithmetic load to the AS task doubled the incidence of reflexive saccades, slowed the latencies of antisaccades by an average of 120 ms, and decreased the accuracy of target identification by more than 20%. Also replicated was a laterality effect for reflexive saccades in the arithmetic condition, with more reflexive saccades when the cue was on the left versus the right side. The shadowing load had less of a negative impact on performance: Percentage of reflexive saccades increased as compared with the no-load version but was significantly less than in the arithmetic version. Shadowing and no-load conditions did not differ in antisaccade latencies or in target identification.

In both the arithmetic and shadowing versions, the subjects listened to the presentation of single digits and verbalized a number after each presentation. The primary difference between the conditions was that the arithmetic version had the additional requirements of mental addition and keeping in mind the current sum as each new number was presented. This additional load appeared to interfere with the processes involved in inhibiting reflexive saccades and initiating antisaccades.

We conducted a third experiment to assess the degree of interference on the AS task of another concurrent load condition, one hypothesized to have even less of a working-memory demand than the shadowing task. Another purpose of the third study was to further examine the possible relation between counting span and measures from the AS tasks.

Experiment 3

In this last study we further examined how variability in the presumed working-memory load of a concurrent task affects performance on the AS task. Most concurrent tasks probably put some demand on working memory, although the extent of that demand must vary widely. Although we expect that the shadowing task involves less demand on working memory than the arithmetic task does, it still requires attending to and encoding each new digit and holding the current number in mind before vocalization. In this third study we examined the impact of another concurrent task, one that involves listening to a tone and vocalizing a single nonchanging digit. As in the shadowing task, the subjects were required to listen to a stimulus and respond vocally. However, the working-memory load was reduced because the subjects did not need to attend to the content of the stimulus (tone), store the identity of the stimulus, or respond according to the content of the stimulus. The tone acted only as a timing cue for when the subject was to verbalize the same, nonchanging digit. We compared this "repeat" condition with the no-load and shadowing conditions. We also tested subjects on the sentence span and counting span tasks to reexamine the marginal correlations found with AS task performance in Experiment 2.

Method

Subjects

Subjects were 26 college students (4 men, 22 women) who were given class credit for their participation; the data from 1 additional subject could not be scored. Subjects ranged in age from 18 to 27 years ($M = 21.4$ years; $SD = 2.4$ years). All subjects had normal or corrected-to-normal vision, and all spoke English as their primary language.

Tasks

Subjects performed the AS task in three concurrent-load conditions: no-load, repeat, and shadowing. The hardware and software used to present the tasks and to collect, calibrate, and score eye movement data were the same as those used in Experiments 1 and 2. Subjects performed two individual difference tests of working memory: the sentence span task (Daneman & Carpenter, 1980) and the counting span task (Case et al., 1982).

Eye movement tasks. The AS task was the same as the one in Experiment 2, except that each condition contained 36 trials. (Analyses from the previous two experiments indicated that 36 trials were sufficient to obtain stable accuracy and RT data.) Procedures for the shadowing and no-load conditions were the same as those followed in the previous experiments. In the repeat condition, subjects repeated a number once every 2 s. Subjects repeated the same number throughout the condition. A number between 1 and 49 was chosen at random for each subject. Subjects paced themselves by repeating the number after hearing a beep from an electronic metronome. A 1-min practice session was given before the dual task during which the subjects repeated the same number after hearing a beep.

Sentence span task. This task was the same as the one described in Experiment 1.

Counting span task. This task was the same as the one described in Experiment 2, with the exception that the highest set size was changed from 6 to 9.

Procedure

Subjects completed all tasks in one session. For the three AS tasks, all subjects received the no-load version first followed by either the shadowing version (14 subjects) or the repeat version (12 subjects). The order of the sentence and counting span tasks was counterbalanced, with one given before, and the other after, the AS tasks. The testing conditions and general procedures were the same as in the prior two experiments.

Results and Discussion

Eye Movements

The findings clearly indicated that the repeat and shadowing concurrent tasks did not have a large impact on the ability to inhibit reflexive saccades or initiate antisaccades.

