Visual memory and the perception of a stable visual environment

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The visual world appears stable and continuous despite eye movements. One hypothesis about how this perception is achieved is that the contents of successive fixations are fused in memory according to environmental coordinates. Two experiments failed to support this hypothesis; they showed that one's ability to detect a grating presented after a saccade is unaffected by the presentation of a grating with the same spatial frequency in the same spatial location before the saccade. A third experiment tested an alternative explanation of perceptual stability that claims that the contents of successive fixations are compared, rather than fused, across saccades, allowing one to determine whether the world has remained stable. This hypothesis was supported: Experienced subjects could accurately determine whether two patterns viewed in successive fixations were identical or different, even when the two patterns appeared in different spatial positions across the saccade. Taken together, these results suggest that perceptual stability and information integration across saccades rely on memory for the relative positions of objects in the environment, rather than on the spatiotopic fusion of visual information from successive fixations.

The visual world appears unified, stable, and continuous even though our eyes are almost constantly moving. Our eyes scan the world by way of ballistic movements, called *saccades*, that are separated by brief periods of time, called *fixations*, during which the eyes are relatively still. During a saccade, visual stimulation smears across the retinas as the eyes move at a velocity of several hundred degrees per second. This smear is not ordinarily perceived under photopic illumination conditions, a phenomenon known as *saccadic suppression*. Because of saccadic suppression, our visual information about the world is registered in discrete glimpses separated in time. From one glimpse to the next, the retinal positions of objects in the world change suddenly and dramatically as the eyes change position. A question that has puzzled psychologists and vision researchers for over a century is how the perceptual system produces the coherent, stable, and continuous representation of the visual world that we ordinarily experience given this temporally discontinuous and rapidly changing visual input. In the present paper,

we test and reject one hypothesis about how this might be accomplished and propose an alternative view.

The hypothesis we tested claims that the visible contents of successive fixations are spatially reconciled across changes in eye position and superimposed in memory according to their environmental, rather than retinal, coordinates. According to this hypothesis, when the eyes move, the contents of the previous fixation are stored in memory and mentally "shifted" to compensate for the eye movement; then they are "fused" with the contents of the new fixation to yield an integrated, composite representation of the visual environment. This *spatiotopic fusion* hypothesis has been proposed in one form or another by a variety of researchers over the years; it is implicit in the sensorimotor theories of perceptual stability proposed by Sperry (1950) and by Holst and Mittelstaedt (1950/1971), for example, and it has been explicitly proposed as a mechanism for information integration across saccades by several others (e.g., Banks, 1983; Breitmeyer, 1984; Jonides, Irwin, & Yantis, 1982; McConkie & Rayner, 1976; Trehub, 1977).

The view that the contents of successive fixations are fused in memory according to their environmental coordinates to yield a unified representation of the visual environment is intuitively appealing; it explains in a satisfying way why the world looks stable and continuous across eye movements. Unfortunately, empirical evidence regarding this hypothesis is mostly negative. For example, stimulus displacements during a saccade are detected only if the magnitude of the displacement is very large, approximately 10%-30% of the saccade amplitude (e.g., Bridgeman, Hendry, & Stark, 1975; Mack, 1970; Whipple & Wallach, 1978). Furthermore, changing the visual characteristics of words and pictures (such as letter case

