Integration and Accumulation of Information across Saccadic Eye Movements

David E. Irwin and Rachel V. Andrews

ABSTRACT

Two experiments investigated the nature of information integration and accumulation across saccadic eye movements. In experiment 1, subjects viewed an array of colored letters while they fixated a central point; this array was erased upon initiation of a saccade to a target. Some time after the saccade, a cue was presented above or below one of the array locations and each subject attempted to report the color and the identity of the letter that had occupied the probed position. Subjects remembered 3–4 color + identity + position units across the saccade; information near the saccade target was remembered better than information appearing in other array locations. Probe delay had little effect on performance. Most errors were mislocations rather than misidentifications. Experiment 2 showed that memory for position and identity information was improved only slightly when subjects made two as opposed to one fixation on the letter array, suggesting that limited information accumulation occurs across multiple eye movements. The results are discussed in terms of a new theory of transsaccadic memory conceived within the theoretical framework for object perception proposed by Treisman (1988).

6.1 INTRODUCTION

Because the visual world contains more information than can be perceived in a single glance, 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; it is generally assumed that somehow the contents of individual eye fixations are integrated or accumulated across saccades to produce the unified and continuous perception of the visual world that we ordinarily experience. There is no feeling of “starting anew” with each fixation; rather, we remember some objects and their spatial relationships and the overall gist of a scene, even if we close our eyes. Some information from successive fixations must be maintained across eye movements (in what we will call “transsaccadic memory”) in order for this percept to be achieved. How this is accomplished has puzzled psychologists and vision researchers for over a century.

Until fairly recently, it was often assumed that something like an integrative visual buffer (McConkie and Rayner 1976) was responsible for the perception of a stable and continuous visual world across eye movements (e.g., Banks
1983; Breitmeyer 1984; Jonides, Irwin, and Yantis 1982; Trehub 1977). According to this view, the visible contents of successive eye fixations are aligned and superimposed in the buffer on the basis of their environmental or spatiotopic coordinates to produce an integrated, composite representation of the visual environment. Irwin (1992b) referred to this assumption as the “spatiotopic fusion hypothesis.”

Although the notion of spatiotopic fusion within an integrative visual buffer is intuitively appealing, it appears to be incorrect. Irwin, Yantis, and Jonides (1983) showed that subjects are unable to integrate two different visual patterns presented in the same spatial location but separated by an eye movement, that is, they are unable to perceive some composite pattern. Specifically, four dots from a $3 \times 3$ matrix of dots were presented while a subject fixated one part of a display, and then four different dots from the matrix were presented in the same spatial location after the subject made an eye movement; together, eight of the nine dots in the matrix were presented, and the subject’s task was to identify the location of the missing dot. Accuracy was very low, even though this task is very easy to perform if subjects do not move their eyes and the two frames of dots are presented to the same retinal and spatial locations. This inability to combine visual patterns across saccades has been replicated several times (e.g., Bridgeman and Mayer 1983; Irwin, Brown, and Sun 1988; O’Regan and Levy-Schoen 1983; Rayner and Pollatsek 1983). Other experiments have shown that both visual masking and visual integration across saccadic eye movements (Irwin, Brown, and Sun 1988) and pursuit eye movements (Sun and Irwin 1987) occur on the basis of retinotopic, and not spatiotopic coordinates. Furthermore, Irwin, Zacks, and Brown (1990) showed that spatiotopic summation does not occur across saccades; namely, one’s ability to detect a sine wave grating presented after a saccade is unaffected by presenting a sine wave grating with the same spatial frequency in the same spatial location before the saccade. Taken together, these findings indicate that the perception of a stable and continuous visual world across eye movements is not accomplished through the spatiotopic superposition and fusion of the visible contents of successive eye fixations.

This conclusion receives further support from the results of other studies showing that changes in the visual characteristics of words and pictures (such as letter case and object size) and changes in spatial position across eye movements frequently are not detected and have little or no disruptive effect on reading, word naming, or picture naming (e.g., Bridgeman, Hendry, and Stark 1975; McConkie 1991; McConkie and Zola 1979; Pollatsek, Rayner, and Collins 1984; Pollatsek, Rayner, and Henderson 1990). Such changes should be quite disruptive if spatiotopic fusion occurs across saccades. In sum, many empirical findings demonstrate that a literal representation of the entire visual scene does not survive a saccadic eye movement, as the spatiotopic fusion hypothesis suggests. Furthermore, recent neurophysiological evidence indicates that stimulus locations are coded in terms of oculocentric rather
than spatiotopic coordinates across saccades (Colby, chap. 7, this volume; Duhamel, Colby, and Goldberg 1992). Thus it appears that there is no internal, spatiotopically integrated stimulus representation that can explain the continuity and stability of visual perception (see also O’Regan 1992). Some other answer must be sought.

Given the demise of the spatiotopic fusion hypothesis, recent research has begun to examine what and how information is accumulated across eye movements. Even though detailed, literal images of successive fixations are not integrated across saccades, several studies have shown that at least some visual information is remembered from one fixation to the next. For example, Palmer and Ames (1992) found that subjects could make precise discriminations between lines of different lengths and shapes of slightly different sizes even when the stimuli were viewed in separate fixations. Irwin, Zacks, and Brown (1990) found that subjects could determine accurately whether two dot-patterns viewed in successive fixations were identical or different, even when the two patterns appeared in different spatial positions across the saccade. This result indicates that some visual information is maintained across eye movements in a location-independent format. However, Hayhoe, Lachter, and Feldman (1991) found that subjects could judge precisely whether or not three points viewed in successive fixations (one point per fixation) formed a right triangle, indicating that, when the task requires it, precise spatial information about several points can be held in a maplike representation across multiple eye movements.

Several other studies have shown that higher-order structural aspects of the stimulus information influence memory across eye movements. For example, Carlson-Radavsky and Irwin (1995) found that structural descriptions, rather than edge-based representations, are retained across eye movements. A structural description is a hierarchical representation whose top level corresponds to a figure as a whole, and whose lower levels represent specific parts of the figure and connections that specify the relations of the parts to each other (e.g., Hummel and Stankiewicz, chap. 5, this volume; Marr 1982; S. E. Palmer 1977; Sutherland 1968). Subjects in this study performed three different tasks. In one, they had to determine whether a part viewed in one fixation was present in a whole viewed in a second fixation; in another, they had to determine whether a whole viewed in one fixation was identical to a whole viewed in a second fixation; in the third, they were required to integrate a part viewed in one fixation with a part viewed in a second fixation and then compare this integrated representation with a presented whole figure. In all three tasks the structural characteristics of the parts and wholes affected performance in a manner consistent with the use of structural descriptions. Additional evidence for the maintenance of higher-order structural information across eye movements was reported by Verfaillie, De Troy, and Van Rensbergen (1994), who found that violations of biological motion in a point-light display were detected better than other kinds of motion violations when they occurred during a saccade.
Priming of long-term memory representations also occurs across saccades. For example, Rayner, McConkie, and Zola (1980) found that a word presented in the parafovea of one fixation facilitated naming latency for a word viewed foveally in a subsequent fixation if the two words shared the same beginning letters, regardless of letter case. Pollatsek et al. (1992) found that shared phonemic codes also provided a preview benefit. Pollatsek, Rayner, and Collins (1984) and Pollatsek, Rayner, and Henderson (1990) also found evidence for visual feature and abstract conceptual priming of pictures viewed during successive fixations. In addition, Henderson (1992) found that a parafoveal preview of an object facilitated its identification in a subsequent fixation, while Boyce and Pollatsek (1992) found that scene context facilitated object identification across saccades.