Saccade direction. We analyzed the proportion of saccades that were reflexive in a mixed ANOVA with order as a between-subjects variable and concurrent-load condition (no-load, repeat, shadowing) and cue side as within-subject variables. As shown in Figure 4(a), the degree of reflexive responding was similar across the three concurrent-load conditions. A marginally significant trend for load condition, $F(2, 48) = 2.7$, $p < .08$, reflected the somewhat lower proportion of reflexive responding in the no-load condition ($M = 30\%$, $SD = 24\%$) than in the repeat condition ($M = 37\%$, $SD = 22\%$) and shadowing condition ($M = 38\%$, $SD = 24\%$). The only other effect was for task order, $F(1, 24) = 5.4$, $p < .05$, which reflected overall less successful performance when the shadowing condition came first ($M = 43\%$, $SD = 20$) than when the repeat condition was first ($M = 26\%$, $SD = 20\%$). The absence of a Task × Order interaction, $F(2, 48) < 1$, *ns,* however, indicated that task order did not differentially affect the two load conditions.

Saccade response times. The latencies of the initial eye movement were analyzed in a mixed ANOVA with task order as a between-subjects variable and response type (anti- and reflexive saccades) and concurrent-load condition as within-subject variables. As seen in Figure 4(b), antisaccades were considerably slower ($M = 320$ ms, $SD = 47$ ms) than reflexive saccades ($M = 182$ ms, $SD = 29$ ms), $F(1, 23) = 244$, $p < .001$, although there were no differences in latencies due to concurrent-load condition, $ps > .4$. Antisaccades were further analyzed to examine possible differences across load condition in the proportion of saccades that were visually triggered in response to target onset. Overall, the proportion of visually triggered antisaccades was low, and there were no differences due to concurrent load with either the 200-ms criterion ($M = 2\%$, $SD = 2\%$) or the 100-ms criterion ($M = 9\%$, $SD = 10$ ms), $Fs(2, 48) < 1$, $ps > .5$.

Similarly, the latencies of corrective saccades to the target side after reflexive saccades did not differ as a function of concurrent load (overall $M = 392$ ms, $SD = 51$ ms), $F(2, 48) < 1$, $p > .5$, nor did the proportions of visually triggered corrective saccades differ (200-ms criterion: $M = 2\%$, $SD = 2\%$; 100-ms criterion: $M = 14\%$, $SD = 16\%$), $F(2, 48) < 1$, $ps > .5$.

Target Identification

Table 3 presents the percentages of correct target identifications as a function of concurrent load. The percentage of correct keypresses (overall $M = 83\%$, $SD = 12\%$) did not differ as a function of task order, cue side, or concurrent-task load, $ps > .1$.

Individual Differences and Working Memory

We examined the relations between performances on the span and the AS tasks (proportion of reflexive saccades, the median latency to make antisaccades, and the proportion of correct target identifications). Trials were combined across the three versions of the task. None of the correlations was significant, $ps > .1$.

Because of the low power inherent in each of the individual studies, we combined performance data across the experiments for the no-load version of the AS task to examine its correlation with the sentence span task (Experiments 1–3, 70 subjects total) and the counting span task (Experiments 2–3, 49 subjects total). The correlations were all statistically nonsignificant, as shown in Table 4.

Summary

Unlike the arithmetic load examined in Experiments 1 and 2, the repeat and shadowing loads had only a minor effect on the ability to inhibit reflexive saccades and had no measurable effects on the timing of anti- or corrective

