the beliefs and desires of other people.

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Notes

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2. Not all object individuation is plausibly viewed as emerging from an innate object module. In particular, the identification of objects in a static scene draws on a person's prior experience with the objects and on sensitivity to cues such as discontinuities in color and texture. These are the same factors that apply for the individuation of nonobject entities such as parts, suggesting that the procedures for nonobject individuation can sometimes extend to objects as well. Note, however, that although infants are sensitive to object properties such as spatiotemporal continuity, the ability to exploit these other types of cues is not present early in development (for discussion, see Baillargeon & Hanko-Summers, 1990; Spelke, Breinlinger, Jacobson, & Phillips, 1993). This developmental dissociation suggests that although the two modes of individuation might sometimes apply to the same entities (objects), they are nonetheless distinct.

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Integrating Information Across Saccadic Eye Movements

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We make rapid eye movements called *saccades* about three times each second in order to examine the world around us. The still periods between saccades are called *fixations*. The average fixation is approximately 300 ms in duration, whereas the average saccade is only 30 ms in duration. We make saccades in order to direct the fovea of the eye, which provides our clearest vision, at objects of interest in the environment. Saccadic eye movements create problems for perception because visual information sweeps across the back of the eyes during each saccade; as a consequence, objects in the world have different positions on the retina from one fixation to the next. Even though the visual input is continually changing in this way, we ordinarily perceive the world as a coherent whole, with objects maintaining their positions in space. There is no feeling of "starting anew" with each fixation; rather, we remember the positions and the identities of at least some of the objects in a scene, even if we close our eyes.

Psychologists and vision researchers have wondered for more than a century how this quality of perception is achieved. One frequently proposed hypothesis is that visual information acquired during individual eye fixations is accumulated across saccades. This view assumes the existence of a *transsaccadic memory* that combines the information from successive eye fixations in such a way that a percept of a stable and continuous visual world is produced. In this article, I summarize research that my colleagues and I have conducted during the past 15 years to explore the properties of this hypothetical transsaccadic memory. When we began our research, we believed that we would find that the entire visual contents of each eye fixation are accumulated in transsaccadic memory. Instead, we have found that surprisingly little information is accumulated across saccades, but information at some spatial locations is remembered much better than information at other spatial locations. In particular, information about the object to which the eyes are sent with each new saccade (i.e., the *saccade target object*) is much more likely than any other information to be stored in transsaccadic memory, and that information plays a critical role in the perception of stability across saccadic eye movements.

THE VISIBLE CONTENTS OF SUCCESSIVE FIXATIONS ARE NOT COMBINED ACROSS SACCADES

When we started our work in the early 1980s, it was widely believed that the perception of a stable visual world occurred because successive "snapshots" of individual eye fixations were combined and accumulated across saccades. This view was expressed most clearly by McConkie and Rayner (1976), who proposed that the visible contents of each eye fixation were stored according to their positions in space (as opposed to their positions on the retina) in an *integrative visual buffer*. When the eyes moved, the contents of the new eye fixation were assumed to combine with the contents of previous eye fixations in the buffer to produce an integrated, composite representation of the visual environment.

Yantis, Jonides, and I attempted to test the hypothesis that transsaccadic memory has the properties of an integrative visual buffer. We reasoned that such a store would make it possible for people to combine a visual pattern presented during one eye fixation with a different visual pattern presented during a second eye fixation. Provided that the two patterns were presented in the same region of space, they should combine into a percept of a composite visual pattern. For example, in one experiment (Irwin, Yantis, & Jonides, 1983), we presented 12 dots from a 5 × 5 matrix of dots in one region of a display while the subjects fixated a different part of the display (Fig. 1). When the subjects started to move their eyes to the 12 dots, we erased the dots from the screen.[2] When the eyes landed, we presented 12 different dots from the matrix in the same spatial region where the first 12 dots had appeared. Considered together, 24 of the 25 dots in the matrix were presented, and the subjects' task was to report the location of the missing dot.