While these studies have provided important insights into the kinds of information that are maintained across eye movements, other studies have examined the capacity and time course of transsaccadic memory. Irwin (1991) found that accuracy in the pattern discrimination task used by Irwin, Zacks, and Brown (1990) was highly dependent on pattern complexity, such that simple dot-patterns were recognized more accurately than complex dot-patterns. Varying the temporal interval separating the two patterns from 0 to 5 seconds, however, had very little effect on performance. As in Irwin, Zacks, and Brown (1990), spatially displacing one pattern relative to the other had no effect on recognition accuracy. These results indicate that transsaccadic memory is, at least in part, a limited-capacity, location-independent, long-lasting memory like visual short-term memory.

Additional support for this conclusion was provided by Irwin (1992a), whose subjects were presented with an array of letters in one fixation and a partial-report cue (e.g., an arrow) in a second fixation, after an eye movement had occurred. Subjects were required to report the letter that had occupied the spatial location indicated by the report cue; in order to respond correctly, they had to remember the position and the identity of the cued letter across the eye movement. Irwin (1992a) found that memory was rather poor; subjects could remember only 3–4 letters (i.e., position + identity units) across an eye movement, regardless of the number of letters (6 or 10) presented in the letter array. Report of the letters spatially near the saccade target was much more accurate than report of other letters in the array, however, suggesting that attention, which precedes the eyes to a saccade target (Shepherd, Findlay, and Hockey 1986), determined which information was stored in transsaccadic memory. Delaying the partial report cue from 40 to 750 ms after the eye movement had only a slight effect on report accuracy, suggesting little loss of information over time. Intra-array errors (erroneous report of a noncued letter from the array) were much more frequent than extra-array errors (erroneous report of a letter not contained in the array), suggesting that identity information may be retained better than location information when the eyes move. To account for these results, Irwin (1992a) proposed that a small number (3–4) of integrated position + identity codes were held.
in short-term memory across the saccade, while priming of “unlocated” identity codes in long-term memory also occurred, producing the preponderance of intra-array errors over extra-array errors. That is, if subjects were unsure what the probed letter was, unprobed items in the array would be more available in memory than unpresented items, leading to location (intra-array) errors rather than intrusion (extra-array) errors.

Based on these results, and following up on a suggestion by Kahneman, Treisman, and Gibbs (1992), Irwin (1992a) proposed a new theory of transsaccadic memory within the conceptual framework for object perception proposed by Treisman (1988) and Kahneman and Treisman (1984). This framework contains four levels of representation: (1) feature maps, which register independently the presence of different sensory features in the display, such as color and shape; (2) a master map of locations, which registers where in the display features are located; (3) temporary object representations or object files, (episodic descriptions of what objects are where in the display), which are formed when attention conjoins features into unitary wholes (e.g., colored shapes); and (4) an abstract, long-term recognition network, which stores descriptions of objects along with their names. This theory accounts for the results of Irwin (1992a) as follows. When a letter array is presented, the letter identities in the array automatically activate their corresponding entries in the recognition network, generating “unlocated” identity codes; at the same time, the shapes of the letters are represented in a feature map. Attention is directed from one array location to the next to produce an object file (i.e., an integrated identity + position code) in short-term memory for each letter. Because attention ordinarily precedes eye movements, object files for letters near the saccade target are more likely to be created than object files for letters at other positions in the array. Given the limited capacity of short-term memory, only a small number (3–4) of object files (integrated position + identity codes) can be retained across the saccade; priming of the unlocated identity codes in long-term memory makes it more likely that subjects will erroneously report an item from the array rather than an unpresented item when the subject is unsure of the correct response. In sum, according to Irwin (1992a), transsaccadic memory consists of the object files that are produced before a saccade and of residual activation in long-term memory.

The conception of transsaccadic memory proposed by Irwin (1992a), which we will call the “object file theory of transsaccadic memory,” is undetailed in many respects; nonetheless, it provides a useful framework for investigating how and what information is maintained across saccadic eye movements. In particular, it makes several specific predictions that can be tested experimentally (it should be emphasized that these predictions are based on Irwin’s 1992a instantiation of the ideas of Kahneman and Treisman, who might not agree with all of the predictions). First, objects (rather than spatial locations, say) should be the fundamental organizing units for representing and maintaining information across saccades. Second, attention should play a critically important role in determining what information is stored in
transsaccadic memory because it controls which object files are created. Third, only a limited number of object files should be created and maintained across a saccade because of short-term memory limitations. Fourth, because object files are held in (relatively) slow-decaying short-term memory, there should be little loss of information from transsaccadic memory over short (<5 sec) retention intervals. Fifth, surface characteristics (e.g., color, form) of at least some of the elements in a display (specifically, the attended ones) should be maintained in transsaccadic memory because object files are formed when attention conjoins the features present at a display location into a unitary whole, containing both pre- and postcategorical information (Kahneman, Treisman, and Gibbs 1992). Note that, according to the object file theory, relatively little information actually accumulates across saccades; rather, one's mental representation of a scene consists of mental schemata and identity codes activated in long-term memory and of a small number of detailed object files in short-term memory.

The experiments reported below used the transsaccadic partial report technique of Irwin (1992a) to investigate further the nature of information retained across eye movements and to test some of the predictions of the object file theory of transsaccadic memory. The first experiment examined whether surface characteristics of the elements in the presaccadic fixation (e.g., color) are maintained across a saccade; whether these characteristics remain bound together over time; and the role of attention in memory for such information. The second experiment examined transsaccadic memory for multiple fixations, to determine whether information accumulates across saccades.

6.2 EXPERIMENT 1

This experiment investigated whether color information is retained with item identity information across a saccade. On each trial the subject fixated a central point on an empty screen, then a saccade target appeared in the left or right periphery. Simultaneous with saccade target onset, two rows of three letters each were presented, as in Irwin (1992a). Each letter appeared in a different color. The letters were presented until a saccade was initiated to the saccade target (approximately 340 ms). After a delay of either 50, 150, or 750 ms, during which the saccade was completed and fixation was established and maintained on the saccade target, a bar marker was presented above or below one of the positions previously occupied by a letter. The subjects’ task was to report the identity and the color of the letter indicated by the marker. Accuracy of letter report and of color report was measured as a function of probe delay, and the accuracy of color report conditionalized on correct letter report was calculated for each delay in order to determine whether, and for how long, color information is retained with identity information in transsaccadic memory. To allow a comparison of memory within and between fixations, data from a no-saccade control condition were also collected.
The object file theory of transsaccadic memory predicts that subjects should remember 3–4 identity + position + color units across the saccade; that is, letter report and color report should be nonindependent because all of the information at a given spatial location in the array should be conjoined via attention into a unitary object file. Accuracy for items near the saccade target should be higher than for items at other array locations because of attention preceding the eyes to the saccade target. There should be little effect of interstimulus interval on performance because the object files are held in short-term memory. The contingency between letter report and color report should also remain relatively constant over interstimulus interval because information in the object files should remain bound together over time. When an incorrect response is made, intra-array errors (report of a noncued item present in the array) should be more common than extra-array errors (report of an unpresented item) because of identity code activation in long-term memory; however, there should be no contingency between letter identity and letter color on intra-array error responses because these responses reflect priming of long-term memory representations rather than specific, episodic properties of the stimulus display.

Method

Subjects  Ten subjects, including the authors, participated in this experiment. Except for Irwin, the subjects were undergraduate and graduate students at the University of Illinois. Most of them had participated in previous eye movement experiments. Except for the authors, the subjects were naive about the experimental hypotheses. The subjects were paid $5 per hour for their participation and received a 1-cent bonus for each correct response.

Stimuli  The stimuli consisted of letter arrays containing six colored letters arranged in two rows and three columns. The letters were drawn randomly without replacement on each trial from the set: D, F, J, L, N, S, T, Z. The colors were drawn randomly without replacement on each trial from the set: light cyan, red, blue, magenta, brown, green, yellow, and white. An asterisk (*) appearing above (top row) or below (bottom row) one of the array locations was used as the partial-report cue.