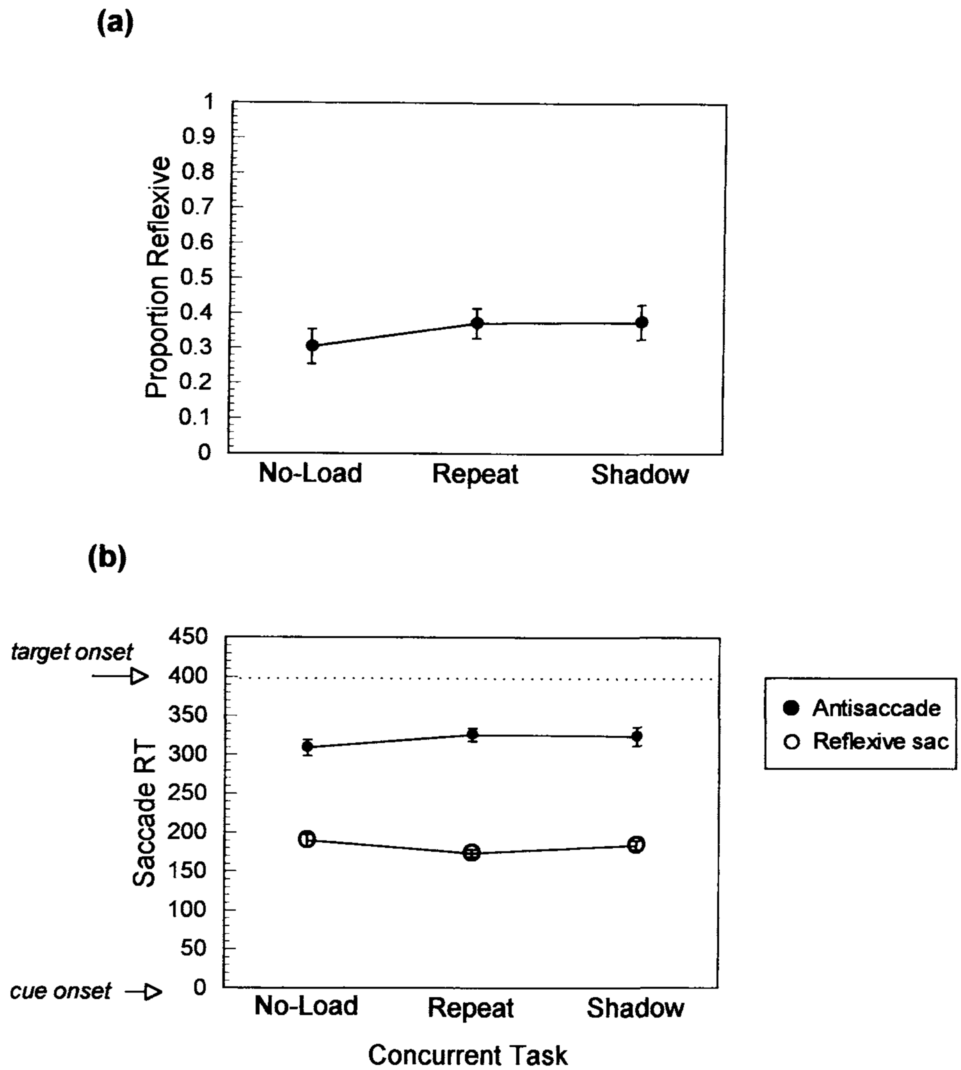

Figure 4. Panel (a): Proportion of reflexive saccades for each of the concurrent-load conditions in the antisaccade task in Experiment 3. Panel (b): Saccade response times (RT; in msec) for reflexive and antisaccades in each of the concurrent-load conditions in the antisaccade task in Experiment 3.

saccades. There were no differences between the shadowing and repeat tasks, suggesting that the additional requirement of encoding and verbalizing a changing stimulus over repeating a constant stimulus did not add enough demand to working-memory processes to make a difference in the AS task. The findings also suggest that individual differences in the working-memory span tasks are not associated with individual differences in the AS task, although further research with larger sample sizes will be required to confirm these findings.

General Discussion

Overview

The findings across the three studies indicate that the concurrent requirement of the arithmetic task disrupted performance on the AS task, whereas the shadowing and repeat concurrent tasks had minor or no effects on performance. All three tasks contained auditory and verbal components, and, according to Baddeley's (1986, 1992) theory of working memory, required a component of working memory referred to as the *phonological loop,* which is involved in the articulatory control and storage of speech. The arithmetic task, however, supposedly made greater demands on another working-memory component, the "central executive," which is viewed as having a coordinative and deliberate attentional function. Previous studies have shown that the arithmetic task disrupts primary tasks that are considered more demanding of this central-executive component of working memory (Logie et al., 1989; Logie, Zucco, & Baddeley, 1990). Whether one does or does not adopt Baddeley's theoretical partitioning of working-memory processes, it appears that the additional computational and

Table 4
Correlations Between the Antisaccade Task (No-Load Condition) and the Working-Memory Span Tasks Combined Across Experiments

	Antisaccade measures		
Span tasks	% reflexive	Antisaccade RT	Target ID
Sentence span[a]	0.12	0.03	−0.10
Counting span[b]	0.07	0.03	0

Note. All correlations are statistically nonsignificant, $ps > .3$. RT = reaction time; ID = identification.
[a] $N = 70$. [b] $N = 49$.

