Research Article

COGNITIVE SUPPRESSION DURING SACCADIC EYE MOVEMENTS

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Abstract—*Saccadic eye movements are made at least 100,000 times each day. It is well known that sensitivity to visual input is suppressed during saccades; we examined whether cognitive activity (specifically, mental rotation) is suppressed as well. If cognitive processing occurs during saccades, a prime viewed in one fixation should exert a larger influence on a target viewed in a second fixation when a long rather than a short saccade separates their viewing. No such effect was found, even though the time difference between long and short saccades was effective in a no-saccade control. These results indicate that at least some cognitive operations are suppressed during saccades.*

The eyes make rapid, saccadic movements from point to point in space several times each second. Between movements, brief fixations are made on objects of interest in the environment. It is well known that sensitivity to visual input is reduced during saccadic eye movements; this phenomenon is usually called saccadic suppression (Matin, 1974; Zuber & Stark, 1966). Suppression of visual sensitivity during saccades appears to be caused primarily by visual masking (Campbell & Wurtz, 1978): The long, high-contrast fixations that precede and follow each saccade inhibit the perception of the brief, low-contrast blur that is present on the retina during the eyes' movement. Some suppression is found even when masking factors are eliminated, however, suggesting a central inhibitory contribution to saccadic suppression as well (Riggs, Merton, & Morton, 1974). The question of interest in the present article is whether cognitive activity is also suppressed during saccadic eye movements. In other words, do people think while they are moving their eyes?

It seems intuitively obvious that thinking occurs during saccades 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 might not be especially salient. And, in fact, several recent studies suggest that eye movements do indeed interfere with cognitive processing. For example, Sanders and Houtmans (1985) found that perceptual operations relevant to stimulus identification were confined to fixations. Matin, Shao, and Boff (1993) found that processing time in a counting task increased when eye movements had to be made to acquire information. Van Duren (1993) reported that memory scanning in a Sternberg character classification task was suspended during saccades. In addition, it is interesting to note that many eye movement and reading researchers appear to assume that no cognitive processing takes place during saccades, because one of the major dependent variables in this area of research is gaze duration, the sum of all fixation durations on a word or region of text (e.g., Just & Carpenter, 1980); saccade durations are typically not included in this measure, so apparently nothing of interest is assumed to happen while the eyes are in motion.

It is important to know whether people process information while they are moving their eyes because the average person makes two to three saccades each second (hence, 115,200 to 172,800 per 16-hr working day) and the average saccade lasts about 30 ms (Rayner, 1978); thus, if cognitive activity is suppressed during saccades, thinking is disrupted for a total of 60 to 90 min each day!

To determine whether cognitive suppression occurs during saccades, we used a task in which 50 ms to 100 ms (the duration of medium to long saccades) has a significant effect on performance: Cooper and Shepard's (1973) primed mental rotation task. Cooper and Shepard had subjects judge the handedness of a stimulus—that is, whether the stimulus was a normal or mirror-image version of itself. They reported that reaction time to make this decision increased as the stimulus was tilted away from the upright, with the maximum reaction time occurring to a stimulus rotated 180° from upright. However, they also showed that performance was improved if subjects were given advance information about the stimulus, such as its identity and the orientation at which it would appear. Moreover, the more time subjects had to process this preview information, the less they were affected by stimulus orientation. Given a sufficiently long preview, even stimuli rotated 180° from the upright were classified just as quickly as upright stimuli. This improvement in performance was believed to be due to the cognitive process of mental rotation: If the subject knew the identity and the orientation of the target stimulus, the subject could imagine it rotating in the mind; given enough time, the mental rotation could be completed before the target was presented, thereby eliminating any effects of target orientation.

We modified Cooper and Shepard's (1973) procedure by presenting the preview information (the *prime*) while subjects fixated one region of a display and then presenting the target stimulus at a different region of the display, after subjects initiated a saccade to that second location. By varying the distance that subjects had to move their eyes, we could determine whether the prime had more effect during a long as opposed to a short saccade, as would be the case if mental rotation occurs during saccades.