Apparatus  Stimuli were presented on a NEC MultiSync 3FGx color monitor equipped with a monitor lens that reduced screen reflectance. A Gateway2000 486 50 MHz microcomputer controlled stimulus presentation with a SVGA graphics adaptor and collected subjects’ keyboard responses. The computer also recorded the output from an Applied Science Laboratories Model 210 scleral reflectance eye tracker by means of an analog-to-digital converter. The eye tracker was mounted on eyeglass frames that were held in place on the subject’s head by a headband. The eye tracker was configured to
record horizontal movements of the left eye only. Eye position was sampled once each ms. 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 eye tracker under these conditions was $+/−0.3$ degree.

During the experiment, subjects were seated 57 cm from the display monitor. At this viewing distance, the total display area subtended 26 degrees of visual angle horizontally and 19.7 degrees vertically. The letter arrays were presented in the center of the display area. The letter arrays subtended 4.3 degrees horizontally and 2.2 degrees vertically. Each letter was 0.3 degrees wide and 0.7 degrees high; the spaces between letters were 1.7 degrees horizontally and 0.8 degrees vertically. The asterisk used as the bar probe was 0.3 degree wide and 0.4 degree high; it was presented 0.2 degree above or below the target letter position. Calibration, saccade target, and fixation points used during the experiment subtended 0.2 degree horizontally and 0.4 degree vertically.

Characters were presented in graphics mode (640 × 200), using the default font which presents characters in an 8 × 8 grid. Colors were chosen from the standard PC color palette to be maximally discriminable from each other. The display background was light gray, while the calibration, saccade target, and fixation points were dark gray.

**Procedure**  Each subject completed several preliminary procedures before participating in the eye movement experiment proper. The purpose of these was to familiarize the subjects with the stimuli and with the partial report task. First the subjects were shown the letter and color sets that would be used in the experiment. They were instructed to use the following color names to refer to the colors; “sky” for light cyan, “red” for red, “blue” for blue, “purple” for magenta, “orange” for brown, “green” for green, “yellow” for yellow, and “white” for white. These names were chosen so that each color could be referred to by a unique beginning initial, S, R, B, P, O, G, Y, and W, respectively, when subjects typed their color responses into the computer keyboard. Subjects were given several minutes to study these materials, and then they completed 50 trials in which a single colored letter was flashed for 100 ms on the display monitor. After each presentation, subjects entered the letter they had seen and the beginning initial of the letter’s color name into the computer keyboard. Half of the subjects responded letter first, color second, while the other half responded color first, letter second. Order of response was constant for an individual subject throughout all practice and experimental sessions. A chart listing the letter set and the color set (including names and initials) was present throughout all sessions. Accuracy on letter and color naming was greater than 90 percent for all subjects in this familiarization task, indicating that they were able to use the response coding scheme accurately and that they had no serious color vision deficiencies.
Next each subject completed 50 partial report trials while maintaining fixation on a central point. During these trials a $2 \times 3$ array of colored letters was presented for 250 ms; then the bar probe was presented for 33 ms immediately after stimulus offset. Probe position varied randomly from trial to trial. Each subject completed 180 more partial report trials while maintaining fixation, but on these trials the probe delay was either 50, 150, or 750 ms. Probe position and probe delay varied randomly from trial to trial. By the end of these practice blocks, subjects had become very familiar with the basic partial report task, the experimental stimuli, and the response scheme. Following this exposure they were introduced to the eye movement (transsaccadic) version of the partial report task; the procedure for these trials is described next.

The sequence of events for a typical trial in the transsaccadic partial report task is depicted in figure 6.1; note that the letters appeared in color. 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 sec, and the subject was instructed to fixate each carefully. Eye position at each location was sampled (at a rate of 1,000 Hz) for 100 ms

![Diagram](image)

**Figure 6.1** Schematic illustration of procedure for trials in saccade condition of experiment 1.
near the middle of this interval. These recordings served to calibrate the output of the eye tracker against spatial position.

After calibration, the first fixation point was presented, always where the second (central) calibration point had appeared. The subject was instructed to fixate this point carefully. After 1.5 sec, 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. As described earlier, the six letters were chosen without replacement from a set of 8 consonants, and they were displayed in six different colors, also chosen from a pool of 8 alternatives. Two rows of three uppercase letters each were presented, with one letter situated 0.2 degree above and another letter situated 0.2 degree below each of the three calibration locations. The letters were presented until a saccade was initiated to the saccade target (mean = 339 ms). Saccade onset was defined as a change in eye position in the same direction with a velocity greater than 50 deg/sec for three consecutive ms. After the offset of the letter array, a delay of either 50, 150, or 750 ms elapsed before the bar probe was presented for 33 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 identity and the color of the letter that had occupied the probed position; these responses were typed into the computer keyboard, using the coding scheme described earlier.

In order for a trial to be acceptable, the subject's eye movement had to have a latency between 100 and 700 ms. 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. Trials in which the eyes were not within 1.0 degree of the central fixation point when the letter array was presented and trials in which a saccade was made in the wrong direction (away from the saccade target) were also discarded. In total, 19 percent of the trials were discarded for one or more of these reasons.

Each subject completed six blocks of 36 trials each in the transsaccadic partial report task. Saccade direction (left and right), probe delay (50, 150, and 750 ms), and probe position were sequenced randomly across trials but were balanced within each block for each subject. Each subject completed several practice blocks of eye movement trials before completing the six experimental blocks. Data collection was spread over two experimental sessions, with three blocks per session.

Following the completion of these eye movement trials, each subject completed a no-saccade control session during which the letter arrays and bar
probes were viewed while the subject maintained fixation on the central fixation point. The exposure duration for each subject was set equal to the mean saccade latency (hence exposure duration) that the subject produced during the eye movement trials. Each subject completed 180 trials in this session, balanced for probe delay and probe position.

Results

Preliminary analysis of the eye movement data showed that mean saccade latency (hence stimulus exposure duration) and mean saccade duration did not vary significantly with saccade direction or across probe delays. Mean saccade latency was 339 ms (s.e. = 14 ms) and mean saccade duration was 27 ms (s.e. = 1 ms).

On each trial, subjects attempted to report the identity and the color of the item that had appeared in the probed position. Order of report (identity first, color second vs. color first, identity second) was included as a factor in all of the analyses reported below, but it had no significant effect on performance in any analysis and so will not be discussed further.

Table 6.1 shows the percentage of response outcomes as a function of probe delay for both the saccade condition and the no-saccade control condition. A separate analysis of variance (ANOVA) was conducted on each response outcome, with probe delay as the single factor. The most common response outcome was for both the identity and the color of the probed item to be recalled correctly (mean = 60.7 percent); this outcome declined as probe delay increased, $F(2,16) = 22.8, p < .001$. Correct identity report with incorrect color report (mean = 11.2 percent) increased with probe delay, $F(2,16) = 17.8, p < .001$, as did the percentage of trials in which both the identity and the color of the probed item (mean = 14.3 percent) were reported incorrectly, $F(2,16) = 16.3, p < .001$. The percentage of trials in which the identity of the probed item was reported incorrectly but its color

<table>
<thead>
<tr>
<th>Table 6.1</th>
<th>Percentage of Response Outcomes as Function of Probe Delay in Experiment 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response outcome</td>
<td>50</td>
</tr>
<tr>
<td>Identity correct, color correct</td>
<td>66.3</td>
</tr>
<tr>
<td>Identity correct, color incorrect</td>
<td>9.0</td>
</tr>
<tr>
<td>Identity incorrect, color correct</td>
<td>13.8</td>
</tr>
<tr>
<td>Identity incorrect, color incorrect</td>
<td>10.6</td>
</tr>
</tbody>
</table>
was reported correctly (mean = 13.8 percent) was constant \((F(2,16) < 1)\) across probe delays. All of the probe delay effects occurred between delays of 150 and 750 ms; there were no significant performance differences between the two shortest probe delays. As is apparent in table 6.1, there was a high degree of contingency between identity report and color report, especially at the two shortest probe delays; the probability of correctly recalling the color of the probed item, conditionalized on correct recall of the identity of the probed item, was 0.87, 0.89, and 0.75 for probe delays of 50, 150, and 750 ms. The pattern of results was similar in the no-saccade control condition, except that fewer incorrect responses were made.

