Memory for Position and Identity Across Eye Movements

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A "transsaccadic" partial report procedure was used to measure memory for position and identity information across saccades. Delaying the partial-report cue after the eye movement had little effect on report accuracy. Mask presentation hindered recall only at the shortest delay. Accuracy was much higher when the letter array contained 6 letters than when it contained 10 letters. Intra-array errors were much more frequent than extra-array errors. These results suggest that memory across eye movements decays slowly, has a limited capacity, is maskable for a brief time, and retains identity information better than position information.

Our 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 world. Our mental representation of the visual environment is built up from these successive views; it is generally assumed that somehow the contents of individual eye fixations are integrated across saccades to produce the unified and coherent percept of the visual world that we ordinarily experience. How transsaccadic integration is accomplished has puzzled psychologists and vision researchers for over a century. The present research investigates this question; in particular, the research examines how the positions and identities of elements in the world are maintained in memory across changes in eye position, motivated by the assumption that our ability to perceive the world as stable and unchanging across saccades depends on memory for such information.

Intuitively, the perception of a stable and continuous visual environment across eye movements seems to require a very detailed, high-capacity memory capable of summating visual information from one fixation to the next. In fact, one frequently proposed hypothesis is that something like an "integrative visual buffer" (McConkie & Rayner, 1976) superimposes the visible contents of successive fixations according to their environmental or spatiotopic coordinates to produce an integrated, composite image of the visual environment. Although this notion is intuitively appealing, substantial empirical evidence suggests that it is incorrect (see Irwin, in press, for a review). Rather, it appears that integration across eye movements relies on priming of word and object representations in long-term memory (Pollatsek & Rayner, in press) and on information accumulation in visual short-term memory (Irwin, 1991). Evidence for a long-term memory contribution to transsaccadic integration comes from the many studies of

Rayner and Pollatsek and their colleagues demonstrating word and picture priming for stimuli viewed in successive fixations (e.g., Pollatsek, Rayner, & Collins, 1984; Pollatsek, Rayner, & Henderson, 1990; Rayner, McConkie, & Zola, 1980). The results of Irwin (1991) suggest that visual short-term memory also plays a role in transsaccadic integration, however. In Irwin's (1991) experiments, subjects viewed a random-dot pattern in one fixation and then judged whether a second dot pattern viewed in a subsequent fixation was identical to or different from the first. The complexity of the dot patterns (e.g., the number of dots they contained) had a large effect on the subject's recognition accuracy, but inter-pattern interval had very little effect on performance even when a 5-s interval separated the two patterns. In addition, presenting the two patterns in different spatial locations across the eye movement had no detrimental effect on recognition accuracy. These experiments indicate that transsaccadic integration relies, at least in part, on a limited-capacity, long-lasting visual memory that is not tied to absolute spatial position; these properties are typically associated with visual short-term memory (e.g., Phillips, 1974).

The present research attempts to provide additional information about the characteristics of transsaccadic memory. The research uses a partial report technique to assess how position and identity information are maintained across eye movements. Partial report has been used extensively to study memory within single eye fixations (as simulated by tachistoscopic presentations to a stationary eye); in the experiments reported later, it was used to study memory across changes in eye position.

In a standard (no eye movement) partial report experiment, a subject maintains fixation on a central point while the following events occur. First, an array of letters is presented for some time. Then the letters are removed, and some time later a cue is presented that signals the subject to report some subset of the letters that appeared in the array. For example, a bar probe might appear above or below one of the letter positions, and the subject must report the indicated letter (e.g., Averbach & Coriell, 1961). To respond correctly, the subject must remember the position and the identity of the cued letter. Typically, report is very accurate when the cue appears immediately after letter offset, but it declines quickly to some asymptotic level as the cue is delayed. This decline in accuracy occurs because position and/or identity infor-

mation fades from memory before the partial report cue is presented (e.g., Sperling, 1960). These results suggest the existence of two kinds of memory for a single fixation: One is a briefly lasting memory with a high capacity ("iconic" memory), and the other is long lasting but has a limited capacity (short-term memory).

Given that accurate partial-report performance relies on memory for the positions and identities of the elements in a fixation, it seems well suited for studying memory and integration across eye movements. For this purpose, a transsaccadic version of the partial-report procedure was used in the experiments reported later. The letter array was presented during one fixation, and the partial report cue (e.g., a bar probe) was presented during a second fixation after an eye movement had occurred. Subjects were required to report the letter that had occupied the spatial position indicated by the bar probe; thus, they had to integrate the contents of the two fixations according to spatial coordinates to respond correctly. Irwin, Brown, and Sun (1988) found that subjects could do this quite accurately as long as the stimulus onset asynchrony between the letter array and the bar probe was sufficiently long that retinotopic visible persistence was not present. These investigators used letter arrays of only five letters, and they used only one probe delay (40 ms), however, so their research revealed little about the properties of transsaccadic memory.

In the experiments reported next, the effect on report accuracy of variables such as probe type (bar probe vs. mask probe), array size (6 letters vs. 10 letters), and probe delay (40 to 750 ms) was investigated to determine some of the fundamental characteristics of transsaccadic memory, such as its vulnerability to masking, its capacity, and its duration.

Experiment 1

The purpose of the first experiment was to investigate the time course and the representational format of transsaccadic memory. In the primary condition of interest, the saccade condition, subjects were presented with an array of six letters in one fixation, and then a partial-report cue was presented after a saccade to a new location. Subjects were instructed to report the letter that had occupied the spatial position indicated by the partial-report cue. To measure the time course of transsaccadic memory, probe delay was varied from 40 to 750 ms. Of interest was whether partial report accuracy would decline quickly to some asymptotic level as probe delay increased, as partial report experiments conducted within fixations (i.e., during maintained fixation) have discovered, or whether accuracy would be fairly constant across probe delay, as one might expect if transsaccadic memory has properties like those of visual short-term memory (Irwin, 1991). To examine the representational format of transsaccadic memory, the partial-report cue was a bar probe on some trials and a mask probe on other trials. Previous partial-report experiments conducted within fixations have demonstrated that mask probes interfere with report accuracy when they are presented soon after stimulus offset (e.g., Averbach & Coriell, 1961), suggesting that the retinotopic memory that exists immediately after stimulus offset is visual by nature. If mask probes interfere with report accuracy across fixations as

well, this would suggest that transsaccadic memory is also visual by nature. McRae, Butler, and Popiel (1987) found evidence for spatiotopic masking across saccades in an earlier investigation. In contrast, if transsaccadic memory contains only abstract identity codes for the letters in the array, such as their names, then mask probes and bar probes should be equally effective partial-report cues. To allow a comparison of memory within and between fixations, data from a no-saccade control condition were also collected.