EXPERIMENT 1: MENTAL ROTATION DURING SACCADES

Method

Fifteen subjects participated in both a prime and a no-prime version of the experiment. Eight subjects completed the prime

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version before completing the no-prime version, and 7 subjects performed in the reverse order.

The procedure for the prime version of the experiment is shown in Figure 1. A subject began each trial by fixating each of four points, which were separated by 16° of visual angle on a display. The subject's 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. Head position was stabilized with a bite-bar. Following calibration, a fixation point appeared on the left side of the display. The subject fixated this point for 1,500 ms, and then an identity prime was presented for 2 s. This prime was always upright and in normal orientation; it informed the subject as to the identity of the target that would be presented later in the trial. Next, an orientation prime, an arrow, was presented in the fixation box; this prime informed the subject about the orientation of the target character, which could be 0°, 90°, 180°, or 270° from vertical. The primes were perfect predictors of the identity and the orientation of the character that the subject would see at the opposite side of the display. Whether the target would be normal or mirror-reversed was not specified. Simultaneously with the presentation of the orientation prime, a saccade target box appeared on the right of the display. In separate blocks of trials, the saccade target box appeared either 15° or 45° away from the left-hand fixation point, and the subject was instructed to initiate a saccade to the box when it appeared. The criterion for saccade detection was an eye velocity greater than 50°/s for a continuous 3-ms interval. The target character was presented in the target box during the subject's saccade and remained there until the subject responded as to whether the stimulus was normal or mirror-reversed.

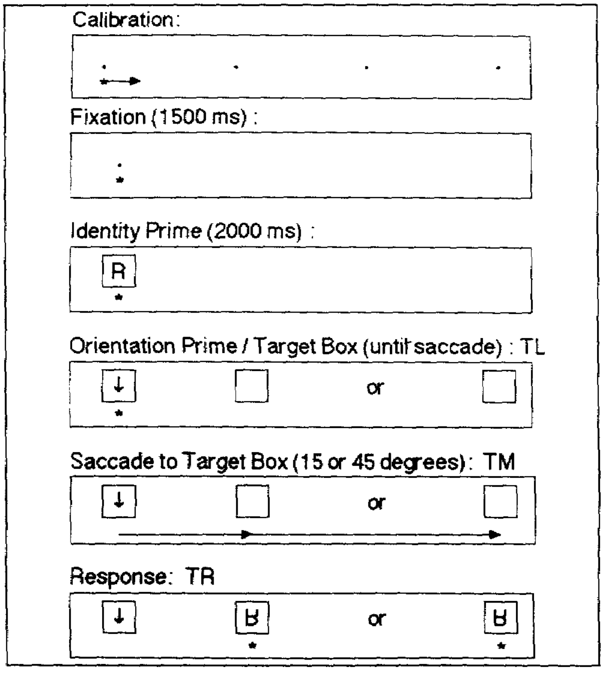

Fig. 1. Sequence of events (from top to bottom) for a trial in the prime version of the transsaccadic mental rotation task. The asterisk represents eye position. *TL* is fixation time before initiating the saccade, *TM* is the duration of the saccade, and *TR* is time elapsed between the subject's eye landing on or near the target and the subject's response.

In addition to the prime condition shown in Figure 1, each subject also completed a no-prime version of this task, conducted to determine whether any performance differences might arise merely as a result of making a long as opposed to a short saccade. For example, visual suppression is sometimes greater for long than for short saccades (Volkmann, 1986), so it might take longer for subjects to acquire visual information about the target after a 45° saccade than after a 15° saccade, thereby masking the effect of any mental rotation that might have occurred during the saccade. The no-prime procedure was similar to that shown in Figure 1, except that instead of an identity prime appearing at the leftmost fixation point, an empty box was presented for 2 s; then, an uninformative orientation prime, a plus sign, was presented instead of an arrow prime above the fixation point, and the saccade target box appeared on the right of the display. The subject initiated a saccade to this box, and the target character was presented during the saccade and remained present until the subject indicated whether the character was normal or mirror-reversed. All other procedural details were the same as in the prime version of the experiment.