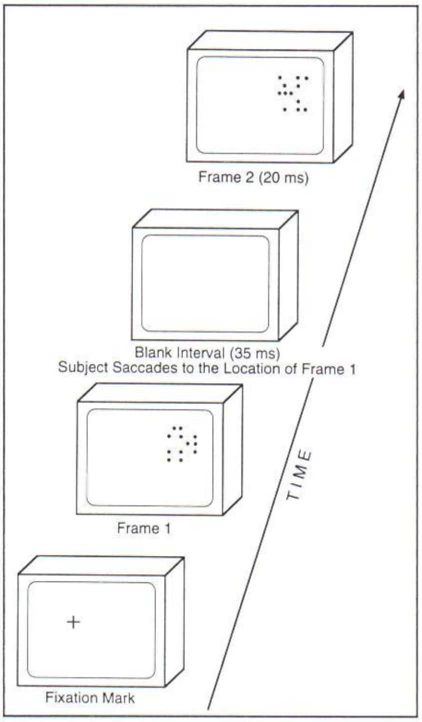

Fig. 1. Schematic illustration of the procedure used by Irwin, Yantis, and Jonides (1983) to investigate whether visual patterns can be integrated across saccades. Twelve dots randomly chosen from a 5 × 5 dot matrix were presented on one side of the display while the subject looked at a central fixation point. When a saccade to the dot pattern was initiated, the pattern and the fixation point disappeared from view. Thirty-five ms later, after the completion of the saccade, 12 different dots from the 5 × 5 dot matrix were presented in the same region of space as the first dot pattern. Across the two patterns, 24 of the 25 dots in the matrix were presented. The subject's task was to report the location of the missing dot.

Note that although the two sets of dots overlapped in space, they stimulated different regions of the retina because of the eye movement. Thus, this task required subjects to combine the two sets of dots according to their spatial positions to perceive an integrated pattern. This is exactly the operation that the integrative visual buffer was hypothesized to perform, so we expected that subjects would indeed experience a percept of an integrated 24-dot display and that they would be able to report with high accuracy the location of the missing dot. Instead, we found Across the two patterns, 24 of the 25 dots in the matrix were presented. That accuracy was very low.[3] There was no experience of visual integration of the two patterns, and performance was no better than that obtained in a control condition in which the two sets of dots were presented side by side to the stationary eye, so that they overlapped neither on the retina nor in space. The same results were obtained when 15-dot and 9-dot patterns were used. In short, there was no evidence that subjects can combine visual information across saccades in the way predicted by the hypothesis that transsaccadic memory operates as an integrative visual buffer.[4] Similar findings have been reported by Bridgeman and Mayer (1983), O'Regan and Levy-Schoen (1983), and Rayner and Pollatsek (1983).

A potential flaw with this study is that it required subjects to integrate visual information that changed during the saccade (i.e., two different visual patterns). It seemed possible that the integrative visual buffer might not operate under these circumstances, given that it may be counterproductive to arbitrarily combine new information with old. To examine this possibility, Zacks, Brown, and I used a task that involved summation of visual information about the same stimulus across a saccade (Irwin, Zacks, & Brown, 1990). The stimuli we used were grids of alternating dark and light fuzzy lines (*sine wave gratings*).

In a sine wave grating, the frequency with which the lines alternate from dark to light (which determines the relative width of the lines) is known as the *spatial frequency* of the grating. Spatial frequency is usually expressed in *cycles per degree,* which refers to the number of dark-light alternations in 1° of visual angle (i.e., 1 cycle equals one dark bar and one light bar). The *contrast* of the grating can be varied by adjusting the difference in brightness between the dark and the light lines. If the contrast is reduced (i.e., the difference in brightness between the dark and the light lines becomes small), it becomes difficult to perceive the stimulus as a grating. For every spatial frequency, and for every subject, there is a minimal contrast (the *contrast threshold*) below which the subject will not see the bars in the grating; instead it will appear to be a blank field. We reasoned that the contrast threshold for a grating presented after a saccade to some location should be different if a grating with the same spatial frequency (as opposed to a different spatial frequency) was presented in the same spatial location before the saccade. If visual information summates across saccades in an integrative visual buffer, the light bars and the dark bars in the two gratings should combine to produce an integrated percept when the two gratings have the same spatial frequency.