It is of interest to examine in more detail the kinds of errors that subjects made because this might reveal whether some kinds of information are remembered better than others across eye movements. One way to examine the errors is to consider the identity and color responses separately, classifying the errors for each response class as either intra-array or extra-array in character. Incorrect responses were classified as intra-array errors if the reported items had not appeared at the probed positions but had appeared elsewhere in the letter array, or as extra-array errors if the reported items 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 assumed to reflect loss of identity information (e.g., Irwin and Yeomans 1986; Mewhort et al. 1981; Townsend 1973). Table 6.2 shows the percentage of correct responses,

<table>
<thead>
<tr>
<th>Response outcome</th>
<th>Probe delay (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td><strong>Saccade condition</strong></td>
<td></td>
</tr>
<tr>
<td>Identity correct</td>
<td>75.6</td>
</tr>
<tr>
<td>Identity intra-array error</td>
<td>21.5</td>
</tr>
<tr>
<td>Identity extra-array error</td>
<td>2.7</td>
</tr>
<tr>
<td>Color correct</td>
<td>80.2</td>
</tr>
<tr>
<td>Color intra-array error</td>
<td>17.5</td>
</tr>
<tr>
<td>Color extra-array error</td>
<td>2.1</td>
</tr>
<tr>
<td><strong>No-saccade condition</strong></td>
<td></td>
</tr>
<tr>
<td>Identity correct</td>
<td>91.9</td>
</tr>
<tr>
<td>Identity intra-array error</td>
<td>6.3</td>
</tr>
<tr>
<td>Identity extra-array error</td>
<td>2.1</td>
</tr>
<tr>
<td>Color correct</td>
<td>94.1</td>
</tr>
<tr>
<td>Color intra-array error</td>
<td>4.4</td>
</tr>
<tr>
<td>Color extra-array error</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 6.2 Percentage Correct and Percentage of Intra-array and Extra-array Errors for Identity Responses (Ignoring Color) and Color Responses (Ignoring Identity) as Function of Probe Delay in Experiment 1
intra-array errors, and extra-array errors for the identity responses (ignoring color) and the color responses (ignoring identity). Each of these response outcomes was analyzed separately in an ANOVA, with probe delay as the single factor.

In the saccade condition, there were significantly more correct identity responses at the two shortest probe delays than at the longest probe delay, $F(2,16) = 10.7, p < .001$. This was true for correct color responses, as well, $F(2,16) = 37.2, p < .001$. There were significantly more identity intra-array errors ($F(2,16) = 8.0, p < .005$), identity extra-array errors ($F(2,16) = 4.0, p < .05$), and color intra-array errors ($F(2,16) = 39.6, p < .001$) at the longest probe delay than at the two shortest probe delays. The slight increase in color extra-array errors as probe delay increased was not significant, $F(2,16) = 2.6, p > .10$. There were many more intra-array errors (mean = 24.1 percent for identity and 22.2 percent for color) than extra-array errors (mean = 3.9 percent for identity and 3.2 percent for color) for both identity and color responses. There was very little contingency between identity and color reports when an intra-array error occurred: The probability of reporting the color of the erroneously reported identity when an identity intra-array error occurred was 0.18, and the probability of reporting the identity of the erroneously reported color when a color intra-array error occurred was 0.19. These values are not much different from chance (0.13). In contrast, recall that there was a high contingency (0.84) between identity and color reports when a correct response was made. The pattern of results was similar in the no-saccade control condition, except that fewer errors occurred.

The data in tables 6.1 and 6.2 are averaged across letter position in the array and eye movement direction (in the saccade condition). The object file theory of transsaccadic memory predicts that accuracy should be higher for items near the saccade target than for items at other display locations because of attention preceding the eyes to the saccade target. Table 6.3 shows the percentage of identity-correct, color-correct trials as a function of probe position under both saccade and no-saccade conditions, averaged across probe delay. An ANOVA was conducted on the saccade condition data with factors of saccade direction (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). There was a significant main effect of position, $F(5,40) = 24.9, p < .001$, and a significant interaction between saccade direction and position, $F(5,40) = 18.2, p < .001$. The first two rows of table 6.3 show the means for this interaction. Report of the leftmost item in the top row (position 1) and report of the leftmost item in the bottom row (position 4) were significantly more accurate when the eyes moved to the left than when the eyes moved to the right. Similarly, report of the rightmost item in the top row (position 3) and report of the rightmost item in the bottom row (position 6) were significantly more accurate when the eyes moved to the right than when the eyes moved to the left. In sum, subjects were most
accurate at reporting the letter + color units that appeared spatially near the location to which they moved their eyes, even though these items fell on the parafovea during display presentation. Report of the items in the center of the display (positions 2 and 5) was significantly worse than report of the other items, even though the central items fell on the fovea during the presentation of the letter array.

For comparison, the last row of table 6.3 shows the percentage of identity-correct, color-correct trials as a function of probe position in the no-saccade control condition. Items in the top row (positions 1–3) were reported more accurately (83.8 percent vs. 75.6 percent) than items in the bottom row, probably reflecting an attentional bias induced by reading experience. A similar top-row advantage was found in the saccade condition as well.

**Discussion**

The results of the first experiment show that identity information and color information are remembered about equally well across an eye movement (table 6.2). Furthermore, they are remembered as integral units (e.g., colored letters), rather than as separate pieces of information (e.g., colors and letters). Thus transsaccadic memory appears to retain surface characteristics of items, such as their color, in addition to abstract identity information. Of course, it is possible that the colors were translated into abstract color names and held in that form in transsaccadic memory. If that were the case, however, one might expect that the number of identities and colors that could be maintained across a saccade would be much lower than what was observed, given the limited capacity of transsaccadic memory. To elaborate, the accuracy results can be expressed as *items remembered* by multiplying the percentage correct by the number of items in the array (Sperling 1960); this calculation shows that subjects remembered 4.0 integrated identity + position + color units at the two shortest probe delays, and 3.0 units at the longest probe delay. This is very similar to what Irwin (1992a) observed (3.9–3.2 identity + position units) when subjects had to report only letter identity. Thus it appears that there is little cost in remembering color information in addition to remembering identity information across an eye movement. Subjects appear to store integrated wholes (e.g., “red T, blue D, purple N, white J”) rather than
separate features (e.g., “red, blue, T, D”) in transsaccadic memory. This result is consistent with the hypothesis that subjects remember a limited number of integrated object files (identity + position + color units) in transsaccadic memory, as predicted by the object file theory. The high degree of contingency between identity reports and color reports on correct trials also supports this conclusion. The results show that the number of object files held in transsaccadic memory is not constant over all probe delays, however, no loss occurred during the first 150 ms after saccade onset, but one object file was lost 150–750 ms after the eyes moved.

When errors occurred, they were much more likely to involve the report of an item from the array, rather than an unpresented item. Of course, chance guessing favors intra-array over extra-array errors, because the six items presented on each trial were chosen from a pool of only eight alternatives. Thus, given that an error occurred, the likelihood of an intra-array error is 5/7, while the likelihood of an extra-array error is only 2/7. In other words, chance guessing predicts that there should be about 2.5 times as many intra-array as extra-array errors. Table 6.2 shows that, on average, there were about 6.5 times as many intra-array as extra-array errors, considerably higher than the 2.5 times expected by chance guessing. Thus it appears that location information is more likely to be lost than identity information when the eyes move. However, an analysis of the distribution of location errors showed that approximately 65 percent of them involved report of the identity or of the color of the item adjacent to the probed position, indicating that some coarse coding of location apparently survives the saccade. This was true for both the identity and the color responses. As predicted by the object file theory, there was very little contingency between identity and color reports when an intra-array error occurred. Integrated identity + color units did not “migrate” together to cause an error; rather, identity and color were independent.