Each subject completed 192 trials each in the prime and no-prime versions of the experiment. There were 96 trials at each saccade distance in each version, 24 at each of the four target orientations. Stimulus characters used were *R*, *J*, *G*, 2, 5, and 7. Each character was 0.9° high; the fixation and saccade boxes were 1.8° squares. Subjects responded via handheld microswitches interfaced with a computer that controlled stimulus presentation, eye sampling, and response timing and collection.

Results and Discussion

Following the completion of a block of trials, the eye movement record for each subject was analyzed, and three measures of interest were calculated: *TL, time left,* the time spent fixating the orientation cue before the saccade was initiated to the target box; *TM, time moving,* the duration of the saccade; and *TR, time right,* the time that elapsed between the subject's eye landing on or near the target letter and the subject's response. Only trials in which the subject's initial saccade landed within 3° of the target letter were analyzed, for the following reason. When the eye landed short of the target, a fixation of some duration took place before a corrective saccade moved the eye the rest of the way to the target. Because additional processing of the prime might take place during this extra fixation, determination of whether mental rotation takes place during eye movements per se might be compromised. The size of the acceptance window for the landing site of the initial saccade was determined by preliminary testing, which showed that subjects could determine the handedness of a target letter at least 3° away from the center of fixation.

Each subject's mean times across trials were entered into separate analyses of variance on *TL*, *TM*, and *TR*. Order (prime condition first vs. no-prime condition first) was a between-subjects factor; prime condition (prime vs. no-prime), saccade distance (15° vs. 45°), and target orientation (0°, 90°, 180°, or 270° from upright) were within-subjects factors.

Table 1 shows some of the results of this experiment: mean *TL*, mean *TM*, and total potential prime-processing time, for both 15° and 45° saccades as a function of target orientation under prime and no-prime conditions. Mean fixation time on the left (*TL*) was significantly longer ($F[1, 13] = 6.3, p < .03$) under prime than under no-prime conditions, suggesting that subjects took time to interpret the informative prime when it appeared. This conclusion is supported by the finding that mean *TL* was significantly longer ($F[1, 13] = 3.2, p < .05$) on trials in which the target orientation was either 180° or 270° than on trials in which the target orientation was 0° or 90°. Inspection of Table 1 suggests that this was true only when an informative prime was presented, but the interaction between prime condition and target orientation was only marginally significant, $F(3, 39) = 1.9$, $p > .10$. Of most importance, saccade length had no significant effect ($F < 1$) on *TL*, nor did it interact with any other factor. As expected, the mean saccade duration (*TM*) was 67 ms (prime condition) and 70 ms (no-prime condition) longer when the eyes had to move 45° rather than 15°. Were subjects able to use this additional time, which took place while the eyes were in motion, to mentally rotate the prime? If so, then target classification judgments should have been faster, and orientation effects should have been weaker, after 45° saccades than after 15° saccades.

They were not. Figure 2 shows mean *TR* times in the prime and no-prime versions of this task as a function of target orientation for 15° and 45° saccades. Table 2 shows the accuracy data, which were consistent with the response time data. The standard effects of target orientation were observed in the *TR* times ($F[3, 39] = 40.6, p < .001$), but there was no difference in response time or in the effect of orientation between the 15° and 45° movement conditions in either version of the task ($F < 1$ for all main effects and interactions involving distance). The results of the no-prime version indicate that there was no cost in target-processing time associated with making a long as opposed to a short saccade. Response times were faster in the prime version of the task than in the no-prime version ($F[1, 13] = 9.1, p < .01$), indicating that subjects did make use of the informative prime, presumably before, after, or both before and after they