and object size) during an eye movement has little or no disruptive effect on reading, word naming, or picture naming (e.g., McConkie & Zola, 1979; McConkie, Zola, Blanchard, & Wolverton, 1982; Pollatsek, Rayner, & Collins, 1984; Pollatsek, Rayner, & Henderson, in press; Rayner, McConkie, & Zola, 1980). If information integration across saccades relies on precise spatial reconciliation and superposition of visual information in memory, stimulus displacements should be readily detected and stimulus changes should be extremely disruptive. Additional negative evidence regarding the spatiotopic fusion hypothesis has been provided by several demonstrations that subjects are unable to integrate two different visual patterns to form some composite pattern when the two patterns are presented in the same spatial location but are separated by a saccade (e.g., Bridgeman & Mayer, 1983; Irwin, Brown, & Sun, 1988; Irwin, Yantis, & Jonides, 1983; Jonides, Irwin, & Yantis, 1983; O'Regan & Levy-Schoen, 1983; Rayner & Pollatsek, 1983). Such integration should be possible if the contents of successive fixations are fused in memory according to their environmental coordinates. Finally, the results of several studies once viewed as favoring the integration hypothesis (e.g., Breitmeyer, Kropfl, & Julesz, 1982; Davidson, Fox, & Dick, 1973; Jonides et al., 1982; White, 1976) have been reinterpreted in ways that don't involve the spatiotopic fusion of visual information from separate fixations (Irwin et al., 1988; Irwin et al., 1983; Rayner & Pollatsek, 1983; Sun & Irwin, 1987; van der Heijden, Bridgeman, & Mewhort, 1986).

Although the studies listed above constitute an impressive body of evidence against the spatiotopic fusion hypothesis, it is possible that the tasks employed in these investigations were simply inappropriate for demonstrating visual integration across saccades. The problem with these studies is that they required subjects to integrate information that changed during the saccade—a displaced stimulus, for example, or two different visual patterns. It's possible that the hypothetical integration mechanism doesn't work under these conditions; after all, the world rarely changes during a saccade, and, if it does, it's not very adaptive to have new information arbitrarily fused with old information. Thus, if one were to use a task that required subjects to summate information about the same stimulus across a saccade, evidence for spatiotopic fusion might be found.

Such evidence has been provided by Ritter (1976) and by Wolf, Hauske, and Lupp (1978, 1980). In Ritter's experiment, a patch of light was presented for 10 msec 4° from fixation just before the onset of a saccade, and it was presented again sometime after the saccade ended. The two light flashes were presented at the same spatial location, but they stimulated different retinal locations because of the eye movement. Nevertheless, the two light flashes were seen as a single flash if the interval separating them was less than about 75 msec; at longer intervals, two separate flashes were seen. This result suggests

the existence of a briefly lasting memory that summates visual information from successive fixations according to its spatial, rather than retinal, coordinates, consistent with the spatiotopic fusion hypothesis. An alternative explanation, however, is that, because of saccadic suppression, the offset of the light was simply not detected when it occurred during the critical 75-msec interval; saccadic suppression is known to precede and to follow the saccade by some time (Latour, 1962; Volkmann, Schick, & Riggs, 1968), so it is conceivable that it, rather than spatiotopic fusion, was responsible for Ritter's results. It should be noted that Ritter attempted to rule out saccadic suppression as an explanation by conducting a control experiment in which subjects had to detect whether a light changed its position during a saccade; but detection of light displacement during a saccade may well differ from detection of light offset, rendering this control suspect.

The results of Wolf et al. (1978, 1980) are more intriguing, however. Wolf et al. (1978) had subjects discriminate between gratings that varied in spatial frequency following a saccade to a target location. They found that the threshold for 3.2 cycles/degree (cpd) gratings decreased if a suprathreshold "priming" grating of the same spatial frequency was presented at the same spatial location before the saccade. This finding suggests a position-specific summation of visual information across saccades, consistent with the spatiotopic fusion hypothesis. Wolf et al. (1980) replicated this result and showed further that misaligning the prime and the target by 0°–180° of phase led to a monotonic decrease in performance. Thus, these two studies provide support for a visual memory capable of summating information from successive fixations based on environmental coordinates when the stimulus information (i.e., spatial frequency) remains the same during the saccade; the failure of other investigators to find evidence for spatiotopic fusion might have been due to the fact that the pre- and postsaccadic stimuli were not identical.

