Research Article

Suppressing *Where* but Not *What*

The Effect of Saccades on Dorsal- and Ventral-Stream Visual Processing

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ABSTRACT—*Some cognitive processes are suppressed during saccadic eye movements, whereas others are not. In two experiments, we investigated the locus of this interference effect. In one experiment, subjects decided whether pictured items were objects or nonobjects while making saccades of different lengths. Saccade distance had no effect on response time, indicating that saccades do not interfere with object recognition. However, in a second experiment, in which subjects decided whether pictured items faced to the left or to the right, response time increased with saccade distance, indicating that processing was suppressed during the saccade. These results (along with others) suggest that dorsal-stream (where) processes are suppressed during saccades, whereas ventral-stream (what) processes are not. Because the dorsal stream is instrumental in generating saccades, we propose that cognitive saccadic suppression results from dual-task interference within this visual subsystem.*

People make rapid, saccadic eye movements to change the locus of fixation three or four times each second when they read, view pictures, or explore the world around them (Rayner, 1978, 1998). This means that saccades are among the most frequent behaviors that people perform, taking place 180 times each minute, 10,800 times each hour, and 172,800 times each 16-hr waking day. Assuming an average saccade duration of 30 ms, the eyes are in motion about 90 min each day.

During saccadic eye movements, sensitivity to visual input is reduced, such that visual perception is confined to fixations—a phenomenon usually called saccadic suppression (Matin, 1974; Zuber & Stark, 1966). Thus, 90 min during the day when people think they are seeing, they actually are not. Recently, several studies have shown that some cognitive processes are also disrupted during saccades, raising the possibility that 90 min during the day when people think they are thinking, they actually are not. The idea that cognitive processing is suppressed during saccades may seem very implausible because people are not aware of pauses in mental activity during eye movements. Saccade durations are typically very brief, however, so any disruptions that might occur may go unnoticed, just as the dis-

ruptions in visual input that accompany saccades and eyeblinks are usually unnoticed.

A variety of cognitive tasks have been shown to be suspended during saccadic eye movements. Sanders and his colleagues have demonstrated that stimulus encoding, the resolution of degraded stimuli, and memory scanning are suppressed during saccades (Sanders & Houtmans, 1985; Sanders & Rath, 1991; Van Duren, 1993). In addition, Matin, Shao, and Boff (1993) reported that processing time in a counting task increases when eye movements must be made to acquire information. More recently, we have found that mental rotation is suppressed during saccades (Irwin & Brockmole, 2000; Irwin & Carlson-Radvansky, 1996), as are changes in attentional scale from local to global levels of a form (Brockmole, Carlson, & Irwin, 2002). Other studies, however, have shown that not all cognitive processes are suppressed during saccades. For example, Van Duren and Sanders (1995) reported that saccades do not interfere with response selection, and we have found that identity priming (Irwin, Carlson-Radvansky, & Andrews, 1995) and word recognition and word identification (Irwin, 1998) continue normally during saccades.

Thus, some mental operations are suppressed during saccades, whereas others are not. In this article, we propose that the distinction between these processes may correspond to the now well-known distinction between the *what* and *where* cortical processing streams proposed by Ungerleider and Mishkin in the 1980s (e.g., Mishkin, Ungerleider, & Macko, 1983). They proposed that two functionally separable streams of visual processing exist in the brain. The ventral stream projects to areas of inferotemporal cortex and is hypothesized to be responsible for perceptual recognition and cognitive representations of objects; ventral-stream processing is involved in identity priming and word recognition, which are not suppressed during saccades. The dorsal stream projects to the posterior parietal cortex and is hypothesized to be responsible for visuospatial operations, including mental rotation and shifts of visual attention, which are disrupted by saccades.