storage demands of the Arithmetic task over the other concurrent tasks induced normal subjects to respond in a manner similar to frontal patient populations: Proportions of reflexive saccades doubled, antisaccades were slowed, and target identification dropped. In contrast, the timing of pro- and reflexive saccades was unaffected by concurrent load, which also holds true for frontal patients. Of course, these findings only suggest a behavioral similarity between frontal patients and normal subjects when under a high working-memory load. Further work is needed to determine more precisely which aspect(s) of the secondary task prove disruptive and whether it is specifically a working-memory deficit in frontal patients that accounts for difficulties in the AS task. Despite these caveats, the results provide tentative support for the hypothesis that a high working-memory load can produce behavior that is functionally similar to more permanent forms of frontal dysfunctioning and that this kind of error is similar to "action-slip" errors made in everyday activity.

Laterality Effects in the AS Task

The arithmetic concurrent load produced a slight laterality effect for reflexive responding, with left-sided cues producing more reflexive saccades than right-sided cues, although there were no such effects in any of the other load conditions of the AS tasks. A variety of hypotheses might explain this finding, but determination of the most likely candidate is complicated by the lack of data and the equivocal findings on laterality in general. If the arithmetic load produced a disproportionate amount of processing in one hemisphere (e.g., Aram & Ekelman, 1988; Ashcraft, Yamashita, & Aram, 1992; Earle, 1988; Jackson & Warrington, 1986; Osaka, 1984; Osborne & Gale, 1976), then the additional load might have interfered with processes in that hemisphere involved in detecting the cue, inhibiting the reflexive response, or generating the antisaccade. For example, parietal and frontal lesions can quicken attentional movements or the salience of objects in the ipsilesional direction of current attention (Kinsbourne, 1977; Ladavas, Petronio, & Umilta, 1990; Posner, Walker, Friedrich, & Rafal, 1987; Rizzolatti, Gentilucci, & Matelli, 1985). In the present case, the prepotency of the cue on the left side might have been heightened by increased processing in the left hemisphere during the arithmetic task. Another possibility is a lateralized disruption in the generation of the antisaccade. If right-going saccades are programmed in the left hemisphere, then an increased load in the left hemisphere caused by the arithmetic load could have disrupted antisaccade generation to the right and resulted in a higher proportion of reflexive saccades to the left. A third possibility comes from the analysis of left–right differences in the response times of prosaccades (Experiment 1), which indicated that saccades to left-sided cues were slightly faster (M = 193 ms, SD = 22 ms) than those to right-sided cues (M = 215 ms, SD = 42 ms), $F(1, 20) = 5.1, p < .05$; this effect did not differ as a function of concurrent processing load.[3] Thus, left-sided cues may be inherently more "attention grabbing" than right-sided cues, perhaps because of lateral asymmetries in the control of attention, eye movements, or both (e.g., Posner & Petersen, 1990; Sava, Liotti, & Rizzolatti, 1988). If the ability to successfully generate an antisaccade depends on a competitive interaction between working-memory processes and the strength of the prepotency, then the arithmetic concurrent load may have tilted the competitive balance far enough so that the slight a priori increase in the prepotency of left-sided cues disproportionately increased the probability of making a reflexive saccade to that side. Determining which of these or other explanations underlies the laterality effect will require further research.

Interaction Between Inhibition and Working Memory

Despite the slight laterality effect, it is important to note that the decrement in performance due to the arithmetic concurrent load was bilateral, supporting the hypothesis that the ability to inhibit a prepotent action interacts with the operations of working memory. It is conceivable that the requirement of solving simple addition problems would not have affected the incidence of reflexive responding in the AS task but would have introduced a global slowing or delaying of antisaccades because of the time required to juggle the extra demands. Although slowing occurred, the classic frontal difficulty in inhibiting the prepotent response was dramatic.

The interactive or competition framework presented in the introduction suggests that working-memory demand, working-memory resources, and the degree of prepotency jointly contribute to the probability of inhibiting the prepotent response. The present study focused on the working-memory side of the competition, but one result indirectly addresses how variation in prepotency affects performance. In the first study, the prosaccade task required subjects to look at the cue as quickly as possible. Although the latencies of these eye movements were not affected by load condition and showed little overall variability, individual differences in the latencies to make reflexive saccades were negatively correlated with the proportion of reflexive responses in the

[3] We did not report in the *Results* section left–right response time differences for antisaccades, because the number of trials for each side for each subject was highly variable and very low in some cases. However, when these data were analyzed, we found no side or Side × Load effects, $ps > .2$.