Before this conclusion can be accepted, however, the Wolf et al. results require reexamination. There are three aspects of their experimental procedure that are troublesome. First, some of their results might have been due to criterion shifts rather than to changes in sensitivity, because not all of their experiments used forced-choice methods for establishing threshold values. Second, the phosphor used by Wolf et al. (P31) is known to decay relatively slowly, so it is possible that their results were due to phosphor persistence on their display rather than to visual persistence in memory; this artifact has plagued other researchers in this area (e.g., Jonides et al., 1982). Finally, there was substantial retinal overlap between the pre- and postsaccadic displays in some of the Wolf et al. experiments; for example, in Wolf et al. (1978), the presaccadic fixation point was 2° to the left of the prime/target area, which subtended 8° of visual angle. If subjects saccaded to the center of this area, the leftmost 2° of the prime would overlap on the retina with

the rightmost 2° of the target; consequently, the integration found in these experiments might have been retinotopic, rather than spatiotopic, in origin.

Given these questions about the Wolf et al. results, we decided to try to replicate their findings using a similar, but improved, procedure. To eliminate concerns about criterion shifts, we employed a forced-choice procedure for estimating thresholds. To eliminate the potentially confounding effects of phosphor persistence, we presented the prime and the target on separate parts of a display that subjects viewed through electromechanical shutters; prisms and a beam-splitter were used to optically combine the prime and target images so that they appeared to occupy the same spatial position. Finally, to ensure that any integration that we found was spatiotopic, rather than retinotopic, in origin, we used a relatively small prime/target area far enough away from the presaccadic fixation point that there would be no retinal overlap between the presaccadic prime and the postsaccadic target.

EXPERIMENT 1

The purpose of Experiment 1 was to determine whether or not one's ability to detect a grating presented after a saccade is affected by a presaccadic presentation of a grating with the same spatial frequency in the same place in space. During the experiment, the subject fixated a central point and then a prime (presaccadic) grating of 0, 3, or 8 cpd was presented in the periphery; when the subject initiated a saccade to the prime, it disappeared and was replaced 40 msec later by a target (postsaccadic) grating of 3 cpd or a blank (zero-contrast) field that had the same luminance as the grating. Thus, prime and target shared the same spatiotopic coordinates but had different retinal coordinates. We used a two-alternative temporal forced-choice procedure to determine the contrast threshold for the target grating for each type of prime. The question of interest was whether the contrast threshold for the target would be different when the prime had the same spatial frequency as the target compared with when it had a different spatial frequency, as predicted by the spatiotopic fusion hypothesis and by the results of Wolf et al.

Two no-saccade control conditions were also conducted. In one, the prime and the target were presented foveally; in the other, the prime and the target were presented peripherally. In both conditions, the prime and the target shared the same retinotopic and spatiotopic coordinates. The purpose of these controls was to allow us to compare retinotopic with spatiotopic priming effects, as well as to assess the effectiveness of the peripheral presaccadic prime.

Given the forced-choice nature of our experimental task, we expected the prime to have an inhibitory, rather than facilitative, effect on contrast threshold. Inhibition (i.e., masking) was expected, because any persistence of the prime in the visual system should affect the visibility of both the blank distractor field and the target grating; by

Weber's law, this should make the discrimination of the target and the blank more difficult, thereby raising the contrast threshold for the target.

Method

Subjects. An undergraduate student (J.D.) who was naive as to the hypotheses of the experiment and two of the authors (D.I. and J.B.) participated.

Apparatus. The two beams of a Tektronix 565 dual-beam oscilloscope equipped with P31 phosphor were used to present vertical sinusoidal gratings on the top and bottom halves of the oscilloscope's display screen. One beam was used to present the prime grating on the top half of the oscilloscope screen, while the other beam was used to present the target grating on the bottom half of the oscilloscope screen. The mean luminance on both halves of the screen was constant at 52 cd/m². Independent time bases controlled the horizontal sweep of each screen (at a frame rate of 833 Hz), while the vertical sweep of each was generated by a single function generator (Circuitmate FG2), running at 500 kHz. A Digital Equipment Corporation Micro-11/23+ computer controlled the spatial frequency of the prime grating by sending analog signals to an Interstate Electronics Corporation F34 function generator; this function generator controlled the contrast of the prime grating by z-axis modulation. The microcomputer controlled the contrast and spatial frequency of the target grating by sending analog signals to a B&K Precision 3020 function generator. Contrast of the gratings is expressed in percent, given by $100(L_{max} - L_{min})/(L_{max} + L_{min})$, where L_{max} and L_{min} are the peak and trough luminances as measured by a Pritchard photometer slowly scanned across the display with a 2'-of-arc spot.