Method

Subjects. Eight subjects, including myself, participated in this experiment (5 men and 3 women). Except for myself, the subjects were undergraduate and graduate students at Michigan State University. The students had not participated in any previous eye-movement experiments, and they were naive about the purpose of the experiment. The students were paid for their participation, and they received a bonus for each correct response.

Stimuli. Two sets of 60 different letter arrays were used as stimuli. Each array contained 6 letters in a two-row × three-column format. The letters were drawn randomly from the set of all consonants excluding the letter *y*. One set of 60 letter arrays was used during the bar-probe trials, and the other set of 60 letter arrays was used during the mask-probe trials; assignment of letter set to condition was counterbalanced across subjects. A short vertical line appearing above (top row) or below (bottom row) one of the array locations was used as the partial-report cue during the bar-probe trials. A rectangular box surrounding one of the array locations was used as the partial-report cue during the mask-probe trials.

Apparatus. Stimuli were presented on a Tektronix 608 X-Y oscilloscope equipped with P-15 phosphor. A Digital Equipment Corporation Micro-11/23+ computer controlled stimulus presentation by means of digital-to-analog converters. The computer also recorded the output from a Gulf + Western Applied Science Laboratories Model 210 scleral reflectance eyetracker by means of analog-to-digital converters. The eyetracker was mounted on eyeglass frames that were held snugly in place on the subject's head by a headband. The eyetracker was configured to record horizontal movements of the left eye only. A bite bar with dental impression compound was used to keep the subject's head steady during the experiment. Subjects completed a calibration sequence (described later) before every experimental trial. The accuracy of the eyetracker under these conditions was ± 0.3 degrees. Display refreshes and eye position sampling took place every 7 ms.

During the experiment, subjects were seated 40 cm from the oscilloscope. At this viewing distance, the oscilloscope subtended 16.7 degrees of visual angle horizontally and 13.4 degrees vertically. The letter arrays subtended 4.32 degrees horizontally and 2.0 degrees vertically. Each letter subtended 0.32 degrees horizontally and 0.5 degrees vertically; the letters were separated horizontally by 1.68 degrees and vertically by 1 degree. The vertical bar probe was 0.25 degree high and 0.04 degree wide; it was presented 0.25 degree above or below the location of the probed letter. The mask probe was a box that measured 0.82 degree wide and 1.0 degree high, and it was presented such that the probed letter would appear centered within it. Calibration and fixation points used during the experiment subtended 0.10 degree horizontally and vertically.

The experimental chamber was dimly illuminated during the experiment. The luminance of the display background was 2 cd/m²; stimulus displays were presented with an effective luminance of 27 cd/m². The P-15 phosphor decays very rapidly; shutter tests similar to those described by Irwin, Yantis, and Jonides (1983) confirmed that no phosphor persistence was visible 5 ms after stimulus offset.

Procedure. The sequence of events for a typical bar-probe trial in the saccade condition is depicted in Figure 1. Each trial began with a calibration routine during which a calibration point (+) stepped across the display at three locations separated by 2.0 degrees. Each point was presented for 1.5 s, and the subject was instructed to fixate each carefully. Eye position at each location was sampled (at a rate of 142.9 Hz) for 100 ms near the middle of this interval. These recordings served to calibrate the output of the eyetracker against spatial position.

After calibration, the first fixation point was presented. This point was always presented where the second (central) calibration point had appeared. The subject was instructed to fixate this point carefully. After 1.5 s, this central fixation point disappeared and the saccade target (another +) appeared in the parafovea. On rightward-movement trials, the saccade target appeared at the location of the rightmost calibration location; on leftward-movement trials, it appeared at the location of the leftmost calibration location. The subject was instructed to saccade to this target when it was presented. Sampling of eye position began with the presentation of the saccade target.

The letter array was presented simultaneously with the onset of the saccade target. Two rows of three uppercase letters each were presented, with one letter situated 0.5 degrees above and another letter situated 0.5 degrees below each of the three calibration locations. The letter array remained visible until the subject initiated a saccade

toward the saccade target (approximately 265 ms); saccade onset was defined as an eye velocity exceeding 70 degrees/ms. After the offset of the letter array, an interval of 40, 120, or 750 ms elapsed before the bar probe or mask probe was presented for 30 ms. Subjects were instructed to maintain fixation on the saccade target during the probe delay and during probe presentation. After presentation of the probe, the subject attempted to report the letter that had occupied the position indicated by the probe as well as the probe's spatial position (i.e., Array Location 1–6). These responses were typed into the computer terminal keyboard.

The subject's eye movement had to have a latency of 100 to 500 ms for the trial to be acceptable. This criterion eliminated anticipatory eye movements that might not have allowed for adequate processing of the letter array and delayed eye movements potentially indicative of attention lapses. Approximately 9% of the trials failed this criterion; they were repeated later in the block of trials. Each subject completed 18 blocks of 20 acceptable trials each. These blocks alternated between bar-probe and mask-probe trials; this was done to equate mean saccade latency across the two conditions. Order was balanced across subjects. Eye-movement direction (left and right), probe delay (40, 120, and 750 ms), and probe position were balanced for each subject across the course of the experiment. Each of the 60 letter arrays in each set of arrays appeared once at each probe delay for each subject.
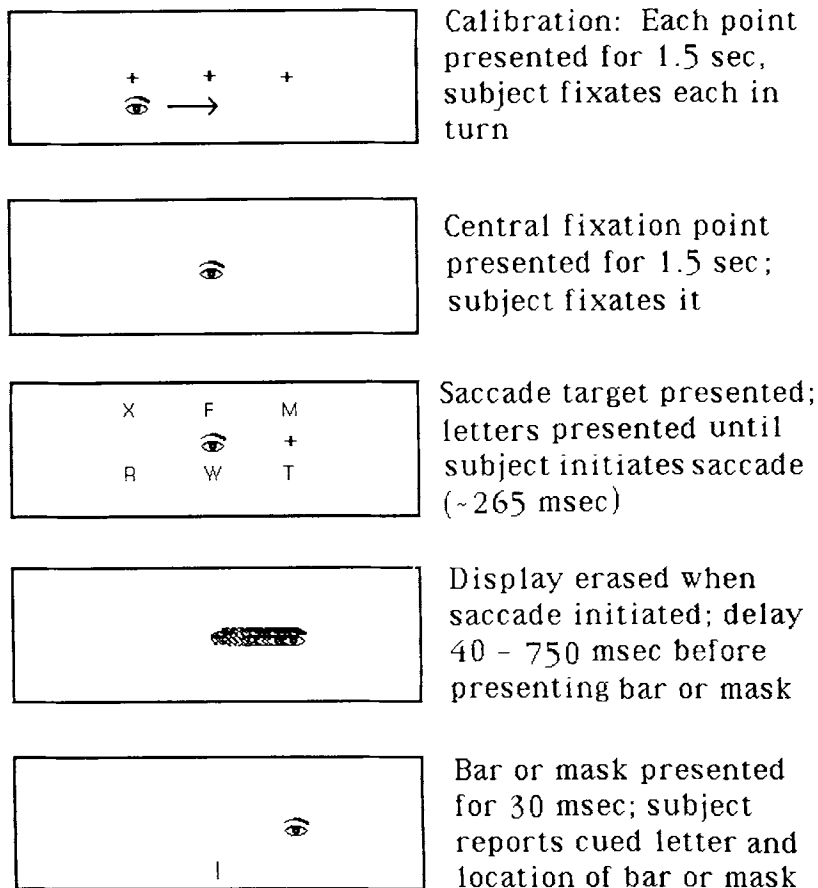