Although more recent evidence has called into question the separability of the dorsal and ventral pathways (e.g., Merigan & Maunsell, 1993), as well as the interpretation of their function (e.g., Goodale & Milner, 1992), this division continues to have useful heuristic value. For present purposes, for example, it suggests a possible explanation for why some cognitive processes are suppressed during saccades while others are not. Saccade generation and saccade execution rely

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on the dorsal stream, especially the parietal cortex (e.g., Schall, 1995). Therefore, the execution of saccades during the execution of cognitive processes that also rely on the dorsal stream might result in dual-task interference and the disruption of cognitive processing. Even though saccades are commonplace and generally go unnoticed, it is nonetheless the case that whenever people are engaged in some task and moving their eyes, they are in a dual-task situation. In dual-task situations, interference generally occurs when both tasks need the same processing structures in order to be executed (e.g., Meyer & Kieras, 1997; Pashler, 1984). Thus, competition would exist between saccades and dorsal-stream processes, but not between saccades and cognitive processes that engage the ventral stream.

This hypothesis is generally consistent with the results of previous research, but is based on a comparison of several different tasks involving different stimuli, different instructions, different settings, and so on. The present research directly tested this hypothesis by having subjects perform different tasks on the same set of stimuli, namely, pictures of objects. Some subjects performed a ventral-stream task on these stimuli (object recognition), whereas others performed a dorsal-stream task (object orientation judgment). We predicted that saccades would interfere with the dorsal-stream task only.

EXPERIMENT 1: OBJECT RECOGNITION DURING SACCADES

Experiment 1 investigated the effect of saccadic eye movements on object recognition. The object recognition task that we employed was based on a study by Kroll and Potter (1984), in which subjects discriminated between pictures of objects and pictures of nonobjects. Gerlach, Law, Gade, and Paulson (1999, 2000) showed that this task relies on the ventral stream. We measured how quickly and how accurately subjects performed this task while they made short or long eye movements. Because saccade duration increases with saccade distance, if saccades interfere with object recognition, then discriminating objects from nonobjects should be slower when subjects execute long as opposed to short saccades. In contrast, if object recognition is not suppressed during saccades, then response time (RT) in this task should not vary as a function of saccade distance.