Analysis of the relationship between eye movement direction and probe position on performance showed that presentation of the saccade target led subjects to shift their attention toward the items that appeared near it, increasing the likelihood that those items would be encoded into transsaccadic memory at the expense of the other items in the array. These results are consistent with the object file theory of transsaccadic memory. The inferior recall of the central items relative to the terminal items on the side opposite the saccade target is somewhat mysterious; perhaps the central items were encoded first, then bumped out of memory as the other array items were encoded.

A no-saccade control condition was included in this study so that comparisons could be made between memory within and across fixations. Accuracy in the no-saccade control condition was considerably higher than in the saccade condition; for example, averaged across probe delays, the identity and the color of the probed item were reported correctly on 79.7 percent of the trials, compared to 60.7 percent in the saccade condition. Subjects
remembered 5.3–4.0 identity + position + color units across probe delays in the no-saccade control condition, compared to 4.0–3.0 in the saccade condition. The superior performance in the no-saccade control condition occurred because subjects can make use of two kinds of memory when they do not move their eyes: “iconic” memory (a brief, retinotopic, high-capacity, veridical representation) and visual short-term memory. Because iconic memory is largely eliminated when the eyes move (Irwin 1992a; Irwin, Brown, and Sun 1988), subjects can use only visual short-term memory in the saccade condition. That accuracy at the shortest probe delay in the saccade condition was equal to accuracy at the longest probe delay in the no-saccade condition is consistent with this conclusion because iconic memory typically decays away within 500 ms of stimulus offset (e.g., Sperling 1960). Error patterns in the no-saccade control condition were quite similar to those of the saccade condition, both in terms of the predominance of intra-array errors over extra-array errors and the spatial distribution of intra-array errors near the probed position.

In summary, the predictions of the object file theory of transsaccadic memory were supported quite well by the results of the first experiment. Subjects remembered 3–4 identity + position + color units across the saccade, and letter report and color report were nonindependent on correct trials. This supports the hypothesis that all of the information at a given spatial location in the array was conjoined via attention into a unitary object file for storage in transsaccadic memory. Accuracy for items near the saccade target was higher than for items at other array locations because of attention preceding the eyes to the saccade target. Intra-array errors were much more common than extra-array errors, perhaps because of identity code activation in long-term memory; there was no contingency between letter identity and letter color on intra-array error responses, consistent with the idea that these responses reflect priming of long-term memory representations rather than specific, episodic properties of the stimulus display. That intra-array errors were distributed close to the spatial location of the probed item seems inconsistent with the conclusion that these errors are due to priming in long-term memory, however, because there is no reason to believe that coarse episodic location information should be maintained in long term memory. The implications of this finding are discussed further in the general discussion (section 6.4). Probe delay had a somewhat larger effect on memory than expected, as information loss occurred between 150 and 750 ms after saccade onset. If object files are held in short-term memory, one might expect little decay over the range of times we explored. It is known that information decays in short-term memory, however (e.g., Reitman 1974), so perhaps this result is not completely surprising.

Experiment 2 investigated a different aspect of the object file theory, the idea that information accumulation across multiple eye fixations is limited by the capacity of transsaccadic memory.
6.3 EXPERIMENT 2

This experiment examined transsaccadic memory for multiple fixations. In the first experiment the letter array was present for only one fixation, disappearing as soon as the subject initiated a saccade to the saccade target. In Experiment 2 the letter array remained visible for either 1 or 2 fixations before it disappeared and the partial report cue was presented. In the two-fixation case, the subject saccaded from the central fixation point to a saccade target on one side of the letter array (as in fig. 6.1), but then saccaded back to the central fixation point. The letter array remained visible during the first saccade and during fixation of the saccade target location, and it was not extinguished until a saccade was initiated back to the central fixation point. After some probe delay, the partial report cue was presented, and the subject attempted to report the identity of the cued letter. An array of 10 letters (2 rows of 5), rather than 6, was used to avoid potential ceiling effects. To simplify the subjects' task, the color of the letters in this experiment was not varied, so this experiment measured memory for letter identity + position information only.

Irwin's (1992a) object file theory of transsaccadic memory makes the following (perhaps counterintuitive) predictions about memory performance in this task. First, subjects should remember only 3–4 letters (i.e., position + identity units) from the array, regardless of the number of fixations they make. Second, report of the letters spatially near the final saccade target should be more accurate than report of other letters in the array, even if those letters were foveated in a prior fixation. These predictions follow from the theory's claims that only a limited number of object files can be held in short-term memory and that object file creation is determined by attentional allocation to items near the saccade target. In the absence of rehearsal, forgetting in short-term memory is first-in, first-out, so that only the final set of object files should be remembered. The bias for errors due to mislocalization rather than to misidentification should be stronger in the two-fixation condition than in the one-fixation condition because subjects have more time to identify the letters in the array and to activate their long-term memory representations.

It seemed possible that some of these predictions might be violated. Intuitively, more fixations on a display should lead to superior memory performance, and, given unlimited viewing time and an unlimited number of fixations, this would no doubt occur because the contents of the letter array could be transferred to long-term memory. Given only 1–2 fixations, however, we expected little transfer of information to long-term memory to occur. Furthermore, there is actually very little empirical support for the intuition that memory should improve with increasing number of fixations. Loftus (1972) found that long-term recognition memory for a series of pictures improved as the number of fixations per picture increased, but using
line drawings as stimuli, Tversky (1974) found the opposite result. In addition, several investigators have found that increasing exposure duration over a range that included several fixations has very little effect on whole-report performance in within-fixation studies of memory for letter arrays (e.g., Irwin and Brown 1987; Sperling 1960), which is also thought to rely on short-term memory. In fact, inverse duration effects (i.e., worse performance with increasing exposure duration) have been found in some partial-report studies (Di Lollo and Dixon 1992). Thus, even though the prediction is counterintuitive, it is not completely unreasonable.

Method

Subjects Seven subjects, including Andrews, participated in this experiment. The subjects were undergraduate and graduate students at the University of Illinois. All but two of them had participated in the first experiment. Except for Andrews, the subjects were naive about the experimental hypotheses. The subjects were paid $5 per hour for their participation and received a 1-cent bonus for each correct response.

Stimuli The stimuli consisted of letter arrays containing ten letters arranged in two rows and five columns. The letters were drawn randomly without replacement on each trial from the set of all consonants, excluding y. An asterisk (*) appearing above (top row) or below (bottom row) one of the array locations was used as the partial-report cue.

Apparatus The apparatus was the same as in experiment 1. The letter arrays subtended 4.3 degrees horizontally and 2.2 degrees vertically. Each letter was 0.3 degree wide and 0.7 degree high; the spaces between letters were 0.7 degree horizontally and 0.8 degree vertically. The asterisk used as the bar probe was 0.3 degree wide and 0.4 degree high; it was presented 0.2 degree above or below the target letter position. Calibration, saccade target, and fixation points used during the experiment subtended 0.2 degree horizontally and 0.4 degree vertically.

Characters were presented in graphics mode (640 × 200), using the default font which presents characters in an 8 × 8 grid. The display background was light gray, while the calibration, saccade target, fixation points, and letters were dark gray.

Procedure To gain familiarity with the 10-letter version of the partial-report task, each subject completed 50 partial report trials while maintaining fixation on a central point. During these trials a 2 × 5 array of letters was presented for 250 ms, then the bar probe was presented for 33 ms immediately after stimulus offset. Probe position varied randomly from trial to trial. Each subject completed 180 more partial report trials while maintaining fixation, but on these trials the probe delay was either 50, 150, or 750 ms. Probe
position and probe delay varied randomly from trial to trial. On each trial, subjects attempted to report the letter that had appeared in the probed position, as well as the position of the probe (i.e., array location 1–10). They used the numbers 1–9 and 0 to report probe position, with 1 referring to the leftmost letter in the top row and 0 (for 10) to the rightmost letter in the bottom row. By the end of these practice blocks, the subjects had become very familiar with the 10-letter partial-report task and with the response scheme. Following this exposure they were introduced to the transsaccadic version of the 10-letter partial-report task; the procedure for these trials is described next.