Calibration: Each point presented for 1.5 sec, subject fixates each in turn

Central fixation point presented for 1.5 sec; subject fixates it

Saccade target presented; letters presented until subject initiates saccade (~265 msec)

Display erased when saccade initiated; delay 40 – 750 msec before presenting bar or mask

Bar or mask presented for 30 msec; subject reports cued letter and location of bar or mask

Figure 1. Schematic illustration of the procedure for bar-probe trials in the saccade condition of Experiment 1. (After a calibration routine, a two-row × three-column matrix of letters was presented until the subject initiated a saccade from the central fixation point to the parafoveal saccade target. After saccade onset, a delay of 40, 120, or 750 ms elapsed before a bar probe was presented above or below one of the letter locations. The subject reported the probed letter and the position of the probe. For this trial, the correct answer would be "W5.")

Eye-movement direction, probe delay, and probe position were sequenced randomly across trials. Each subject completed several practice blocks of eye-movement trials before completing the 18 experimental blocks. Data collection was spread over a period of several sessions; subjects typically completed 4 to 6 blocks per session.

In addition to these eye-movement trials, each subject also completed a no-saccade control session using bar-probe and mask-probe report cues. In this session, the subject viewed the letter arrays and the probes while maintaining fixation on the central fixation point. All experimental parameters were yoked to those of the saccade trials. This was accomplished in the following way: During the saccade condition trials, a record was kept of stimulus exposure duration (determined by the subject's saccade latency on that trial), letter array, probe delay, and probe position; during the no-saccade control session, this record was used to determine the corresponding parameters on each trial. Thus, subjects saw the same letter arrays under the same timing conditions in the saccade and no-saccade conditions. Rather than alternating between blocks of bar-probe and mask-probe trials, however, each subject completed 180 trials with one probe type before completing 180 trials with the other probe type. Order was balanced across subjects.

Results and Discussion

Preliminary analysis of the eye-movement data showed that mean saccade latency (hence, stimulus exposure duration) did not significantly vary across probe type, $F(1, 7) = 0.9, p > .35, MS_e = 109.2$, or probe delay, $F(2, 14) = 1.0, p > .35, MS_e = 28.3$, conditions. The Probe Type × Probe Delay interaction was nonsignificant, $F(2, 14) = 3.0, p > .08, MS_e = 34.9$; mean latencies ranged from 261 ms to 270 ms across conditions. Thus, the results described here are unlikely to be due to differences in eye-movement behavior across experimental conditions.

The subjects' letter responses were classified as correct only if the letter they reported had appeared at the probed position. Table 1 shows the percentage of correct responses for bar-probe and mask-probe trials as a function of probe delay in the saccade condition and in the no-saccade control condition.

A separate analysis of variance (ANOVA) was conducted on the data from each condition with factors of probe type (bar probe vs. mask probe) and probe delay (40, 120, 750 ms). In the saccade condition, accuracy on bar-probe trials was marginally higher than accuracy on mask-probe trials, $F(1, 7) = 3.7, p < .10, MS_e = 20.0$. Accuracy declined as probe delay increased, $F(2, 14) = 11.0, p < .002, MS_e = 17.6$. There was a significant interaction between probe type and

Table 1
Percentage Correct as a Function of Probe Delay in Experiment 1

| Condition | Probe delay (ms) | | |
	40	120	750
Saccade			
Bar-probe trials	64.6	60.5	53.0
Mask-probe trials	55.4	60.0	55.2
No saccade			
Bar-probe trials	80.7	79.3	68.0
Mask-probe trials	71.3	70.4	69.8

probe delay, $F(2, 14) = 4.4, p < .05, MS_e = 32.0$; simple effects tests showed that there was a significant decrease in accuracy as probe delay increased in the bar-probe condition, $F(2, 14) = 11.8, p < .001, MS_e = 23.3$, but no effect on probe delay in the mask-probe condition, $F(2, 14) = 2.3, p > .14, MS_e = 26.3$. The percentage of correct reports was lower in the mask-probe condition than in the bar-probe condition at the shortest probe delay only, $F(1, 7) = 9.4, p < .02, MS_e = 35.9$.

The analysis of the no-saccade control condition data yielded almost identical results. Accuracy on bar-probe trials was marginally higher than accuracy on mask-probe trials, $F(1, 7) = 4.4, p < .10, MS_e = 81.8$. Accuracy declined as probe delay increased, $F(2, 14) = 10.4, p < .002, MS_e = 22.5$. There was a significant interaction between probe type and probe delay, $F(2, 14) = 20.0, p < .001, MS_e = 8.1$. Simple effects tests showed that there was a significant decrease in accuracy as probe delay increased in the bar-probe condition, $F(2, 14) = 24.7, p < .001, MS_e = 15.9$, but no effect of probe delay in the mask-probe condition, $F(2, 14) = 0.3, p > .75, MS_e = 14.8$. In addition, the percentage of correct reports was lower in the mask-probe condition than in the bar-probe condition at the 40-ms probe delay, $F(1, 7) = 12.9, p < .01, MS_e = 28.0$, and at the 120-ms probe delay, $F(1, 7) = 13.7, p < .01, MS_e = 23.1$, but not at the 750-ms probe delay $(F < 0.3)$.