The face of the oscilloscope was masked with black construction paper, except for two rectangular regions, 1.63 cm wide and 1.27 cm high, separated vertically by 3.7 cm; the bottom beam display (target grating) was visible through the bottom rectangle, and the top beam display (prime grating) was visible through the top rectangle. A tiny hole was poked through the construction paper 3.3 cm to the right of each rectangle to serve as a fixation point.

The subjects viewed the oscilloscope monocularly with the left eye through an optical system composed of right-angle prisms, electromechanical shutters (Uniblitz model 100-2B), and a mirror-type beam-splitter (see Figure 1). The positions of the prisms and the beam-splitter were adjustable so that it was possible to align the images of the top and bottom displays such that they appeared to be perfectly superimposed. Thus, even though the prime and the target were presented on physically separated regions of the display, they appeared to the subject to be in exactly the same spatial position. The shutters were interfaced with the microcomputer and controlled the subject's view of the top and bottom displays. Viewed through the optical system, the top and bottom displays had effective luminances of approximately 21 cd/m². All of the room lights in the experimental area were turned off during experimental sessions, so the display background was effectively dark.

The subjects used a bite bar with dental impression compound to keep their heads steady during the experiment, and they viewed the displays at an optical distance of 47 cm. At this distance, the prime and target rectangles subtended 2° of visual angle horizontally and 1.6° vertically, and the fixation points were 4° to the right of each rectangle. The subject's eye position was monitored with a Gulf+Western Applied Science Laboratories Model 210 scleral reflectance eyetracker configured to record horizontal movements of the left eye only. The output of the eyetracker went to the microcomputer through analog-to-digital converters that sampled eye position at the rate of 1000 Hz.

Procedure. Each trial consisted of two observation intervals cued by tones and separated by a dark interval of 1 sec. The subject's task was to indicate which interval contained the 3-cpd target grat-
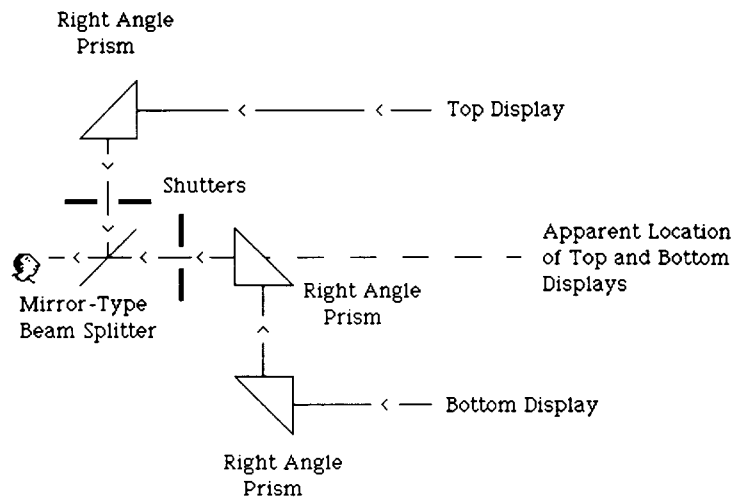
Right Angle
Prism

Figure 1. Diagram of the optical system used in Experiments 1 and 2. Stimuli were presented on the top and bottom halves of a dual-beam oscilloscope screen. Light from the bottom display was reflected by one prism up to another prism and then through a shutter to a beam-splitter that was directly in front of the subject's eye. Light from the top display was reflected down through a shutter to the beam-splitter. The optical distances between the subject's eye and the two displays were equivalent. The shutters were interfaced with a microcomputer that controlled visual access to the top and bottom displays: When the top shutter was open, only the top display was visible; when the bottom shutter was open, only the bottom display was visible. When both shutters were open, the two displays appeared to be perfectly superimposed into a single, unified display.

ing. Figure 2 portrays a schematic illustration of the sequence of events for a single observation interval with a 3-cpd prime grating in the saccade condition.