Method

It was crucial that saccades be executed during object processing, before object recognition was completed. Neurophysiological evidence shows that it takes 50 to 80 ms for visual information to travel from the retina to visual cortex (Clark, Fan, & Hillyard, 1995). The earliest effects of perceptual categorization occur 125 to 175 ms after stimulus onset (Schendan, Ganis, & Kutas, 1998). Object identification per se occurs approximately 300 ms after stimulus onset (Pietrowsky et al., 1996; Schendan & Kutas, 2002). Thus, to ensure that saccades were executed during the processes of interest, we had two groups of 8 naive subjects each complete slightly different versions of the experiment. The groups differed with respect to the time at which the saccade occurred during stimulus processing (see Fig. 1).
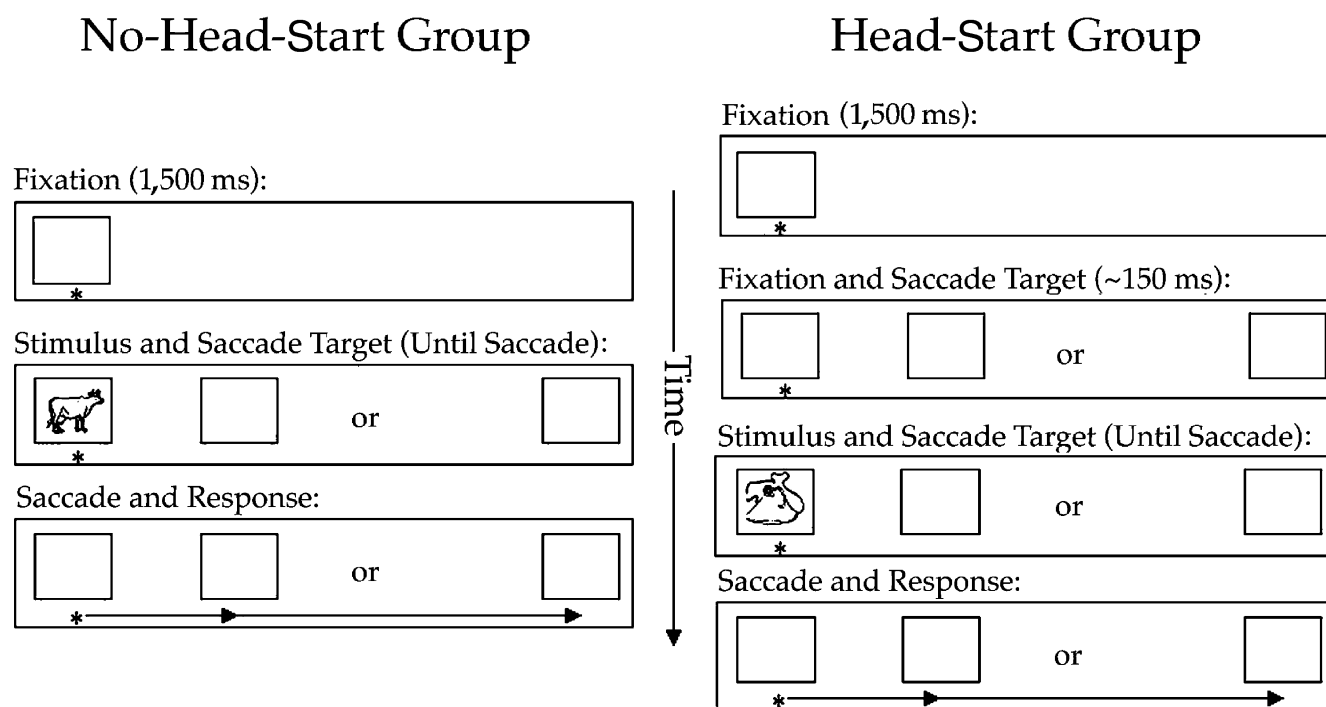

Fig. 1. Schematic illustration of the procedure in Experiment 1. Subjects indicated whether the stimulus picture depicted an object or a nonobject. The saccade target appeared simultaneously with the stimulus picture for subjects in the no-head-start group, whereas it appeared approximately 150 ms before the stimulus picture for subjects in the head-start group. Consequently, subjects in the no-head-start group viewed the picture (a cow in this example) for approximately 250 ms before moving their eyes, whereas subjects in the head-start group viewed the picture (a nonobject in this example) for only approximately 100 ms before moving their eyes. Subjects were instructed to decide whether the stimulus picture was an object or a nonobject while moving their eyes, and their response time and accuracy were recorded. Saccade distance (10° vs. 40°) was varied across blocks of trials. The asterisk represents eye position.

All subjects began each trial by fixating each of five points that were separated by $12°$ of visual angle on a display (not shown in Fig. 1). Eye position was monitored with a scleral-reflectance eyetracker during this procedure, which served to calibrate the output of the eyetracker against spatial position. Eye position was sampled once each millisecond, and head position was stabilized with a bite bar. Following calibration, a fixation box ($8.4°$ wide and $7.4°$ tall) appeared on the left side of the display. The subject fixated the center of this box for 1,500 ms, and then a saccade target box ($8.4°$ wide and $7.4°$ tall) was presented on the right side of the display. In separate blocks of trials, the saccade target box appeared either $10°$ or $40°$ away from the leftward fixation box.