Our procedure is shown in Figure 2. On each trial, a grating of some spatial frequency was presented while the subject fixated a nearby point. When the subject began an eye movement toward the grating, it disappeared from the display. It was replaced a short time later by either a blank field or a target grating of some spatial frequency. Subjects had to report whether a blank field or a grating had been presented. The contrast of the target grating was varied across trials so that we could determine its contrast threshold.

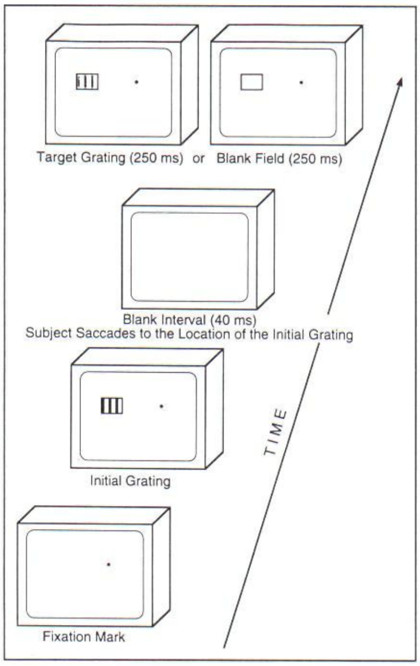

Fig. 2. Schematic illustration of the procedure used by Irwin, Zacks, and Brown (1990) to investigate whether summation of visual information occurs across saccades. A grating with a spatial frequency of either 0, 3, or 8 cycles per degree was presented on one side of the display while the subject fixated a point on the other side of the display. When a saccade to the grating was initiated, it disappeared from view. Forty ms later, after the completion of the saccade, a target grating of 3 cycles per degree or a blank field was presented in the same spatial location as the first grating. The subject's task was to report whether a grating or a blank field had appeared.

Contrary to the predictions of the integrative visual buffer hypothesis, the contrast threshold of the target grating was the same regardless of whether the target had the same spatial frequency as the first grating or a different spatial frequency. Thus, again we found no evidence that visual information summates across saccades in the manner predicted by the hypothesis that transsaccadic memory operates as an integrative visual buffer.[5]

Taken together, these findings indicate that the perception of a stable and continuous visual world across eye movements is not accomplished by accumulating and integrating the visible contents of successive eye fixations in a spatially defined integrative visual buffer (see Irwin, 1992b, for a more thorough review). This conclusion is supported further by the results of other studies which have shown that changes in visual characteristics of words and pictures (such as letter case and object size) and changes in spatial positions of objects 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, & Stark, 1975; McConkie & Zola, 1979; Pollatsek, Rayner, & Henderson, 1990; Rayner, McConkie, & Zola, 1980). Such changes would be quite disruptive if the contents of successive fixations were integrated across saccades because the contents of the old and new fixations would mismatch. Thus, it appears that there is no internal, highly detailed, spatially integrated stimulus representation that can explain the continuity and stability of visual perception.

PROPERTIES OF TRANSSACCADIC MEMORY

Having discarded the notion that transsaccadic memory operates as an integrative visual buffer, my colleagues and I have recently begun to investigate the fundamental properties of transsaccadic memory by examining what information is remembered across eye movements and how it is remembered.