These analyses indicate that patterns of performance in the two conditions were very similar. Mean accuracy was considerably higher in the control condition (73%) than in the saccade condition (58%), however. Subjects were highly accurate at reporting the probe's spatial position in the saccade condition, so the drop in letter-report accuracy in the saccade condition was not caused by a failure to recognize which array location had been probed. Mean accuracy at reporting the probe's spatial position was 98.6%, with a range from 98.0% to 99.3% across probe-type and probe-delay conditions. Accurate report of the probe's spatial position was unaffected by probe type, $F(1, 7) = 2.2, p > .15, MS_e = 1.6$, probe delay, $F(2, 14) = .08, p > .90$, and their interaction, $F(2, 14) = 1.1, p > .30, MS_e = 2.4$. Thus, rather than being due to spatial uncertainty regarding the probe's position, the lower letter-report accuracy in the saccade condition relative to the control condition appears to be caused by a loss of letter information from memory as a result of the eye movement.

To determine whether stimulus exposure duration (determined by saccade latency) had any effect on performance, subsidiary analyses of the saccade- and control-condition data were conducted using exposure duration as an additional factor. Exposure durations of 100 to 249 ms were classified as "short," and exposure durations of 250 to 500 ms were classified as "long" for this analysis; these two categories accounted for all of the data because of the saccade latency criteria that were enforced during the experiment. ANOVAs conducted on the saccade- and control-condition data showed that exposure duration had no effect on accuracy and did not interact with any other variable. These results are consistent with those of Irwin and Yeomans (1986), who studied the effects of exposure duration and masking on partial report during maintained fixation.

The accuracy analyses just reported disregarded letter position in the array and eye-movement direction (in the saccade condition). Because attentional allocation appears to be tied to the direction of an eye movement (e.g., Rayner, McConkie, & Ehrlich, 1978), it is of interest to determine whether letter-report accuracy varied as a function of probe position and eye-movement direction. An ANOVA was conducted on the saccade-condition data with factors of probe type (bar probe vs. mask probe), direction of eye movement (left vs. right), and probe position (1–6, where 1 refers to the leftmost letter in the top row and 6 refers to the rightmost letter in the bottom row). Accuracy of letter report was higher when subjects moved their eyes to the left (60.7%) than to the right (55.7%), $F(1, 7) = 13.7, p < .01, MS_e = 87.9$. Accuracy was higher for letters in the top row (67.1%) than for letters in the bottom row (49.3%), and accuracy for the middle letter in a row (34.0%) was lower than accuracy for the terminal letters in a row (70.3%), $F(5, 35) = 14.3, p < .001, MS_e = 1,008.9$. There was a significant interaction between eye-movement direction and probe position, $F(5, 35) = 19.5, p < .001, MS_e = 318.9$. The first two rows of Table 2 show the means for this interaction. Simple effects tests showed that report of the leftmost letter in the top row (Position 1), $F(1, 7) = 20.1, p < .005, MS_e = 379.6$, and report of the leftmost letter in the bottom row (Position 4), $F(1, 7) = 43.3, p < .001, MS_e = 206.3$, were significantly more accurate when the eyes moved to the left than when the eyes moved to the right. Similarly, report of the rightmost letter in the top row (Position 3), $F(1, 7) = 17.6, p < .005, MS_e = 471.9$, and report of the rightmost letter in the bottom row (Position 6), $F(1, 7) = 27.0, p < .001, MS_e = 193.0$, were significantly more accurate when the eyes moved to the right than when the eyes moved to the left. Accurate report of the middle letter in each row was marginally higher when the eyes moved to the left than when they moved to the right: (Position 2, $F(1, 7) = 5.1, p < .06, MS_e = 174.8$; Position 5, $F(1, 7) = 5.2, p < .06, MS_e = 256.6$). In sum, subjects were most accurate at reporting the letters spatially near the location to which they moved their eyes even though these letters fell on the parafovea. Interestingly, even though subjects fixated between the middle letters of each row when the letter array was presented, report of those letters was always less accurate than report of the terminal letters. Because the middle letters fell on the fovea, one might expect their recall to be superior rather than inferior. Presentation of the saccade target apparently led subjects to shift their attention toward the letters near the saccade target, boosting their recall at the expense of the other letters in the array. The inferior recall of the middle letters relative to the terminal letters on the side opposite the saccade target may

have been due to "inhibition of return" (Posner & Cohen, 1984).

For comparison, the last row of Table 2 shows accuracy by probe position in the no-saccade control condition. An ANOVA of these data found only a significant effect of position such that letters in the top row (Positions 1–3) were reported more accurately (80% vs. 66.6%) than letters in the bottom row (Positions 4–6), $F(1, 7) = 12.4, p < .01, MS_e = 346.9$. Letters in the middle of the array (Positions 2 and 5, above and below the point of fixation, respectively) were reported somewhat more accurately than the terminal letters, but this was not significant. The superior recall for letters in the top row relative to the bottom row is probably due to an attentional bias induced by reading experience.

Summary

The results of the no-saccade control condition replicate those of many previous investigators who have examined partial report during maintained fixation (e.g., Averbach & Coriell, 1961; Irwin & Yeomans, 1986; Mewhort, Campbell, Marchetti, & Campbell, 1981; Townsend, 1973): Accuracy declined as probe delay increased, and presentation of a masking stimulus shortly after stimulus offset hindered accurate performance. Although accuracy at the shortest probe delay in the bar-probe condition was less than perfect, it was in the range found by these previous investigators (idealized textbook renditions of partial-report performance notwithstanding).

Of primary interest, of course, were the results of the saccade condition. These results indicate that even when the letter array and the partial-report cue appear in separate fixations, somewhat more information about the contents of the letter array is available shortly after its offset than some time later. Furthermore, this information is vulnerable to the presentation of a masking stimulus as long as the mask is presented soon (40 ms) after stimulus offset. Because the letter arrays and the probe stimuli were viewed in separate fixations only, these results provide evidence for the existence of a maskable, spatially addressable representation across eye movements. This finding is consistent with that of McRae et al. (1987), who also found evidence for spatiotopic masking across saccades. At longer probe delays (120 and 750 ms), somewhat less information is available, but it is impervious to masking. It appears that transsaccadic memory retains visual aspects of a stimulus but perhaps for a brief time only. Accuracy of letter report depended strongly on the interaction between saccade direction and probe position: Accuracy was very high when the letter that had been presented above or below the saccade target was probed for report. Because movements of attention precede movements of the eyes, it is suggested that attentional allocation strongly influences which items in a fixation are encoded and stored in transsaccadic memory instead of all items being stored in a passive, automatic manner.