The subject was instructed to saccade to the saccade target box as soon as it appeared. For one group of 8 subjects (the *no-head-start* group, left side of Fig. 1), a stimulus picture (approximately $5.3°$ wide and $3.8°$ tall) was presented within the leftward fixation box simultaneously with the presentation of the saccade target box. Because it takes approximately 250 ms to program a saccade, subjects in this group executed their saccades approximately 250 ms after picture onset. For the other group of 8 subjects (the *head-start* group, right side of Fig. 1), the stimulus picture appeared in the leftward fixation box approximately 150 ms after the presentation of the saccade target box. This allowed subjects to begin saccade programming before the picture was presented, and thus the saccade was executed approximately 100 ms after picture onset. For both groups of subjects, the picture was removed from the display upon saccade onset. For the head-start group, each subject's saccade latency was monitored continuously during the experiment, and the time that elapsed between the presentation of the saccade target and the presentation of the stimulus was adjusted on each trial to track a 100-ms mean exposure time for the picture (see Irwin, 1998).

The other experimental details were identical for the two groups. On half the trials, the stimulus was a picture of an object (taken from Snodgrass & Vanderwart, 1980), whereas on the other half of the trials, the stimulus was a picture of a nonobject (taken from Kroll & Potter, 1984). Subjects were instructed to decide whether the stimulus picture was an object or a nonobject while moving their eyes. Subjects responded via handheld microswitches interfaced with a computer that controlled stimulus presentation, eye sampling, and response timing and execution. Subjects used their dominant hand to indicate that the stimulus was an object and their nondominant hand to indicate that it was a nonobject; RT and accuracy were recorded. Each subject completed four blocks of 36 trials each; saccade distance was counterbalanced across blocks.

Results and Discussion

If object recognition is suppressed during saccades, then object-decision RT should have been longer when subjects had to execute a long saccade (which took on average 92 ms) as opposed to a short saccade (which took on average 37 ms). In fact, if suppression is complete, then RT in the $40°$-saccade condition should have been 55 ms ($92-37$) longer than RT in the $10°$-saccade condition. In contrast, if object recognition is not suppressed during saccades, then object-decision RT should have been unaffected by saccade distance. Table 1 shows the results for both groups of subjects as a function of saccade distance and stimulus type.

We conducted analyses of variance (ANOVAs) on the RT (correct trials only, RT measured from the onset of the picture in the leftward

TABLE 1

Mean Response Time (RT; in milliseconds) and Percentage Correct as a Function of Saccade Distance and Stimulus Type in Experiment 1

Group and saccade distance	Stimulus type			
	Object		Nonobject	
	RT	% correct	RT	% correct
No head start				
$10°$	488	94.9	566	89.9
$40°$	508	91.7	561	91.1
Head start				
$10°$	529	89.6	591	91.9
$40°$	533	94.0	606	92.6

fixation box) and accuracy data, with group as a between-subjects factor and saccade distance and stimulus type as within-subjects factors. No main effects or interactions were significant in the analysis of the accuracy data; overall accuracy was 92%. With respect to RT, the main effect of group was not significant, and group did not interact with any other factor. Responses to nonobjects ($M = 581$ ms) were slower than responses to objects ($M = 514$ ms), $F(1, 14) = 25.2$, $MSE = 2,828$, $p < .001$, but this difference did not interact with saccade distance, $F(1, 14) = 0.3$, $MSE = 777$, $p > .6$. Of most importance, mean RT in the $40°$-saccade condition ($M = 552$ ms) was statistically the same as mean RT in the $10°$-saccade condition ($M = 544$ ms), $F(1, 14) = 0.6$, $MSE = 1,731$, $p > .4$. The half-width of the 95% confidence interval for this difference was 22.3 ms, demonstrating that there was enough statistical power to detect an effect equivalent to 4.1% of the overall mean RT. The results indicate that object processing is not suppressed during saccades. Subjects performed object decisions just as quickly and just as accurately when they made long saccades as when they made short saccades. Thus, processing must not have been suspended while the eyes were in motion.