One series of experiments examined the time course and form in which information is represented, as well as the capacity of transsaccadic memory. These questions were addressed by requiring subjects to compare a visual pattern viewed during one fixation with a visual pattern presented during a second fixation (Irwin, 1991). The procedure was similar to that shown in Figure 1, except that subjects were required to compare the two patterns, rather than to integrate them into a composite pattern. On each trial, a random-dot pattern was presented in the near-periphery while the subject viewed a central fixation point. When the subject began a saccade to the pattern, it disappeared, to be followed some time later by a second pattern that was either identical to the first pattern or different by the movement of a single dot. The subject had to report whether the two patterns were identical or different.

When the pattern contained 8 dots chosen randomly from a 4 × 4 matrix, subjects were correct about 70% of the time. I also varied the complexity of the patterns and found that accuracy was higher for simple (e.g., symmetric) patterns than for complex (e.g., asymmetric) patterns. In addition, accuracy was higher when 6-dot patterns were used than when 8- or 10-dot patterns were used. These results indicate that transsaccadic memory has a limited capacity. Varying the temporal interval that separated the two patterns from 1 ms to 5,000 ms had little effect on the subjects' accuracy, suggesting that information can be held in transsaccadic memory for a relatively long duration. Displacing one pattern in space relative to the other also had no reliable effect on performance, indicating that at least some information in transsaccadic memory is stored in a location-independent format.[6] These characteristics (limited capacity, long duration, location-independent representation) suggest that transsaccadic memory may rely in large part on visual short-term memory, which has similar properties (see also Carlson-Radvansky & Irwin, 1995).

Further insights into the properties of transsaccadic memory have come from a series of experiments using a *partial-report* technique (Averbach & Coriell, 1961). Partial report has been used by many researchers to study memory within a single eye fixation. In such experiments, the subject maintains fixation on a central point while a display of letters is presented briefly. Some time after the letters disappear, a short vertical line (a *partial-report cue*) is presented near one of the previously occupied letter locations. The subject must respond with the name of the letter that had appeared in the cued location. Because the location probed by the partial-report cue varies randomly across trials, the subject must remember the positions and the identities of all the letters in the display in order to respond with perfect accuracy. Typically, one finds that report is very accurate when the cue appears immediately after the letters disappear, but accuracy declines quickly as the cue is delayed before leveling off. This decline in accuracy occurs because memory for the contents of the letter display fades before the partial-report cue is presented. These results have been interpreted as evidence for two kinds of memory within individual fixations: a short-duration, high-capacity store (traditionally called *iconic memory*) and a long-duration, limited-capacity store (short-term memory).

Because accurate performance in the partial-report task relies on memory for the positions and the identities of the elements in a display, this technique seemed appropriate for studying transsaccadic memory, which appears to maintain exactly this kind of information. Thus, in one study (Irwin, 1992a), the subject was presented with an array of letters while fixating a central point (Fig. 3). The letters disappeared when the subject started a saccade to another point (the saccade target) that appeared at one side of the letter array. Some time after the eye movement, while the subject fixated the saccade target, a partial-report cue was presented near one of the array locations, and the subject attempted to report the letter that had appeared at the cued location. The position and the identity of the cued letter had to have been stored in transsaccadic memory for the subject to respond correctly.

Memory was rather poor when a saccade intervened between the offset of the letter display and the onset of the partial-report cue. Only 3 to 4 letters (i.e., position-plus-identity units) could be remembered across a saccade, regardless of the number of letters (6 or 10) presented in the letter array. When the location just above or just below the saccade target was cued for report, however, letter report was much more accurate than when other array locations were probed. Subsequent experiments