Table 2
Percentage Correct as a Function of Probe Position in Experiment 1

Condition	Probe position					
	1	2	3	4	5	6
Saccade to left	94.2	49.8	62.0	76.1	29.9	52.2
Saccade to right	63.3	39.2	94.2	42.7	17.0	77.8
No saccade	79.1	82.2	78.5	70.0	70.4	59.3

Experiment 2

The first experiment provided some evidence about the time course and representational format of transsaccadic

memory; the second experiment was designed to provide additional information about these characteristics as well as information about its capacity. Experiment 2 repeated the bar-probe condition of Experiment 1, but arrays of 10 letters rather than 6 letters were used. As in Experiment 1, each subject participated in a saccade condition and in a no-saccade condition.

Method

Subjects. The 8 subjects who participated in Experiment 1 participated in this experiment.

Stimuli. Sixty different letter arrays were used as stimuli. Each array contained 10 letters in a two-row × five-column format. The letters were drawn randomly from the set of all consonants excluding the letter *y*. A short vertical line appearing above (top row) or below (bottom row) one of the array locations was used as the partial-report cue.

Apparatus. The apparatus used in Experiment 1 was used in this experiment. As in Experiment 1, the letter arrays subtended 4.32 degrees horizontally and 2.0 degrees vertically. Each letter subtended 0.32 degree horizontally and 0.5 degree vertically; the letters were separated horizontally by 0.68 degree and vertically by 1 degree. All other aspects of the apparatus were identical to Experiment 1.

Procedure. The sequence of events for saccade condition trials was identical to that used in Experiment 1. After a calibration sequence, the first fixation point was presented for 1.5 s. Then this fixation point disappeared, and the saccade target appeared in the parafovea. Simultaneous with the onset of the saccade target, the letter array was presented. Two rows of five uppercase letters each were presented until the subject initiated a saccade toward the saccade target (approximately 253 ms). After the offset of the letter array, an interval of 40, 120, or 750 ms elapsed before the bar probe was presented for 30 ms. After presentation of the probe, the subject attempted to report the letter that had occupied the position indicated by the probe as well as the probe's spatial position (i.e., Array Location 1–10). These responses were typed into the computer terminal keyboard.

Each subject completed 9 blocks of 20 acceptable trials each. Approximately 9% of the trials failed the saccade latency criteria described in Experiment 1; these trials were repeated later in the block of trials. Eye-movement direction (left and right), probe delay (40, 120, and 750 ms), and probe position were balanced for each subject across the course of the experiment. Each of the 60 letter arrays appeared once at each probe delay for each subject. Eye-movement direction, probe delay, and probe position were sequenced randomly across trials. Data collection required two experimental sessions; subjects completed 3 to 6 blocks per session.

After these eye-movement sessions, each subject completed a no-saccade control session of 180 trials during which they viewed the letter arrays and probes while maintaining fixation on the central fixation point. All experimental parameters were yoked to those of the saccade trials as described in Experiment 1. Thus, subjects saw the same letter arrays under the same timing conditions in the saccade and no-saccade conditions.

Results and Discussion

Preliminary analysis of the eye-movement data showed that mean saccade latency (hence, stimulus exposure duration) did not significantly vary across probe delays (mean = 253 ms, 252 ms, and 254 ms for probe delays of 40 ms, 120 ms, and

750 ms, respectively, $F < 1$). Mean saccade latency was slightly faster in this experiment than in Experiment 1 (265 ms) probably because of practice.

As in Experiment 1, in each trial subjects made two responses: the letter they thought had occupied the probe's spatial position and the probe's spatial position. Subjects were less accurate at reporting the probe's spatial position in this experiment than in Experiment 1; mean accuracy averaged across probe-delay conditions was 88.1% (range = 86.1%–91.4%). Accuracy of reporting the probe's spatial position was unaffected by variations in probe delay, $F(2, 14) = 1.6$, $p > .25$, $MS_e = 36.9$. Apparently it was more difficult to localize the probe's position across eye movements when 10 locations were used rather than 6. There was greater spatial uncertainty because more locations were used, and the locations were closer together. Because subjects had been instructed to report the letter that had appeared at the probe's spatial position, apparent (i.e., reported) probe position rather than true probe position was used to classify responses as correct. In other words, the subject's letter response was classified as correct only if the reported letter had appeared at the reported probe position (using actual probe position rather than reported probe position to classify responses as correct would decrease the percentage of correct reports by less than 1% and would not significantly change the results either quantitatively or qualitatively).

Analyses of the subjects' letter responses showed that accuracy declined as probe delay increased in the no-saccade control condition, $F(2, 14) = 32.8$, $p < .001$, $MS_e = 38.8$, and in the saccade condition, $F(2, 14) = 4.7$, $p < .03$, $MS_e = 29.9$. Mean accuracy in the no-saccade control condition was 62.7%, 55.6%, and 38.2% for probe delays of 40 ms, 120 ms, and 750 ms, respectively. A 95% confidence interval for the difference between two means (planned comparison) was calculated and yielded a confidence interval half-width of 6.0%; thus, accuracy at each probe delay was different from accuracy at the other probe delays. Mean accuracy in the saccade condition was 36.9%, 39.2%, and 31.1% for probe delays of 40 ms, 120 ms, and 750 ms, respectively. The 95% confidence interval half-width for the difference between two means for these data was 5.3%, indicating that accuracy at the two shortest probe delays did not differ from each other, but each was significantly higher than accuracy at the longest probe delay. In sum, there was a large decline in accuracy as probe delay increased in the no-saccade control condition and a small but significant decline in accuracy as probe delay increased in the saccade condition.

As in Experiment 1, subsidiary analyses of the letter report data were conducted to investigate whether accuracy varied as a function of letter position in the array and eye-movement direction (in the saccade condition). Experiment 1 showed that letter-report accuracy was much higher when the probed letter appeared near the saccade target than when it appeared elsewhere in the array, presumably because attention shifted to the saccade target area before the eye movement was executed. An ANOVA was conducted on the saccade condition data of Experiment 2 with factors of eye-movement direction (left vs. right), row probed (top vs. bottom), and column probed (1–5, where 1 = leftmost and 5 = rightmost).