AS task alone, $r = -.46$, $p < .05$, and in the AS task with the arithmetic load, $r = -.57$, $p < .01$. Thus, faster responding in the prosaccade task correlated with worse performance on the antisaccade tasks. Faster reflexive responding may reflect between-subject differences in the prepotency of the cue in the AS task and may suggest individual differences in the timing thresholds required for inhibiting a reflexive saccade (see below).

The interactive model also suggests that successful inhibition may often be an associated by-product of increased working-memory activation that underlies the production of the alternative response (cf. Goldman-Rakic, 1987). As long as working-memory resources are actively involved in preparing for the upcoming response, then likely alternative responses, which could be specific or nonspecific in nature, are inhibited. In the present case, the superior colliculus (SC) has been implicated in the production of reflexive saccades (e.g., Schiller & Sandell, 1983) and receives projections directly and indirectly from dorsolateral prefrontal cortex (Fuster, 1989; Goldman-Rakic, 1988). Working-memory processes in the prefrontal cortex that are involved in producing intentional goal-directed saccades, especially in anticipation of a currently unseen target (as in the AS task), may send inhibitory signals to the SC to prevent other unwanted, potentially conflicting saccades. If working-memory resources are not engaged in preparing for the upcoming action at some threshold level, then the degree of inhibition drops correspondingly, and the reflexive saccade becomes more probable. Another related hypothesis, suggested by Hallet and Adams (1980) and Guitton et al. (1985), is that a cancellation signal must be sent to the SC within a specific time frame after the onset of the cue. If the signal is later than some critical value, then the reflexive saccade will occur. Guitton et al. (1985) also suggested that the timing of the cancellation signal is proportional to "quantity of information processed" and the "rate at which this information can be processed by the nervous system." Although this explanation separates the inhibition and antisaccade-generation components, it still highlights the interactive nature between working-memory processes and inhibition.

This interactive framework also has implications for several measures of prefrontal functioning, as presented in Table 1. One implication concerns the striking and often-reported phenomena of frontal subjects behaving in such a way as to simultaneously give evidence of the correct and incorrect response. Examples include sorting perseveratively on color in the Wisconsin Card Sort Task while verbally indicating that color is not the correct category, and searching for the hidden object in the A-Not-B task in the incorrect location while looking at the new location. The interactive framework suggests this kind of equivocation would occur only when the competition between working memory and the strength of the prepotency is in very close balance, which would not be expected to occur often. This seems to be the case, because these equivocal responses are usually reported only anecdotally and, when examined specifically in one study that used the A-Not-B task, occurred only about 1% of the time (Janowsky, 1993).

Further Elaborating the Working-Memory Construct

A weakness of the interactive framework, and a difficult problem for the field in general, is how to best conceptualize and eventually differentiate working-memory processes. The construct, as applied to understanding the cognitive processes associated with prefrontal cortex, has the potential problem of becoming a catch-all concept that offers little explanatory power beyond what is already offered by other global descriptors, such as "executive functions." Fortunately, recent progress in cognitive psychology, primate neuroanatomical studies, and computational modeling of prefrontal functioning provides direction for better defining and differentiating the working-memory construct. One question concerns the degree to which there are separate working memories that are specialized for processing different types of information and the degree to which there are more global resources or bottlenecks that apply across domains (cf. Baddeley, 1992; Goldman-Rakic & Friedman, 1991; Wickens et al., 1983). There is evidence for domain-specific as well as domain-independent working memories. For example, Funahashi et al. (1993) convincingly demonstrated in rhesus monkeys that neurons in the prefrontal cortex (in and around the principal sulcus) maintain information about specific spatial locations that are relevant for generating upcoming actions. In humans, Logie et al. (1990) demonstrated a behavioral dissociation between a working memory related to a "visuospatial sketch pad" and a language-based "phonological loop." Much less is known about more centralized working-memory processes, although the primary characteristic associated with a central working memory, the coordination or integration across component processes, appears to be separable from the component working-memory processes themselves (Logie et al., 1990). In the present study, the bulk of the interference was assumed to derive from a more global working-memory bottleneck, although further studies with alternative secondary tasks will be required to examine the degree and type of interference associated with various types of concurrent task demands.