Additional support for this conclusion comes from examining how processing time was distributed during task performance. If processing continues during saccades, then less time needs to be spent processing the stimulus before or after long saccades than before or after short saccades. We analyzed the eye movement record for each subject, breaking down the total RT on each trial into three component measures (Sanders, 1970): TL, *time left*, the time spent fixating the stimulus picture before the saccade to the target box was initiated; TM, *time moving*, the duration of the saccade; and TR, *time right*, the time that elapsed between when the subject's eye landed on or near the target box and when the subject responded (i.e., even though subjects were instructed to make their object decision while their eyes were moving, they rarely pressed the response button before their eyes had landed near the saccade target box). Figure 2 shows the results of this breakdown as a function of stimulus type and saccade distance, for both the no-head-start group (top panel) and the head-start group (middle panel).

Separate ANOVAs were conducted on the TL, TM, and TR times (from correct trials only), with group as a between-subjects factor and saccade distance and stimulus type as within-subjects factors. As expected, the time spent fixating the stimulus picture before saccade onset (TL) was shorter for the head-start group ($M = 116$ ms) than for
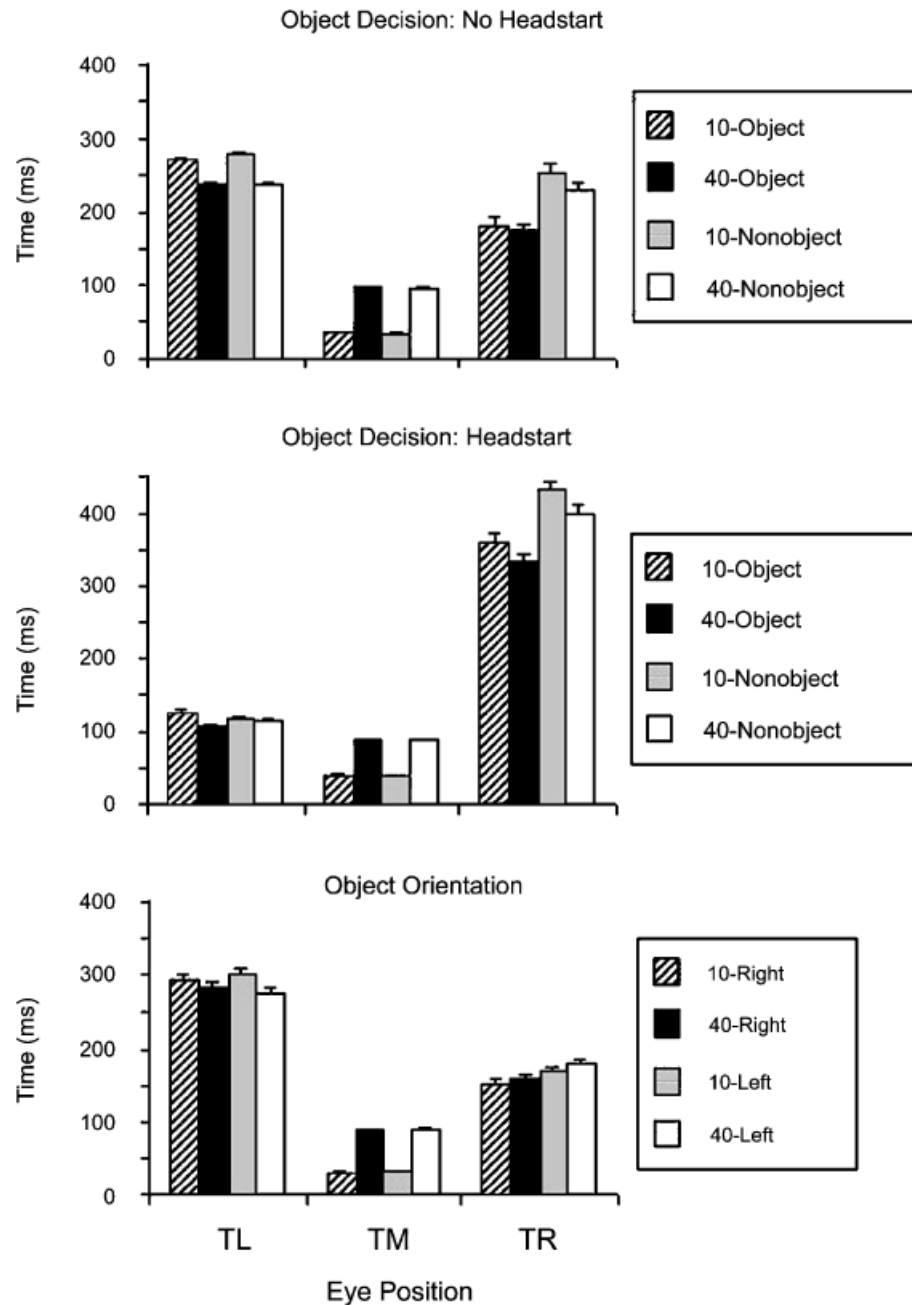
Object Decision: No Headstart