Table 3

Percentage Correct as a Function of Probe Position in Experiment 2

Condition	Column				
	1	2	3	4	5
Top row					
Saccade to left	88.9	21.7	26.1	38.9	75.4
Saccade to right	75.1	2.8	13.9	13.9	86.0
No saccade	67.6	39.6	72.2	61.9	61.1
Bottom row					
Saccade to left	56.3	2.8	15.3	17.3	39.3
Saccade to right	31.3	4.2	2.8	22.2	65.3
No saccade	46.7	22.5	69.3	34.6	31.6

Accuracy was higher when the eyes moved to the left than when they moved to the right, $F(1, 7) = 15.2$, $p < .01$, $MS_e = 109.5$. Accuracy for the top row was higher than accuracy for the bottom row, $F(1, 7) = 8.3$, $p < .025$, $MS_e = 1,662.5$. Accuracy was higher for the terminal letters in a row than for the interior letters, $F(4, 28) = 72.0$, $p < .001$, $MS_e = 341.1$. There were significant interactions between eye-movement direction and column probed, $F(4, 28) = 3.8$, $p < .025$, $MS_e = 433.9$, row probed and column probed, $F(4, 28) = 4.1$, $p < .001$, $MS_e = 380.9$, and eye-movement direction and row probed and column probed, $F(4, 28) = 2.9$, $p < .05$, $MS_e = 189.6$. The means for this three-way interaction are shown in Table 3. As in Experiment 1, accuracy was higher when the eyes moved toward the letter that was probed; for example, correct report of column 1 (the leftmost letter) in each row was higher when the eyes moved to the left than when they moved to the right, $F(1, 7) = 11.1$, $p < .025$, $MS_e = 268.6$, and correct report of column 5 (the rightmost letter) in each row was higher when the eyes moved to the right than when they moved to the left, $F(1, 7) = 6.7$, $p < .05$, $MS_e = 400.9$. It appears that subjects attend selectively to the location to which they will move their eyes, boosting correct report of the letters near that location. Correct report of the terminal letter at the side opposite the saccade target was also high, however, suggesting that the terminal letters in general may be more perceptible than the interior letters perhaps because of lateral masking of the interior letters. As in Experiment 1, report of the middle letter in each row was inaccurate, even though these letters fell on the fovea during the presaccadic fixation.

For comparison, Table 3 also shows accuracy by probe position in the no-saccade control condition. Report of the middle letter in each row (above and below the fixation point) was more accurate than report of the other letters in each row, $F(4, 28) = 9.5$, $p < .001$, $MS_e = 372.3$. Report of the top row was more accurate than report of the bottom row, $F(1, 7) = 26.7$, $p < .002$, $MS_e = 264.3$, except that there was no difference in accuracy between the top and bottom rows for the middle letter, $F(1, 7) = 0.4$, $p > .5$, $MS_e = 115.9$. Taken together, the position analyses of the saccade and control condition data show, perhaps not surprisingly, that subjects remember best those letters they attend to while the letter array is present.

Experiments 1 and 2 Compared

Accuracy. To examine the capacity of transsaccadic memory, it is necessary to compare the results of Experiment 1, which used arrays of 6 letters, with the results of Experiment 2, which used arrays of 10 letters. In both experiments, the percentage of correct reports decreased as probe delay increased in the saccade and control conditions. The percentage of correct reports was much lower in Experiment 2 than in Experiment 1, however, in both the saccade (35% vs. 60%) and control (52% vs. 73%) conditions. Comparing percentage of correct responses across the two experiments may be somewhat misleading, however, because different array sizes were used. To facilitate comparisons across experiments, the accuracy data were converted into a scale that took the number of letters available into account (Sperling, 1960). The percentage of correct reports was multiplied by the number of letters in the array (6 in Experiment 1 and 10 in Experiment 2) to form a new (i.e., recoded) variable: letters remembered. Table 4 shows the results, expressed in terms of letters remembered, for the bar-probe trials of the saccade and control conditions of Experiments 1 and 2 as a function of probe delay.

Table 4 shows that the number of letters remembered correctly across eye movements was relatively small regardless of whether 6 or 10 letters were present in the array. Subjects remembered about 3.8 letters correctly at the shortest probe delay and about 3.2 letters correctly at the longest probe delay; thus, transsaccadic memory appears to hold few letters, but there is little lost from memory as time passes. By contrast, the number of letters remembered in the no-saccade control condition was much higher especially when the letter arrays contained 10 letters. The superior performance for 10-letter as opposed to 6-letter arrays in the control condition is probably due to the fact that the visual extent of the letter arrays was held constant as array size increased, thereby positioning more letters near the fovea in the 10-letter condition than in the 6-letter condition. There was a much greater loss in letter memory as probe delay increased in the control condition than in the saccade condition; for the 10-letter arrays, for example, correct reports fell from 6.3 letters to 3.8 letters as probe delay increased from 40 to 750 ms. This is a loss of 2.5 letters as opposed to the loss of 0.6 letters in the saccade condition. It is also interesting to note that the number of letters remembered at the shortest probe delay in the saccade condition was approximately equal to the number of

Table 4

Letters Remembered as a Function of Probe Delay for Bar-Probe Trials in Experiments 1 and 2

Condition	Probe delay (ms)		
	40	120	750
Saccade			
Experiment 1 (6-letter array)	3.9	3.6	3.2
Experiment 2 (10-letter array)	3.7	3.9	3.1
No saccade			
Experiment 1 (6-letter arrays)	4.8	4.8	4.1
Experiment 2 (10-letter arrays)	6.3	5.6	3.8

letters remembered at the longest probe delay in the no-saccade control condition. These results suggest that when the eyes do not move, a form of visual memory exists for a brief time after stimulus offset that greatly improves letter report; when the eyes move, however, this visual memory (presumably "iconic" memory) is eliminated. Transsaccadic memory thus appears to be a slowly decaying memory with a limited capacity of about three to four items.

Error analyses. In an attempt to obtain additional information about the way in which information is stored in transsaccadic memory, an analysis of the kinds of errors that subjects made in Experiments 1 and 2 was conducted. Incorrect responses were classified as intra-array errors if the reported letter had not appeared at the probed position but had appeared elsewhere in the letter array or as extra-array errors if the reported letter had not appeared anywhere in the letter array. These two categories account for all errors because response omissions were not allowed. In partial report research, intra-array errors are generally assumed to reflect loss of location information from memory, whereas extra-array errors are generally assumed to reflect loss of identity information (e.g., Irwin & Yeomans, 1986; Mewhort et al., 1981; Townsend, 1973). Thus, examination of these error patterns might provide useful insights into what information is remembered across eye movements and what information is lost.

To facilitate comparisons across experiments, the percentage of intra-array and extra-array errors were converted into letters forgotten by multiplying by 6 for Experiment 1 and by 10 for Experiment 2. ANOVAs were then conducted on the error data with factors of error type (intra-array vs. extra-array), display size (6 letters vs. 10 letters), and probe delay (40, 120, and 750 ms). Table 5 shows the mean number of intra-array and extra-array errors (expressed in terms of letter units) as a function of probe delay for the bar-probe trials of the saccade and no-saccade conditions of Experiments 1 and 2.