The sequence of events for a one-fixation trial in the transsaccadic partial-report task was very similar to that depicted in figure 6.1, except that ten letters were displayed instead of six. After a calibration sequence, the first fixation point was presented where the second (central) calibration point had appeared. After 1.5 sec, the saccade target (another +) appeared in the parafovea, 2 degrees to the left or right of the central fixation point, which remained visible. 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 target. After the offset of the letter array, an interval of 50, 150, or 750 ms elapsed before the bar probe was presented for 33 ms. Only the saccade target was visible 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; these responses were typed into the computer terminal keyboard, using the coding scheme described earlier.

The sequence of events on two-fixation trials was very similar, except that the letter array remained visible during the first saccade and while the subject fixated the saccade target. The letter array was extinguished when the subject initiated a saccade back from the saccade target to the central fixation point. An interval of 50, 150, or 750 ms then elapsed before the bar probe was presented for 33 ms. Only the central fixation point was visible during the probe delay and during probe presentation. The subject then attempted to report the letter that had occupied the probed position and the position of the probe, as in the one-fixation condition.

In order for a trial to be acceptable, the subject must have fixated the letter array between 100 and 1,000 ms in the one-fixation condition and between 100 and 2,000 ms in the two-fixation condition. Trials in which the eyes were not within 1.0 degree of the central fixation point when the letter array was initially presented and trials in which a saccade was made in the wrong direction (away from the saccade target) were also discarded. In total, 7 percent of the trials in the one-fixation condition and 11 percent of the trials in the two-fixation condition were discarded for one or more of these reasons.

Each subject also completed two no-saccade control sessions during which the letter arrays and bar probes were viewed while the subject maintained
fixation on the central fixation point. In one session (short-duration condition) the exposure duration for each subject was set equal to the approximate mean saccade latency (hence exposure duration) that the subject had produced during the one-fixation eye-movement trials (mean = 391 ms); in the other session (long-duration condition) the exposure duration for each subject was set equal to the approximate mean exposure duration (the sum of the two fixations plus the duration of the intervening saccade) that the subject had experienced during the two-fixation eye movement trials (mean = 760 ms). Eye position was monitored to ensure that subjects maintained fixation at the center fixation point throughout the presentation of the letter array and the probe. Less than 1 percent of the trials had to be deleted in each control condition for failure to maintain fixation.

In total, each subject completed six blocks of 40 trials each in the one-fixation and two-fixation transsaccadic partial-report tasks, and six blocks of 40 trials each in the short-duration and long-duration no-saccade control conditions. Probe delay (50, 150, and 750 ms), probe position, and saccade direction (in the eye movement blocks) were sequenced randomly across trials, but were balanced throughout the course of the experiment for each subject. Three subjects completed all of the one-fixation saccade trials and short-duration no-saccade trials before completing the two-fixation saccade trials and long-duration no-saccade trials, while four subjects completed all of the two-fixation saccade trials and long-duration no-saccade trials before completing the one-fixation saccade trials and short-duration no-saccade trials. Each subject completed several practice blocks of eye movement trials before completing the six experimental blocks. Data collection was spread over 9–10 experimental sessions, typically with three blocks per session.

Results

Mean saccade latency (hence mean exposure duration) was 389 ms (s.e. = 4 ms) in the one-fixation saccade condition. Mean exposure duration in the two-fixation saccade condition was 773 ms (s.e. = 8 ms), approximately twice that of the one-fixation saccade condition. Mean saccade duration was 26 ms (s.e. < 1 ms). Mean saccade latency and mean saccade duration did not vary significantly across probe delays. Because preliminary analyses showed that order of task completion (one-fixation vs. two-fixation) had no significant effect on performance, this factor was not included in any of the analyses reported below.

On each trial subjects attempted to report the letter that had occupied the probed position, and the position of the probe (array location 1–10). Accuracy for the probe position responses was examined first. A two-way ANOVA was conducted on the data from the saccade conditions with factors of number of fixations (one vs. two) and probe delay (50, 150, 750 ms). There was a significant effect of probe delay, $F(2,12) = 10.2$, $p < .005$, and a significant interaction between number of fixations and probe delay, $F(2,12) = 4.4$,
Accuracy of probe position report in the one-fixation condition was 72 percent, 80 percent, and 88 percent for probe delays of 50, 150, and 750 ms, whereas it was 87 percent, 91 percent, and 92 percent in the two-fixation condition. It is clear that subjects had some difficulty in localizing the probe in the one-fixation case, especially at the shortest probe delay. The effect of probe delay on probe localization accuracy is reminiscent of findings from the literature on visual direction constancy showing that people's ability to locate a stimulus briefly flashed just before, during, or shortly after a saccade is rather poor (see Matin 1986 for a review). The accuracy of spatial coding appears to be disrupted at least momentarily when the eyes change position. The difference between the one-fixation and two-fixation conditions is probably due to the fact that subjects were fixating the edge of the letter display when the probe was presented in the one-fixation condition, whereas they were fixating the center of the display when the probe was presented in the two-fixation condition. In support of this hypothesis, when the probe was presented at an “internal” array location (locations 2, 3, 4, 7, 8, 9), it was localized much more accurately in the two-fixation condition (91 percent) than in the one-fixation condition (70 percent), whereas number of fixations mattered little when “terminal” locations (locations 1, 5, 6, 10) were probed (88 percent vs. 94 percent for two vs. one fixations). For reasons of visual acuity and perceptual organization, it is probably easier to locate the position of a stimulus in space when it is presented to symmetric locations around a central fixation point (as in the two-fixation condition) than when it is presented to peripheral locations that vary in eccentricity in one direction from the fixation point (as in the one-fixation condition).

In contrast, a two-way ANOVA conducted on the data from the no-saccade conditions found that probe localization accuracy decreased from 98 percent to 96 percent as probe delay increased, \(F(2,12) = 3.9, p < .05\). There was no significant effect of exposure duration (mean = 96.8 percent) in the short-exposure condition and 97.2 percent in the long-duration condition) in the no-saccade conditions.

Because it seemed possible that subjects might be able to use the probe to access the appropriate location in their memory of the letter display without being able to accurately report the position of the probe (i.e., they might know that the probe appeared above the letter R, but be unsure whether R had appeared at location 2 or 3), subjects' letter responses were classified as correct if the reported letter had appeared at the probed position, regardless of whether subjects reported the position of the probe correctly. Table 6.4 shows accuracy of letter report as a function of probe delay for the one-fixation and two-fixation saccade conditions, the corresponding results for the no-saccade control conditions, and error breakdowns for each condition.