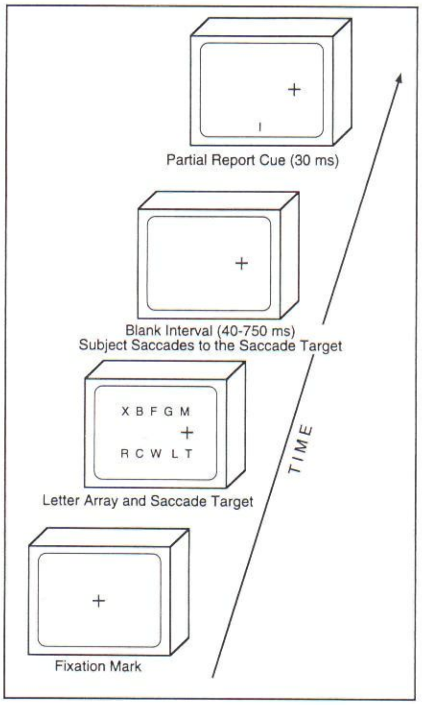

Fig. 3. Schematic illustration of the transsaccadic partial-report procedure used by Irwin (1992a). A 2 × 5 matrix of letters and a saccade target (a plus sign at one side of the letter array) were presented while the subject fixated a central point. The letters disappeared when the subject initiated a saccade to the saccade target. After 40, 120, or 750 ms, during which time the subject completed the saccade and fixated the saccade target, a partial-report cue was presented above or below one of the letter locations, and the subject attempted to report the letter that had appeared in that location.

have shown that this difference in performance occurred because attention preceded the eyes to the saccade target, thereby influencing what information was stored in transsaccadic memory. Delaying the partial-report cue from 40 ms to 750 ms after the eye movement had only a slight effect on report accuracy, suggesting that little information was lost over time.

Analysis of the kinds of errors that subjects made suggested that information about letter identity may be remembered better than information about letter location in transsaccadic memory. Because subjects were required to respond on every trial, there were only two kinds of errors they could make. They could report a letter that had appeared in the display, but not at the cued location (*mislocation error*); or they could report a letter that had not appeared in the display (*misidentification error*). We found that mislocation errors were much more frequent than misidentification errors, suggesting that subjects remembered what letters had been presented in the display, but forgot exactly where those letters were located. Analysis of the spatial distribution of mislocation errors showed that the vast majority of them involved report of an item spatially near the cued location, however, suggesting some coarse coding of location information in transsaccadic memory.

In another study (Irwin & Andrews, in press), we used the partial-report technique with arrays of colored letters and found that there was little cost in remembering color information in addition to remembering identity information across a saccade: Subjects remembered three to four color-plus-identity-plus-position units. This finding suggests that transsaccadic memory stores integrated object representations (e.g., colored letters), rather than separate features (colors and letters).

In another experiment, the letter array remained visible during the saccade to the saccade target and disappeared when the subject saccaded back to the central fixation point, so that the subject viewed the letter array for two saccades rather than one. Memory for position and identity information was improved only slightly, indicating that information accumulation across multiple saccades is limited by the capacity of transsaccadic memory to about four items. This finding contradicts the common intuition that a rich and elaborate mental representation of the visual environment is built up over the course of several eye fixations.

AN OBJECT-FILE THEORY OF TRANSSACCADIC MEMORY

Based on the findings summarized here, I (Irwin, 1992a; Irwin & Andrews, in press) have proposed an *object-file theory of transsaccadic memory* conceived within the theoretical framework for object perception proposed by Kahneman and Treisman (1984). This framework maintains that to explain the perception of objects, one must assume the existence of four levels of representation: *feature maps*, a *master map of locations*, temporary object representations called *object files*, and an abstract *long-term recognition network*.

According to the object-file theory of transsaccadic memory, when a display is presented, the features in the display are represented in the visual system in feature maps that register the presence of various 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. Unlike Kahneman and Treisman (1984), I assume that coarse or partial location information is registered with each feature as well (see Cohen & Ivry, 1991). Attention must be directed to a display location to combine the separate features and to obtain precise spatial location information from the master map of locations to produce an integrated object file (e.g., in the case of the partial-report experiments, an integrated shape-plus-color-plus-position unit; note that letter shapes, rather than letter parts, are treated as features in this account). Because attention precedes the eyes to the saccade target, object files for display locations near the saccade target are more likely to be created than are object files for other display locations. Only a limited number (three to four) of these object files can be maintained when the eyes move because of short-term memory limitations. Object files make contact with information stored in the abstract long-term recognition network, however, so that activation of long-term memory representations can also occur across saccades (Henderson & Anes, 1994; Pollatsek et al., 1990).