Object Decision: Headstart

Object Orientation

Eye Position

Fig. 2. Component measures of total response time as a function of saccade distance and stimulus type in Experiment 1 (top and middle panels) and Experiment 2 (bottom panel). In both experiments, saccade distance varied between 10° and 40°. In Experiment 1, stimuli were objects or nonobjects; in Experiment 2, stimuli either faced right or faced left. TL = time left, the time spent fixating the stimulus picture before the saccade was initiated to the target box; TM = time moving, the duration of the saccade; TR = time right, the postsaccadic processing time. Error bars indicate standard errors.

the no-head-start group ($M = 255$ ms), $F(1, 14) = 121.1$, $MSE = 2,534$, $p < .001$. TL was also shorter in the 40°-saccade condition than in the 10°-saccade condition, but the effect of saccade distance interacted with group, $F(1, 14) = 5.5$, $MSE = 585$, $p < .05$. The interaction occurred because saccade distance had a significant effect on TL only when the saccade target box appeared simultaneously with picture onset (i.e., for the no-head-start group). For this group of subjects, TL

was shorter in the 40°-saccade condition ($M = 236$ ms) than in the 10°-saccade condition ($M = 274$ ms). Stimulus type had no effect on TL, and no other interactions were significant.

Not surprisingly, mean saccade duration (TM) was longer in the 40°-saccade condition ($M = 91.8$ ms) than in the 10°-saccade condition ($M = 36.9$ ms), $F(1, 14) = 232.5$, $MSE = 207$, $p < .001$. The mean distance of the initial saccade was 11.7° in the 10°-saccade

condition, whereas it was 35.2° in the 40°-saccade condition. Stimulus type had no effect on TM, and no interactions were significant.

Postsaccadic processing time (TR) was longer for the head-start group ($M = 383$ ms) than for the no-head-start group ($M = 209$ ms), $F(1, 14) = 13.9$, $MSE = 34,404$, $p < .005$. This makes sense given the shorter TL period for the head-start group; because less processing could occur prior to the saccade, more processing had to occur after the saccade. Results for TR were consistent with the overall faster RT for object pictures in that TR was also significantly shorter when the stimulus picture was an object ($M = 263$ ms) than a nonobject ($M = 329$ ms), $F(1, 14) = 28.1$, $MSE = 2,480$, $p < .001$. Of most importance, for both groups, TR was significantly shorter in the 40°-saccade condition ($M = 285$ ms) than in the 10°-saccade condition ($M = 307$ ms), $F(1, 14) = 5.9$, $MSE = 1,294$, $p < .03$, indicating that less postsaccadic processing was required after longer saccades.