Another question concerns what characteristics of working memory describe different aspects of its functioning. In cognitive psychology, many researchers have focused on concurrent storage and processing and on measurements of capacity (e.g., Carpenter & Just, 1989; Case et al., 1982). The span tasks in the present studies are examples of capacity measures. Some researchers have attempted to further differentiate the storage component from the computational requirements involved in processing. Another characteristic of working memory, which has been examined most frequently in the primate and human infant literature, is the maintenance of information over time (Diamond & Goldman-Rakic, 1989; Funahashi et al., 1993; Fuster, 1991). The infant or monkey must remember something (e.g., a location) that is useful for generating an upcoming response (e.g., an eye movement) over various time intervals. The significant variable of interest is time, not capacity, and performance typically worsens as time increases. Another characteristic, one that has not been as widely discussed but seems particularly relevant to the AS task, is vigilance, or level of activation at a particular moment in time. For example, the AS task does not appear to tax concurrent storage and computation (capacity) or maintenance over a delay. Instead, it seems to require a high degree of vigilance or activation at the somewhat indeterminate moment the cue flashes in the periphery. Within a relatively short time interval, the subject will be vulnerable to making the reflexive saccade. Generally, both frontal patients and controls evenly distribute reflexive and antisaccades across experimental trials, suggesting that the difficulty is not in forgetting the relevant information across the duration of the task; instead, successful performance seems dependent on maintaining a high enough level of activation of the relevant self-instructions to make an eye movement to the opposite side at the moment the cue is presented.

These characteristics of working memory—capacity (or storage and processing), maintenance over time, and level of moment-to-moment activation—as well as other possible characteristics, may interact, but they may also be separable defining features that are differentially assessed in various tasks. A suggestion that they interact comes from the current studies, where strongly taxing capacity (arithmetic concurrent load) presumably affected moment-to-moment activation levels of self instructions to prepare for an antisaccade. The degree of separability of various working-memory characteristics is an empirical question, but it appears that some working-memory and frontal neuropsychological tasks pull more strongly for one or another characteristic. Span tasks pull for capacity, problem-solving tasks (e.g., Tower of Hanoi, Wisconsin Card Sort) tax for on-line inferencing and computation, delayed-search tasks call for maintenance of information over delays, and tasks such as the antisaccade and Go–No-Go tasks require high levels of activation during the interval when a response is likely.

These and other attributes of working memory may partially explain why such tasks do not always show consistent intercorrelations. In the present studies, the lack of a relation between the antisaccade task and the span tasks may be due to the possibility that the two tasks measure different aspects of working memory: capacity and short-term vigilance. Although individual differences in these attributes may not correlate in a normal adult sample, extreme dysfunctioning related to one characteristic would presumably affect the other (such as in our arithmetic load condition and presumably in subjects with frontal lesions).

Various characteristics of working memory may also map onto different aspects of neural functioning, as reflected in some current connectionist models of frontal functioning and working memory. For example, recurrent models contain "hidden" processing modules that form internal representations. These modules send recurrent signals back to themselves to keep current representations active across time (e.g., Cohen & Servan-Schreiber, 1992; Elman, 1990). Different architectural features and operational parameters of these networks would conceivably relate to different functional working-memory characteristics, including the size of these modules (in terms of the number of individual processing units); the interconnections between units; the clarity, or directness, of the recurrence; the equations governing the activation of the units; and the nature of the connections (e.g., inhibitory ones) between these units and other areas of the brain. Similarly, different forms of transient and relatively stable dysfunctioning may be caused by breakdowns in one or more of these parameters, and such patterns may help explain similarities and differences in the manifestations of frontal dysfunctioning. The modeling work of Cohen and Servan-Schreiber (1992), Kimberg and Farah (1993), and Levine and Prueitt (1989) offer important starts in this direction. Clearly, further behavioral, neural anatomical, imaging, and modeling studies will contribute to a more elaborate and differentiated understanding of working memory.

Conclusion

The present studies demonstrate that increasing concurrent working-memory load increases reflexive responding and slows antisaccades in the AS task. The findings are consistent with the framework presented in the introduction, which describes a common interactive dynamic across many assessments of prefrontal functioning. The framework suggests that behavior results from an interaction between competing tendencies and the associated processes that underlie action alternatives. Many everyday action errors and the mistakes made by subjects with frontal lesions occur for different reasons but may reflect a common processing dynamic.

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