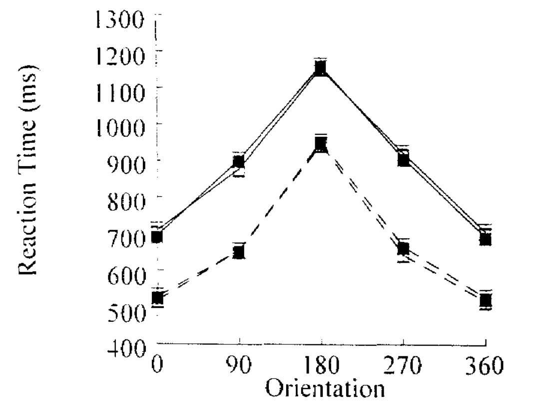

Fig. 2. Reaction time (*TR*) as a function of target orientation for 15° (white squares) and 45° (black squares) saccade trials under prime (dashed lines) and no-prime (solid lines) conditions. The data for 15° and 45° are so close that the white and black squares overlap and in many cases cannot be distinguished. Standard error bars appear around each plot symbol.

Table 1. *Mean fixation* (TL) *and movement* (TM) *times and standard errors (in parentheses) for 15° and 45° saccade trials in Experiment 1*

Orientation of target	Prime condition *TL*	Prime condition *TM*	Prime condition Total	No-prime condition *TL*	No-prime condition *TM*	No-prime condition Total
			15° saccades			
0°	361 (24)	44 (1)	405 (24)	318 (29)	43 (1)	361 (29)
90°	366 (25)	44 (1)	410 (25)	326 (32)	42 (1)	368 (32)
180°	375 (30)	43 (1)	418 (30)	320 (32)	43 (1)	363 (31)
270°	393 (26)	44 (1)	437 (27)	316 (31)	42 (1)	358 (32)
			45° saccades			
0°	369 (24)	110 (3)	479 (25)	315 (25)	110 (3)	425 (26)
90°	375 (24)	112 (3)	487 (26)	314 (22)	113 (3)	427 (23)
180°	395 (27)	111 (3)	506 (29)	317 (26)	113 (3)	430 (26)
270°	390 (25)	110 (3)	500 (27)	318 (30)	114 (3)	432 (31)
Mean, 15°	374 (13)	44 (1)	418 (13)	320 (15)	43 (1)	363 (15)
Mean, 45°	382 (12)	111 (1)	493 (12)	316 (13)	113 (1)	429 (13)
Difference	8 (9)	67 (1)	75 (9)	−4 (8)	70 (1)	66 (8)

Note. All times are expressed in milliseconds.

Table 2. *Percentage correct as a function of target orientation in Experiments 1 and 2*

Condition	Target orientation 0°	90°	180°	270°
	Experiment 1			
Prime				
15° saccade	99	96	85	99
45° saccade	99	98	78	97
No-prime				
15° saccade	98	96	80	96
45° saccade	97	99	82	93
	Experiment 2			
0-ms prime-to-target interval	99	97	87	98
50-ms prime-to-target interval	98	97	84	99
100-ms prime-to-target interval	99	97	86	99

moved their eyes; for example, mental rotation of the target after the saccade could begin more quickly if its identity and orientation were known as opposed to unknown.

The effect of target orientation was modulated somewhat by the prime; averaged across saccade distance, the difference in response time to targets rotated by 180° versus 0° was 32 ms less in the prime (949 ms vs. 524 ms) version of the task than in the no-prime (1,159 ms vs. 702 ms) version. This interaction was not significant ($F[3, 39] = 1.1$, $p > .35$), however, suggesting that relatively little mental rotation occurred before the saccade. Most important, the results of the prime version show that target classification judgments were no faster after 45° saccades than after 15° saccades, despite the extra 67 ms of potential processing time allowed by the longer saccade. This result indicates that subjects cannot, or at least do not, perform mental rotation during saccadic eye movements. Thus, it appears that at least one kind of cognitive activity, mental rotation, is suppressed during saccades.