In sum, averaging over stimulus types and groups, in the 10°-saccade condition subjects spent 198 ms fixating the stimulus (TL), 37 ms moving their eyes (TM), and then an additional 307 ms before making their response (TR). In the 40°-saccade condition, subjects spent 174 ms fixating the stimulus (TL), 92 ms moving their eyes (TM), and then an additional 285 ms before making their response (TR). These results show that in the 40° condition, subjects were able to use the extra time during the longer saccade to reduce the time needed for stimulus processing in the pre- and postsaccadic fixation periods. Thus, object processing must not have been suppressed during the saccade. These results were obtained regardless of whether the saccade occurred early (116 ms after picture onset for the head-start group) or late (255 ms after picture onset for the no-head-start group) during stimulus processing, suggesting that saccades do not interfere with either early or late stages of the object recognition process.

EXPERIMENT 2: JUDGING OBJECT ORIENTATION DURING SACCADES

The results of Experiment 1 support the hypothesis that saccades do not interfere with ventral-stream processes such as those involved in object recognition. Experiment 2 examined whether saccades interfere with a dorsal-stream task, judging an object's orientation in space (Eacott & Gaffan, 1991; Faillenot, Decety, & Jeannerod, 1999; Turnbull, Beschin, & Della Sala, 1997). Subjects were presented with pictures of the same objects that had been used in Experiment 1, but half of the objects faced to the right and half faced to the left. Subjects were instructed to decide, while moving their eyes, whether each object faced to the left or to the right. Making this judgment requires subjects to identify the stimulus and to impose a spatial frame of reference upon it in order to identify the front of the stimulus and which direction it is facing. This is a visuospatial operation; hence, we expected that saccades would interfere with this process.

Method
Eight naive subjects participated; none had participated in Experiment 1. The procedure was similar to that of the no-head-start group in Experiment 1. Following calibration, a fixation box appeared on the left side of the display. The subject fixated the center of this box, and then a picture of an object was presented within it. A saccade target box was presented on the right side of the display, either 10° or 40° away, simultaneously with picture onset. Subjects were instructed to

TABLE 2
Mean Response Time (RT; in milliseconds) and Percentage Correct as a Function of Saccade Distance and Stimulus Type in Experiment 2

| | Stimulus type | | | |
| | Left-facing object | | Right-facing object | |
Saccade distance	RT	% correct	RT	% correct
10°	503	90.9	479	99.2
40°	547	93.1	533	96.7

saccade to the saccade target box and to decide whether the object faced to the left or to the right while moving their eyes. The stimulus was removed from the display upon saccade onset. Subjects pressed a left-hand response button if the object faced to the left and a right-hand response button if it faced to the right; RT and accuracy were recorded. Each subject completed two blocks of 36 trials each; saccade distance was counterbalanced across blocks.

Results and Discussion
We conducted ANOVAs on the RT (correct trials only, RT measured from the onset of the picture in the leftward fixation box) and accuracy data, with saccade distance and stimulus orientation as within-subjects factors (see Table 2). No main effects or interactions were significant in the analysis of the accuracy data; overall accuracy was 95%. RT, however, was reliably different across saccade distance, $F(1, 7) = 11.4$, $MSE = 1,674$, $p < .02$. Mean RT was slower in the 40°-saccade condition ($M = 540$ ms) than in the 10°-saccade condition ($M = 491$ ms). RT was divided into TL, TM, and TR as in Experiment 1, and ANOVAs were conducted on each measure. Only TM varied across saccade distance. Mean saccade duration (TM) was longer in the 40°-saccade condition ($M = 89.9$ ms) than in the 10°-saccade condition ($M = 31.6$ ms), $F(1, 7) = 454.8$, $MSE = 60$, $p < .001$. The mean distance of the initial saccade was 9.9° in the 10°-saccade condition, whereas it was 36.8° in the 40°-saccade condition. No main effects or interactions were significant in the analysis of the pre-saccadic (TL) and postsaccadic (TR) processing times; the mean TL time was 286 ms, and the mean TR time was 165 ms (see Fig. 2, bottom panel).