Because only three to four object files are remembered across a saccade, the subject will make an error if a location for which there is no object file is probed for report. To explain why mislocation errors are more common than misidentification errors, the theory assumes that the links between the feature maps and the master map of locations are disrupted when the eyes move, 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, so that mislocation errors are distributed spatially near the correct item. In sum, I propose that transsaccadic memory consists of the object files that are produced before the saccade and of residual activation in the feature maps and in the long-term recognition network.

PERCEIVING A STABLE VISUAL ENVIRONMENT

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 seems to require a detailed memory for the contents of successive fixations. This intuition may be exactly backward, however; 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. The experience of a panoramic visual environment may be generated by the contents of individual eye fixations, rather than by some detailed internal representation (O'Regan & Levy-Schoen, 1983). After all, as mentioned in the introduction, fixation durations are approximately 10 times longer than saccade durations; thus, during 90% of a person's perceptual experience, a relatively stable image of the world is continuously present on the retinas.

According to the object-file theory of transsaccadic memory, the perception of instability across saccades should be experienced only if one of the few objects encoded in transsaccadic memory is changed during the saccade; otherwise, stability should be assumed by the perceptual system (cf. MacKay, 1973). A recent study provides support for this hypothesis (Currie, McConkie, Carlson-Radvansky, & Irwin, 1995). While subjects made a saccade to an object in a picture, either the entire picture, just the object, or just the background behind the object was shifted in space. Detection of the shift depended critically on whether the object to which the eyes were sent (the saccade target object) maintained its spatial position. If this object changed its position during the saccade, the shift (i.e., instability) was usually perceived; however, if this object maintained its position, then stability was usually perceived even if everything else in the picture changed position!

In sum, the perception of stability across saccades appears to depend on a very local evaluation process centered on the saccade target object, which is the object that is most likely to be stored in transsaccadic memory (see Deubel & Schneider, 1994, for a similar view). Thus, the object-file theory of transsaccadic memory appears to provide a unified account of the nature of information integration across saccades and of the perception of a stable visual world across eye movements.

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Notes

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2. In all the experiments reported in this article, the stimuli were presented on video display terminals, and eye position was monitored with an eyetracker; both were interfaced with a high-speed computer that allowed us to change the contents of the display when the subject's eye position changed.

3. Initially (Jonides, Irwin, & Yantis, 1982), we found that accuracy in this task was quite high, but these results turned out to be due to a phosphor persistence artifact on our display screen.

4. The dot-integration task can be performed with high accuracy when the two sets of dots are presented in the same retinal and spatial positions during maintained fixation; with the appropriate timing parameters, one does perceive a unified 24-dot pattern instead of two separate patterns (Di Lollo, 1980). This finding demonstrates the existence of a detailed visual memory (often called visible persistence) that is coded with respect to retinal position. The results of Irwin, Yantis, and Jonides (1983) show that there is no analogous memory that is coded with respect to spatial position (see also Irwin, Brown, & Sun, 1988).

5. In no-saccade control conditions in which the first grating and the target grating were presented to the stationary eye, we found that the contrast threshold of the target grating was very different when it had the same as opposed to a different spatial frequency as the first grating. This finding demonstrates that summation of visual information can occur when the gratings stimulate the same region of the retina. The results of Irwin, Zacks, and Brown (1990) show that there is no analogous summation based on spatial position alone.

6. 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. This ability also appears to be capacity-limited, however, because performance declines precipitously when the positions of six points, rather than three, have to be remembered (Lachter, Hayhoe, & Feldman, 1991).

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