Before this conclusion can be accepted, one more issue must be addressed: Is 67 ms sufficiently long for appreciable mental rotation to occur? Experiment 2 addressed this question.

EXPERIMENT 2: MENTAL ROTATION DURING FIXATIONS

Method

To examine whether a 67-ms difference in saccade duration between 15° and 45° eye movements is sufficiently long to allow enough mental rotation to occur to produce a detectable difference in target classification time, we asked each of the 15 subjects who participated in Experiment 1 to participate in Experiment 2. This experiment was a no-eye-movement version of the prime condition of Experiment 1. In Experiment 2, subjects maintained fixation on a central point, and the prime and the target information were presented at that point. The identity of the target was presented for 2 s, as in Experiment 1, and then the orientation prime was presented for a duration determined by each subject's individual *TL* in Experiment 1 ($M = 378$ ms). Then, to mimic what might happen during different *TM*s, the orientation prime was presented for an additional 0, 50, or 100 ms before the target character was presented, and then the subject's reaction time to determine whether the target was normal or mirror-reversed was measured. In essence, Experiment 2 was a partial replication of Cooper and Shepard (1973), using the prime durations experienced by our subjects in the first experiment.

Each subject completed 96 trials (24 trials at each of the four target orientations) at each prime-to-target interval. The trials were completed in six blocks of 48 trials each. Prime-to-target interval was constant within a block, but was varied across blocks so that order was approximately counterbalanced across subjects.

Results and Discussion

The results of Experiment 2 are shown in Figure 3 and Table 2. As the prime-to-target interval increased from 0 to 50 to 100 ms, mean reaction time decreased ($F[2, 28] = 189.5$, $p < .001$) from 778 to 733 to 695 ms. The half-width of the 95% confidence interval for the difference between two means was 8 ms, so all pair-wise differences were significant. In addition, the interaction between prime-to-target interval and target orientation was significant ($F[6, 84] = 32.4$, $p < .001$), reflecting the fact that target orientation had a smaller effect as prime processing time increased from 0 to 50 ms. The difference in response time to targets rotated by 180° versus 0° decreased from 671 ms (1,210 ms vs. 539 ms) to 547 ms (1,093 ms vs. 546 ms) as the prime-to-target interval increased from 0 to 50 ms. (There was no difference in this measure between prime-to-target intervals of 50 and 100 ms, however.) The accuracy data (Table 2) did not

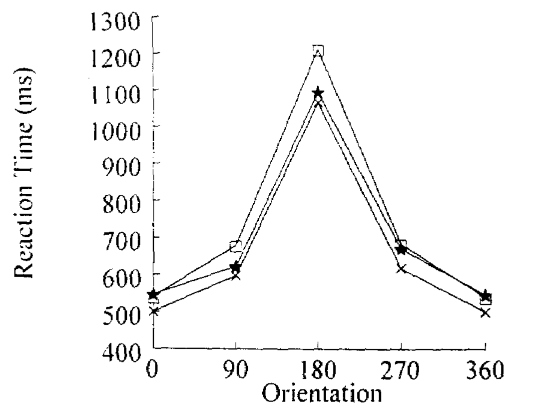

Fig. 3. Reaction time as a function of target orientation for prime-to-target intervals of 0 ms (white squares), 50 ms (black stars), and 100 ms (*X*s) in the no-saccade control condition. Standard errors are smaller than the plot symbols.

vary as a function of prime-to-target interval. These results are consistent with those of Cooper and Shepard (1973) and demonstrate that even 50 ms is sufficiently long for enough mental rotation to occur to produce a detectable difference in target classification time. Thus, if subjects had been performing mental rotation while they were moving their eyes in Experiment 1, response time in that experiment should have been faster in the 45° movement condition than in the 15° movement condition. It was not. In sum, subjects can and do perform mental rotation when their eyes are still, but not when their eyes are moving. At least one kind of cognitive activity, mental rotation, is suppressed during saccadic eye movements.