Separate ANOVAs were conducted on the saccade and no-saccade conditions on the percentage of correct letter reports. Letter report was slightly, but not significantly, more accurate in the two-fixation saccade condition (mean = 46 percent) than in the one-fixation saccade condition (mean = 43
Table 6.4  Percentage Correct and Percentage of Intra-array and Extra-array Errors as Function of Probe Delay in Experiment 2

<table>
<thead>
<tr>
<th>Condition</th>
<th>Probes delay (ms)</th>
<th>50</th>
<th>150</th>
<th>750</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Correct letter reports</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-fixation saccade</td>
<td></td>
<td>45.9</td>
<td>43.3</td>
<td>39.9</td>
</tr>
<tr>
<td>Two-fixation saccade</td>
<td></td>
<td>46.1</td>
<td>48.9</td>
<td>41.4</td>
</tr>
<tr>
<td>Short-duration no-saccade</td>
<td></td>
<td>67.4</td>
<td>66.1</td>
<td>52.6</td>
</tr>
<tr>
<td>Long-duration no-saccade</td>
<td></td>
<td>66.9</td>
<td>63.7</td>
<td>54.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Intra-array errors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-fixation saccade</td>
<td></td>
<td>46.1</td>
<td>50.4</td>
<td>49.3</td>
</tr>
<tr>
<td>Two-fixation saccade</td>
<td></td>
<td>45.7</td>
<td>42.0</td>
<td>46.3</td>
</tr>
<tr>
<td>Short-duration no-saccade</td>
<td></td>
<td>25.0</td>
<td>27.7</td>
<td>38.0</td>
</tr>
<tr>
<td>Long-duration no-saccade</td>
<td></td>
<td>25.6</td>
<td>27.0</td>
<td>37.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extra-array errors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-fixation saccade</td>
<td></td>
<td>7.7</td>
<td>6.3</td>
<td>11.1</td>
</tr>
<tr>
<td>Two-fixation saccade</td>
<td></td>
<td>8.3</td>
<td>8.9</td>
<td>12.0</td>
</tr>
<tr>
<td>Short-duration no-saccade</td>
<td></td>
<td>7.9</td>
<td>6.6</td>
<td>9.7</td>
</tr>
<tr>
<td>Long-duration no-saccade</td>
<td></td>
<td>8.1</td>
<td>9.3</td>
<td>8.7</td>
</tr>
</tbody>
</table>

percent), $F(1,6) = 1.5; p > .25$. Accuracy of letter report declined as probe delay increased, $F(2,12) = 3.9; p < .05$; accuracy was lower at the longest probe delay (40 percent) than at the two shorter probe delays (46 percent). Similar results were obtained in the no-saccade conditions. Letter report accuracy was 62 percent in both the short- and long-exposure conditions ($F < 1$), but declined from 66 percent at the two shortest probe delays to 53 percent at the longest probe delay, $F(2,12) = 23.8; p < .001$. Thus memory during maintained fixation was superior to memory across fixations, as in experiment 1, but neither making an additional fixation on the letter array nor viewing the letter array for a longer duration during a single fixation increased the number of letters that subjects could remember from the display.

Errors were classified as intra-array or extra-array, as in experiment 1, and each error class was analyzed in a separate ANOVA. There were significantly more intra-array errors in the one-fixation saccade condition (48 percent) than in the two-fixation saccade condition (45 percent), $F(1,6) = 9.7, p < .025$. There was no effect of probe delay. Number of fixations had no effect on the percentage of extra-array errors (8 percent vs. 10 percent), $F < 1$, but there were significantly more extra-array errors at the longest probe delay (12 percent) than at the two shortest probe delays (8 percent), $F(2,12) = 4.7, p < .05$. In the no-saccade conditions, there was no effect of exposure duration on the percentage of intra-array or extra-array errors, but there were more intra-array errors at the longest probe delay than at the two shortest probe delays, $F(2,12) = 9.4, p < .005$. As in experiment 1, most of the intra-array errors (55 percent) in the saccade conditions and 61 percent in the
Table 6.5  Percentage of Correct Letter Reports as Function of Probe Position in Experiment 2

<table>
<thead>
<tr>
<th>Condition</th>
<th>Probe position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>One-fixation saccade</td>
<td>78.5</td>
</tr>
<tr>
<td>Two-fixation saccade</td>
<td>87.3</td>
</tr>
<tr>
<td>Short-duration no-saccade</td>
<td>66.6</td>
</tr>
<tr>
<td>Long-duration no-saccade</td>
<td>64.0</td>
</tr>
</tbody>
</table>

Note: Results are averaged across top and bottom rows of the array. Probe position in the saccade conditions refers to position relative to the initial saccade target (1 = saccade target location, 5 = side opposite the saccade target location). Probe position in the no-saccade conditions refers to columns 1–5 in the letter array (1 = leftmost, 5 = rightmost).

no-saccade conditions) involved report of a letter adjacent to the probed position, suggesting some coarse coding of location information in memory.

The effect of saccade direction and probe position on accuracy of letter report was also examined. Because of the large number of positions and conditions involved, the results were averaged across rows (top and bottom) in the letter array. The positions were then coded as being either in the direction of the initial saccade or in the direction opposite the initial saccade and the data collated, based on that classification; the results are shown in table 6.5. For the saccade conditions, position 1 reports the average percentage correct for the positions above and below the initial saccade target, averaged over saccade direction. Position 3 reports the average percentage correct for the position in the center of the letter display, averaged across rows and saccade direction. Recall that this position corresponds to the location of the second saccade target in the two-fixation condition. Position 5 reports the average percentage correct for the array location furthest removed from the initial saccade target, averaged across rows and saccade direction. Positions 2 and 4 refer to the intermediate positions. For comparison, the results of the no-saccade condition, averaged across rows only, are also shown. For the no-saccade conditions, “position” refers to columns 1–5 of the letter array (1 = leftmost, 5 = rightmost), averaged across rows.

Table 6.5 shows that letter report was more accurate when the position above or below the initial saccade target (position 1) was probed than when other array locations were probed, $F(4, 24) = 34.6, p < .001$. This was true for both the one-fixation and two-fixation saccade conditions. Accuracy was next highest for the letter position furthest removed from the saccade target in the one-fixation condition, but in the two-fixation condition it was next highest for the middle position (the target of the return saccade). Accuracy of letter report was better for every probe position except for the one furthest removed from the initial saccade target (which dropped dramatically) in the two-fixation condition than in the one-fixation condition, $F(4, 24) = 6.5, p < .001$. Thus, even though there was little improvement in overall letter report
accuracy as number of fixations increased in the saccade condition, there was a big difference in which letter positions were available in memory. In contrast, report of the middle position was always most accurate in the no-saccade conditions, and there were no effects of exposure duration.

Discussion

As predicted, the accumulation of information across multiple eye fixations was limited by the capacity of transsaccadic memory. Even though subjects identified the position of the probe more accurately in the two-fixation condition than in the one-fixation condition, letter report was only slightly more accurate when two fixations were made on the letter display (46 percent) than when only one fixation was made (43 percent). Subjects remembered 4.6 to 4.0 position + identity units across probe delays in the one-fixation condition and 4.6 to 4.1 units in the two-fixation condition. This is more than they remembered in experiment 1 (4.0 to 3.0), but not much more. These results provide good support for the object file theory of transsaccadic memory. It is important to note that the theory does not predict that information accumulation across multiple fixations will never occur, but only that it will be limited to approximately four items. If subjects were presented with a sparsely populated display containing widely separated items, such that only one item could be identified within a single fixation (as in the study of Hayhoe, Lachter, and Feldman 1991 described in the introduction), then accumulation across multiple eye fixations should occur, up to the capacity limit of transsaccadic memory. Because four items could be identified within a single fixation in the present experiment, no additional accumulation occurred in subsequent fixations (although which items were remembered did change, as the position analyses showed).

Other results provide mixed support for the theory. We predicted that report of the letters spatially near the final saccade target would be more accurate than report of other letters in the array, because of attentional allocation and the limited-capacity nature of transsaccadic memory. In support of the theory, even though the total number of position + identity units remembered across eye movements was constant, the array positions that were remembered changed if two fixations rather than one were made on the letter display. Memory for every position except for the position furthest removed from the initial saccade target improved in the two-fixation condition; memory for that position dropped precipitously. It was not the case that letters near the final saccade target location were recalled best in the two-fixation condition; rather, letters near the initial saccade target location retained their advantage. One problem with this analysis is that there is no independent measure of where attention was allocated in the letter display; we merely assumed that it always preceded the eyes to the saccade target. The question of attentional allocation and how it affects the encoding of information into transsaccadic memory is a complex one that requires further investigation.
We also predicted that extra-array errors would decrease when two fixations rather than one were made on the letter array, because subjects would have more time to identify the letters in the array and to activate their long-term memory representations. This did not occur. Rather, the percentage of intra-array errors decreased in the two-fixation condition relative to the one-fixation condition; there was actually a slight increase in extra-array errors in the two-fixation case. This is inconsistent with the object file theory of transsaccadic memory. As in experiment 1, most of the intra-array errors involved report of a letter spatially near the probed position. This, too, is awkward for the theory in its present form.