Table 5

Number of Intra-Array and Extra-Array Errors (Expressed in Letter Units) as a Function of Probe Delay for Bar-Probe Trials in Experiments 1 and 2

Error type	Probe delay (ms)		
	40	120	750
Saccade condition			
Intra-array errors			
Experiment 1 (6-letter arrays)	1.4	1.6	1.5
Experiment 2 (10-letter arrays)	4.9	5.0	5.0
Extra-array errors			
Experiment 1 (6-letter arrays)	0.7	0.8	1.3
Experiment 2 (10-letter arrays)	1.5	1.1	1.9
No-saccade condition			
Intra-array errors			
Experiment 1 (6-letter arrays)	0.7	0.6	0.9
Experiment 2 (10-letter arrays)	2.8	3.2	4.3
Extra-array errors			
Experiment 1 (6-letter arrays)	0.4	0.6	0.9
Experiment 2 (10-letter arrays)	0.9	1.3	1.8

In the analysis of the saccade conditions of the two experiments, there were significantly more intra-array than extra-array errors in each experiment, $F(1, 7) = 174.4$, $p < .001$, $MS_e = 0.551$. There were more errors when the letter arrays contained 10 letters than when they contained 6 letters, $F(1, 7) = 315.4$, $p < .001$, $MS_e = 0.315$. There were more errors at the longest probe delay than at the two shortest probe delays, $F(2, 14) = 13.4$, $p < .001$, $MS_e = 0.074$. The interaction between error type and probe delay was significant, $F(2, 14) = 7.0$, $p < .01$, $MS_e = 0.155$: The number of intra-array errors was constant as probe delay increased, but the number of extra-array errors was higher at the longest probe delay than at the two shorter probe delays. The interaction between error type and display size was also significant, $F(1, 7) = 291.8$, $p < .001$, $MS_e = 0.176$: Both kinds of errors increased significantly as display size increased from 6 to 10 letters, but the increase for intra-array errors (from 1.5 to 5.0 letters) was much larger than the increase for extra-array errors (from 0.9 to 1.5 letters). Thus, although the number of letters remembered remained constant as display size increased, the number of intra-array errors increased dramatically. Of course, some increase in the number of intra-array errors is expected by chance guessing alone. Given the population size of 20 letters used in these experiments, there was a 5 of 19 (26%) chance that an error would be an intra-array error in Experiment 1 (because the arrays contained 6 letters) and a 9 of 19 (47%) chance that an error would be an intra-array error in Experiment 2 (because the arrays contained 10 letters). Thus, chance guessing alone predicts an increase in intra-array errors of about 2 letter units between Experiments 1 and 2, whereas an increase of 3.5 letter units was actually found. It is also interesting to note that chance guessing predicts that extra-array errors should be about three times more likely than intra-array errors in Experiment 1 and about equally likely in Experiment 2; these predictions are far from accurate, however. In sum, it seems unlikely that chance guessing had much impact on the kinds of errors that subjects made. The theoretical implications of these error patterns are discussed further in the General Discussion.

Additional analysis of the intra-array errors revealed that most were due to report of a letter that had appeared in a location spatially near the probed position; 31.4% of the intra-array errors involved report of an adjacent letter in the same row, whereas 61.8% of the errors involved report of an adjacent letter in the same row or in the other row. These values are higher than the chance expectations of 17.8% and 46.7%, respectively, that would be generated if intra-array errors were randomly distributed. Thus, when subjects made an intra-array error, they tended to report a letter that was spatially near the correct letter's position.

The analysis of the no-saccade control conditions yielded similar results. There were significantly more intra-array than extra-array errors in each experiment, $F(1, 7) = 44.9$, $p < .001$, $MS_e = 0.668$. There were more errors when the letter arrays contained 10 letters than when they contained 6 letters, $F(1, 7) = 201.0$, $p < .001$, $MS_e = 0.343$. There were more errors at the longest probe delay than at the two shortest probe delays, $F(2, 14) = 35.1$, $p < .001$, $MS_e = 0.147$. The interaction between error type and probe delay was not significant

($F < 1$) in the control-condition data, indicating that both types of errors increased as probe delay increased. The interaction between display size and probe delay was significant, however, $F(2, 14) = 14.9, p < .001, MS_e = 0.114$: There was a greater increase in the number of errors as probe delay increased when 10-letter arrays were used than when 6-letter arrays were used. The interaction between error type and display size was also significant, $F(1, 7) = 47.9, p < .001, MS_e = 0.483$: Both types of errors increased as display size increased from 6 to 10 letters, but the number of intra-array errors increased more (from 0.8 to 3.4 letters) than did the number of extra-array errors (from 0.6 to 1.3 letters). As in the saccade condition data, most of the intra-array errors were due to the report of an adjacent letter in the same row (29.7% of the intra-array errors) or the report of an adjacent letter in the same row or in the other row (70.7% of the intra-array errors).

Summary

The main purpose of Experiment 2 was to examine what effect increasing the number of letters in the array would have on memory across eye movements. The most striking result was that few letter units (i.e., identity plus position units) were remembered correctly across eye movements: Between 3 and 4 letter units were remembered correctly regardless of how many letters appeared in the letter array. In addition, increasing probe delay had only a small, detrimental effect on letter memory. These results suggest that transsaccadic memory has a limited capacity and a slow rate of decay. Increasing the display size led to a much larger increase in one type of error than in another: The number of intra-array errors increased from 1.5 to 5 letter units as display size increased from 6 to 10 letters, whereas the number of extra-array errors increased only slightly. Indeed, comparison of Tables 4 and 5 shows that intra-array errors were made more frequently than correct reports when the stimulus display contained 10 letters. In contrast, in the no-saccade control condition, more letters were remembered as array size increased, and there was a rapid and substantial decrease in letter memory as probe delay increased. The results of the no-saccade control condition indicate that a high-capacity, quickly decaying iconic memory exists for the contents of individual fixations as many others have argued; the results of the saccade condition suggest that transsaccadic memory has no equivalent, high-capacity, quickly decaying component.

General Discussion

The purpose of the present research was to investigate how position and identity information are remembered across changes in eye position to determine some of the fundamental characteristics of transsaccadic memory, the memory responsible for accumulating information across saccadic eye movements. Memory for position and identity was assessed by a partial-report technique that required subjects to integrate the contents of a letter array viewed in one fixation with a partial-report cue viewed in a second fixation. The number of letters

in the array, the characteristics of the partial-report cue, and cue delay were varied to determine the capacity, representational format, and duration of transsaccadic memory. The experimental results indicated that transsaccadic memory has a limited capacity, decays relatively slowly, and maintains visual (i.e., maskable) characteristics of the letter array for at least a brief time after stimulus offset. These characteristics are typically associated with visual short-term memory (e.g., Phillips, 1974), lending support to the hypothesis that visual short-term memory plays an important role in transsaccadic integration (Irwin, 1991). By contrast, memory for position and identity during maintained fixation can make use of a high-capacity, quickly decaying, iconic memory in addition to short-term memory. This high-capacity, quickly decaying memory is lost when an eye movement occurs.