One unexpected finding was that overall response time was somewhat slower in Experiment 2 than in Experiment 1. Because the target stimulus was presented in the same spatial location immediately after the offset of the orientation prime in Experiment 2, it is possible that some forward masking occurred, slowing overall response time. In Experiment 1, the primes and the target appeared in separate spatial locations, and their viewing was separated by a "blank" interval during the eye movement, so forward masking would have been minimized. These differences in visual quality make it difficult to compare individual response times directly between the two experiments, but because our conclusions rely on comparisons among within-experiment difference scores, this difficulty is not a major concern.

GENERAL DISCUSSION

The results of Experiments 1 and 2 show that at least one kind of cognitive activity, mental rotation, which is important for skills such as object identification and spatial reasoning (Just & Carpenter, 1985), is suppressed during saccadic eye movements. Saccades are useful in many ways; for example, they allow people to bring their high-resolution foveal vision to bear on objects of interest in the world. Nonetheless, there appear to be several costs associated with saccades as well. Little information is remembered across saccades (e.g., Irwin, 1991, 1992); visual sensitivity is reduced during saccades; and the present results show that at least some cognitive operations are interfered with as well. Given these costs, perhaps saccades should be eliminated whenever possible.

Of course, the results of the present research do not show that all forms of thought are suppressed during saccades. Several investigators have argued that mental imagery and visual perception share common brain mechanisms (e.g., Farah, 1988; Finke, 1980; Kosslyn, 1987; Shepard & Cooper, 1982); because mental rotation relies on mental imagery, perhaps it is not so surprising that mental rotation is interfered with by eye movements. Other kinds of mental operations may not be affected in the same way.

However, it is entirely possible that many cognitive activities are suppressed during saccades. Although this possibility seems very counterintuitive, suppression of cognitive activity may be no more noticeable than the suppression of visual input that accompanies saccades, or the disruptions in visual input that accompany eye blinks. These events are rarely noticed, even though they occur at least a hundred thousand times each day; perhaps cognitive "blackouts" during saccades go equally unnoticed.

We believe that at least some processing takes place during saccades, however, based on recent data obtained in a transsaccadic version of Posner and Snyder's (1975) primed letter-matching task (Irwin, Carlson-Radvansky, & Andrews, in press). In this study, subjects viewed a prime letter in one fixation and then made a saccade to a new location that contained two letters; subjects had to judge whether the two target letters were identical to each other. Response time was facilitated when the prime had the same identity as the target letters, and there was more facilitation when a long than when a short saccade separated the viewing of the prime and target letters. These results suggest that certain priming operations may occur during saccadic eye movements, even though mental rotation does not. Van Duren and Sanders (1995) have recently reported that target classification and response selection may take place during saccades, as well.

Based on their results, Van Duren and Sanders (1995) suggested that perceptual processes, such as those required for stimulus encoding, might be suppressed during saccades, whereas postperceptual processes, such as target classification and response selection, might not. One problem with this suggestion is that it is often difficult to classify a process as perceptual as opposed to postperceptual. In our experiments, mental rotation might seem to have been a postperceptual process because the identity of the stimulus was provided to the subject for 2 s before the orientation cue and the saccade target were presented. What seemed to be suppressed in our experiments was a memorial (postperceptual) process of mental rotation.

We think it might be more profitable to consider this issue in terms of dual-task performance. Although eye movements feel effortless and one might not even be aware that they are occurring, it is still the case that whenever people are engaged in some task and also moving their eyes, they are in a dual-task situation. In such cases, sometimes interference occurs and sometimes it does not. Viewed from this perspective, suppression of cognitive processing during saccades might be expected to occur only when limited processing resources must be shared. The nature of these resources and the mechanisms by which suppression occurs require further investigation.

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