These results indicate that processing of object orientation is suppressed during saccades. RT was 49 ms slower when subjects had to execute a long saccade as opposed to a short saccade; the difference in saccade duration was 58 ms, so suppression was nearly complete. The analyses of the component processing times (TL, TM, and TR) also indicate that processing of object orientation was suppressed during saccades; that is, unlike in Experiment 1, subjects were not able to use the time during the longer saccade to reduce the amount of time they processed the stimulus before and after the saccade.

GENERAL DISCUSSION

Saccadic eye movements are one of the most frequent behaviors that people perform, and they are essential for the successful completion of many cognitive tasks. Previous research has shown that in some cases saccades actually interfere with cognitive processing, however. The

results of the present research support the hypothesis that saccades interfere with dorsal-stream but not with ventral-stream processes. Experiment 1 showed that object recognition is not suppressed during saccades. Subjects discriminated between pictures of objects and pictures of nonobjects just as quickly and just as accurately when they made long saccades as when they made short saccades, and postsaccadic processing time was decreased after long saccades. Experiment 2, in contrast, showed that processing of object orientation is suppressed during saccades; when subjects had to judge whether an object faced to the right or faced to the left, RT was longer when a long as opposed to a short saccade was executed during stimulus processing, and the difference in RT was approximately equal to the difference in saccade duration.

The results of the present experiments are consistent with those of previous studies of cognitive saccadic suppression, which have shown that dorsal-stream operations such as mental rotation and shifts of attentional scale are suppressed during saccades (Brockmole et al., 2002; Irwin & Brockmole, 2000; Irwin & Carlson-Radvansky, 1996), whereas ventral-stream operations such as identity priming and word recognition are not (Irwin, 1998; Irwin et al., 1995).

We propose that the suppression of cognitive processing during saccades occurs because of dual-task interference; because saccade generation and execution rely primarily on the dorsal stream, cognitive processes that also rely on the dorsal stream cannot be executed at the same time. The precise nature of this interference is not completely clear. One possibility is that interference occurs for neuroanatomical reasons. That is, cognitive suppression during saccades may occur only when the cognitive task must use the same brain areas that are active during saccade programming and execution. This hypothesis is consistent with Kinsbourne's (1980) functional-cerebral-distance account of dual-task interference. Alternatively, suppression may be more functional and more specific. For example, the programming and execution of saccadic eye movements require considerable visuospatial processing—a saccade target location must be specified, and neuronal representations of space are updated and reorganized during saccades (e.g., Dassonville, Schlag, & Schlag-Rey, 1993; Duhamel, Colby, & Goldberg, 1992); thus, perhaps only cognitive processes that also require visuospatial processing are suppressed during saccades. A third possibility, however, is that it is not visuospatial processing per se that causes interference during saccades, but rather the shift of spatial selective attention that obligatorily precedes a saccadic eye movement to some location. That is, there is considerable evidence (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Irwin & Gordon, 1998; Kowler, Anderson, Dosher, & Blaser, 1995; Rayner, McConkie, & Ehrlich, 1978) that prior to the onset of a saccade, spatial selective attention is allocated to the to-be-fixated location in an obligatory and involuntary fashion. Thus, when spatial selective attention is bound to the saccade target location during saccade programming and execution, perhaps it is unavailable for use by other cognitive tasks. This hypothesis predicts that only cognitive tasks that require spatial selective attention will be suppressed during saccades.

These different versions of the dual-task interference hypothesis are not mutually exclusive in all respects; spatial updating and shifts of selective attention both accompany saccades, for example, and both activities rely on the same brain areas. Nonetheless, we think it is possible (at least to some extent) to discriminate among these hypotheses, and that is the goal of future research.

In conclusion, cognitive processing cannot always occur while the eyes are moving, but whether it can or cannot depends on the nature of the processing involved. Saccades have a differential effect on dorsal- and ventral-stream visual processes, which leads to the suppression of *where* but not *what*.

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