The results of the present research are in good agreement with the results of previous investigations of transsaccadic memory. As described in the Introduction, Irwin (1991) found that comparison of random-dot patterns across eye movements appears to rely on a long-lasting, limited-capacity memory for visual information. Several other studies also have provided evidence that visual information can be accumulated and compared across eye movements. For example, Hayhoe, Lachter, and Feldman (in press) found that subjects could judge whether or not three points viewed in successive fixations (one point per fixation) formed a right triangle, and Palmer and Ames (1989) found that subjects could make precise discriminations between lines of different lengths even when the lines were viewed in separate fixations. Using a letter-matching task, Posner and Keele (1967) and Hansen and Sanders (1988) found that physical matches were made more quickly than name matches even when the two letters were viewed in separate fixations. Furthermore, Hansen and Sanders (1988) found that when both the first and second stimulus were visually degraded, processing of the second stimulus was faster than when only the second stimulus was degraded; these results suggest that visual features of the two stimuli are compared across eye movements rather than abstract name codes (see also Sanders & Houtmans, 1985). Finally, Pollatsek et al. (1984, 1990) found that visual features of objects appear to be combined across saccades; this integration may be accomplished through priming of long-term memory representations rather than through information accumulation in short-term memory, however (Pollatsek & Rayner, in press).

The qualitative error analyses conducted on the data of Experiments 1 and 2 provide additional information about the way in which information is represented in transsaccadic memory. When the number of letters in the display was increased from 6 to 10, the number of intra-array errors increased dramatically, whereas the number of extra-array errors increased only slightly. In addition, there were many more intra-array errors than extra-array errors. This pattern of results allows a discrimination to be made between two possible models of information representation in transsaccadic memory. If transsaccadic memory held a passive fading image of the stimulus display similar to the traditional conception of iconic memory, for example, then extra-array errors should occur more frequently than intra-array errors:

As the image faded, less information about the identities of the letters would be available, and, by chance (because there are more letters not present in the display than present in the display), extra-array errors would predominate. This model is not supported by the present results. Rather, the results are consistent with the hypothesis that transsaccadic memory is a postcategorical store with a limited capacity. The accuracy and error data suggest that items are represented in memory according to integrated position and identity codes (e.g., "T is at position 1", "S is at position 2", and so on). Relatively few (three to four) of these codes can be represented, and attention determines which codes are built. When a partial-report probe is presented, the subject can respond correctly if the probed position has an identity code linked to it. If the probe signals the subject to report from a position that does not have an identity code associated with it, however, the subject responds (most of the time) with the identity of some other item that was present in the display (i.e., an intra-array error is made). There are two possible reasons why this might occur. First, transsaccadic memory might contain "unlocated" identity codes (Dixon, 1986) in addition to integrated position and identity codes; that is, the subject may know that certain identities were present in the display without knowing precisely which positions they occupied, and a response might be selected from among these. Note that this would occur not because the subject was uncertain about which position was probed, because probe localization was quite accurate; rather, the problem would be one of knowing which identity code was in the probed position. Alternatively, transsaccadic memory might contain only integrated identity plus position codes and no "unlocated" identity codes, and intra-array errors might result from a guessing bias to respond with an item from the array, even if it is an incorrect item, if the probed position does not have an identity code associated with it. This would be a perverse strategy, because the subject would report one of the integrated identity plus position codes in memory even though the position component of the code did not match the position indicated by the probe; in other words, the subject would knowingly make an error. Of course, this bias could be unconscious rather than conscious, but this argument has little foundation unless one assumes that the information-processing system has more *confidence* in identity codes than in position codes; without this assumption, it is difficult to understand why this bias would exist because chance guessing favors extra-array errors over intra-array errors. However, this position seems not too different from the argument that identity information about an item is represented more *accurately* than position information about an item. In sum, it seems most reasonable to conclude that transsaccadic memory contains a small number of integrated identity plus position codes along with "unlocated" identity codes for the rest of the items in the display.

This conception of transsaccadic memory fits nicely within the theoretical framework for object perception proposed by Treisman (1988; see also Kahneman & Treisman, 1984; Treisman & Gormican, 1988; Treisman & Souther, 1985). Treisman's framework contains four levels: feature maps, which register the presence of different sensory features in the display; a master map of locations, which registers where in the display features are located; temporary object representations (object files), or episodic descriptions of what objects are where in the display, formed by conjoining features by way of attention; and a recognition network that stores descriptions of objects along with their names. This framework could account for the results of the present experiments as follows. When the presaccadic display is presented, the letter identities present in the display automatically activate their corresponding entries in the recognition network, generating "unlocated" identity codes. At the same time, the features of the letters are represented in the feature maps. Attention is directed from one array location to the next to conjoin the features and to produce an object file (i.e., an integrated identity plus position code) for each letter. Within this framework, transsaccadic memory would consist of the object files that were produced before the saccade and of residual activation in the recognition network. The results of the present research indicate that only three to four object files survive a saccade; an interesting correspondence is that Kahneman, Treisman, and Gibbs (in press) found that only three to four object files appear to be constructed during maintained fixation as well. Perhaps this limit arises because object files are held in short-term memory. Exploring the relationship between object files and transsaccadic memory is an interesting area for further research.

In conclusion, the results of the present research indicate that our memory for the positions and identities of elements in the world is rather poor when the eyes move. We may remember the identities of objects in the environment better than where those objects are located, however. These results seem rather surprising given the properties of our perceptual experience: How could a memory with these characteristics explain why the world appears stable and continuous across eye movements? Intuitively, this perception seems to require a detailed memory for the contents of successive fixations. Instead, the converse may be true: the world may appear stable and continuous across eye movements not because a detailed memory exists but because very little is remembered from one fixation to the next. Our perceptual systems may treat each fixation relatively independently of the previous fixation and simply assume the world remains stable and unchanging across saccades (MacKay, 1973). The mental representation of the environment that is built up across eye and head movements may be fairly abstract and no more detailed than the mental representation that exists when we close our eyes. The panoramic perception that we ordinarily experience could be due to the visible contents of the current fixation rather than to some representation of previous fixations built up in memory (O'Regan & Levy-Schoen, 1983). This conclusion makes sense when one considers that fixation durations are approximately 10 times longer than saccade durations: 90% of our perceptual experience is spent in a state in which the eyes are relatively stable and an image of the world is continuously present on the retina.

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