The no-saccade control conditions were included in this study to measure any differences that might arise merely as a result of longer processing time in the two-fixation as opposed to the one-fixation saccade condition; they also allow comparisons to be made between memory within and across fixations. As in experiment 1, accuracy in the no-saccade control conditions was considerably higher than in the saccade conditions, but it did not vary with exposure duration. This replicates other studies that have examined the effects of exposure duration on partial report (e.g., Irwin and Brown 1987; Irwin and Yeomans 1986). Interestingly, the performance advantage in the no-saccade conditions seems to be due to more accurate position coding in memory. Table 6.5 shows that there is essentially no difference in the percentage of extra-array errors made within and across eye fixations, but there is a large difference in the percentage of intra-array errors. What “iconic” memory appears to do is maintain high-fidelity position information; when it decays, or when it is eliminated by an eye movement, this precise spatial information is lost.

6.4 GENERAL DISCUSSION

The goal of the present research was to investigate the nature of information integration and accumulation across saccadic eye movements by testing some of the predictions of Irwin’s (1992a) object file theory of transsaccadic memory. This theory claims that only a limited number of feature-integrated, episodic descriptions of objects are retained across a saccade in short-term memory, with residual activation of unlocated identity codes for other objects in long-term memory. The theory predicts that 3–4 integral objects should be remembered across a saccade; objects near the saccade target should be remembered better than objects at other locations because of attention; little loss of information should occur over time; mislocation errors should be more prevalent than misidentification errors; and information accumulation over multiple fixations should be limited by the capacity of transsaccadic memory.

In experiment I, subjects viewed an array of colored letters while they fixated a central point. This array was erased upon initiation of a saccade to a saccade target. Some time after the saccade, a bar probe was presented above or below one of the array locations and subjects attempted to report the color
and the identity of the letters that had occupied the probed positions. To do this accurately, subjects had to integrate the probe with some representation of the positions, identities, and colors of the letters in the display. Subjects remembered 3–4 color + identity + position units across the saccade. Information near the saccade target was remembered better than information appearing in other array locations. Probe delay had little effect on performance. Most errors were due to mislocations rather than to misidentifications.

Experiment 2 investigated the accumulation of position and identity information across saccades. In the “one fixation” condition, procedure was similar to experiment 1. Subjects viewed an array of letters until they initiated a saccade to a target; some time after the saccade, they were probed to report the contents of one of the letter positions. In a second condition (“two fixation”) the array of letters remained visible during the saccade and during a second fixation on the letter display, and disappeared only when a saccade was initiated back to the central fixation point. Some time after this second saccade, subjects were probed to report the contents of one of the letter positions. Memory for position and identity information was improved only slightly in the two-fixation condition, relative to the one-fixation condition, suggesting that information accumulation across multiple eye movements is limited by the capacity of transsaccadic memory (approximately four items). In sum, the predictions of the object file theory of transsaccadic memory were largely supported by the results of the present research. Two results were unexpected, however. First, we expected the number of misidentifications to decrease as the number of fixations increased in experiment 2 because of greater activation of identity codes in long-term memory. This did not occur. Second, analysis of the spatial distribution of mislocation errors showed that the vast majority of the errors involved report of an item spatially near the probed item. If mislocation errors are due to residual activation of unlocated identity codes in long-term memory, as Irwin (1992a) proposed, there is no reason to expect this to occur; rather, the errors should have been randomly distributed over array locations. Both of the unexpected results call into question the idea that mislocation errors occur because of the presence of unlocated identity codes in long-term memory.

To account for these results, we propose the following revision to Irwin’s (1992a) model. Most of the elements of the model remain intact, but mislocation errors are attributed to a different source. According to the revised model, when a display is presented, the features in the display are represented in the visual system in feature maps that register the presence of different sensory features (e.g., color, shape) in the display; in addition, a master map of locations registers the precise spatial location of each feature in the display (e.g., Treisman 1988). However, unlike Treisman’s model, our revised model assumes that coarse or partial location information is registered with each feature as well. Cohen and Ivry (1989, 1991) proposed this modification to Treisman’s model based on several visual search and illusory conjunction experiments, and we adopt it here. As before, we assume that attention must
be directed from one array location to the next to conjoin features and to obtain precise spatial location information from the master map of locations to produce an integrated object file (e.g., for displays like those used in experiment 1, an identity + color + position unit). Note that letter shape, rather than letter parts, are assumed to be features in this account. We propose, as before, that a limited number of these object files can be maintained in short-term memory. According to our revised model, when the eyes move, the links between the feature maps and the master map of locations are disrupted (e.g., retinal positions change), so that precise spatial information about the locations of the features is lost. The coarse location information registered with each feature in the feature maps is still available, however, as long as the feature itself is available (presumably feature maps also decay with time after stimulus offset). In sum, according to the revised model, performance in the transsaccadic partial-report task is based on the object files that are produced before the saccade and of residual activation in the feature maps, rather than in long-term memory. The revised model accounts for the same phenomena that the original model did, but in addition it now accounts for the two unexpected results as well. Persistence of shape information in the feature maps explains why mislocations are more prevalent than misidentifications, and coarse coding of spatial location in the feature maps explains why mislocation errors are distributed spatially near the correct item.

Note that although the revised model proposes that performance in the transsaccadic partial report task is based on a limited number of object files and on residual activation in coarsely coded feature maps, we still believe that a complete account of transsaccadic memory must include activation of long-term memory representations as well. This seems necessary to account for the results of Rayner, Pollatsek, Henderson, and colleagues discussed in the introduction, and for recent results reported by Henderson and Anes (1994). The relationship between these representations and object files requires further investigation.

One final comment concerns the relationship between the object file theory of transsaccadic memory and the perception of a stable visual world across eye movements. If transsaccadic memory consists of a few object files and of residual activation in feature maps and in long-term memory, why does the world appear stable and continuous across eye movements? Intuitively, this perception would seem to require a detailed memory for the contents of successive fixations. Irwin (1992a,b) argued that this intuition may be exactly backward; the world may appear stable and continuous across saccades not because a detailed memory exists but because very little is remembered from one fixation to the next. According to this account, instability across saccades would be detected only if one of the few objects encoded in transsaccadic memory were involved; otherwise, stability would be assumed by the perceptual system (cf. MacKay 1973). Very recent research provides support for this argument (Currie et al. 1994; see also Irwin et al. 1994; McConkie and Currie 1993). In this research we have found
that the perception of stability across eye movements depends critically on whether the object to which the eyes are sent maintains its spatial position. If this object changes its position during a saccade, instability is usually perceived; if this object maintains its position, then stability is usually perceived—even if everything else in the scene changes position! Thus the perception of stability across saccades seems to depend on a very local evaluation process centered on the saccade target object, which is the object most likely to be stored in transsaccadic memory. In sum, the object file theory of transsaccadic memory may provide a unified account for the nature of information integration across saccades and for the perception of a stable visual world across eye movements. It would be interesting to know whether the spatial representation in parietal cortex investigated by Colby (chap. 7, this volume) codes only a few stimulus locations (as opposed to an entire display), with a bias to code the saccade target location. Such a finding would provide a satisfying neurophysiological corollary to the behavioral data reported above.

NOTE

This research was supported by National Science Foundation Grant SBR 93-09564 to David E. Irwin. We thank Carol Colby, Jon Driver, John Duncan, Mel Goodale, John Hummel, Art Kramer, Gordon Logan, and Jay McClelland for helpful comments on the research, and Natalie Lambajian and Corey Medders for assistance with data collection. Correspondence concerning the chapter should be addressed to David E. Irwin, Department of Psychology, University of Illinois at Urbana-Champaign, 603 East Daniel Street, Champaign, Illinois 61820 (E-mail: dirwin@s.psych.uiuc.edu).

REFERENCES