At the beginning of each trial, blank (zero-contrast) fields were presented on the top and bottom displays of the oscilloscope; both shutters in the optical system were closed, however, so the subject saw only darkness. The subject initiated the trial sequence by pressing a key on the computer terminal keyboard. Five hundred milliseconds later, the top shutter opened, revealing the fixation point and the blank prime field. Data for calibrating the output of the eyetracker against spatial position were then collected in the following way. A tone (generated by the terminal keyboard) instructed the subject to fixate the fixation point; when the subject had done so, he pressed a key on the keyboard and his eye position was sampled for 100 msec. The average of these 100 samples was used as the calibration value for the fixation point. A second tone instructed the subject to fixate the center of the blank prime field, and 100 msec of eye-position data were collected in the same way. The average of those 100 samples was used as the calibration value for the saccade target area.

Following calibration, a single tone cued the subject that the first observation interval was ready to begin. At this point, the subject fixated the fixation point again and pressed a key on the keyboard; 100 msec later, a tone sounded and the blank prime field was replaced by the prime grating (0, 3, or 8 cpd). The subject was instructed to saccade to the prime grating when the tone sounded, and sampling of eye position began with tone presentation. When saccade initiation was detected (defined as a change in eye-position velocity greater than $0.05°/msec$ for a 3-msec interval), the top shutter closed, removing the prime (and any phosphor persistence) from view. Forty milliseconds later, the 3-cpd target grating or a blank (zero-contrast) field was presented on the bottom display and the bottom shutter opened, revealing the target or blank at the same apparent position that the prime had occupied. The target or blank was exposed for 250 msec and then the bottom shutter closed, leav-

ing the viewing field in darkness. Following a 500-msec delay, blank fields were again presented on the top and bottom displays and, 500 msec later, the top shutter opened for presentation of the second observation interval. The sequence of events during this observation interval was the same as described above (i.e., calibration, prime presentation, interstimulus interval, blank or target presentation). Following the second observation interval, the subject typed "1" or "2" on the computer terminal keyboard to indicate during which observation interval the target grating had appeared. No feedback was provided. The target appeared equally often in the first and second interval in a randomly ordered fashion during a block of trials.

The subject's eye movement during both observation intervals had to meet two criteria in order for the trial to be acceptable. First, the latency to initiate the saccade to the prime/target area had to be greater than 100 msec but less than 400 msec; this criterion eliminated anticipatory eye movements that might not allow for processing of the peripheral prime and delayed eye movements indicative of attention lapses. Second, to ensure that the prime grating and the target grating overlapped only spatiotopically, and not retinotopically, the eye movement had to exceed 2° of visual angle in extent. Approximately 25% of the saccade trials were rejected for failing to satisfy these criteria.

The procedure in the two no-saccade control conditions was quite similar. As in the saccade condition, each trial contained two observation intervals. At the beginning of each interval, blank fields were presented on both displays and both shutters in the optical system were closed. The subject pressed a key to initiate the trial sequence, and, 500 msec later, a tone sounded and the top shutter opened to reveal the fixation point and the prime/target field. In the foveal no-saccade condition, the subject fixated the center of the prime/target field; in the peripheral no-saccade condition, the subject fixated the fixation point. The subject was instructed to maintain fixation throughout the experimental trial; thus, in the foveal no-saccade condition, the prime and the target were both presented

Calibration; subject fixates fixation point, then center of prime/target field

Subject fixates fixation point; presses key to start trial

Tone sounds; prime presented until subject initiates eye movement to it

40 ms delay during which eyes move to prime/target location

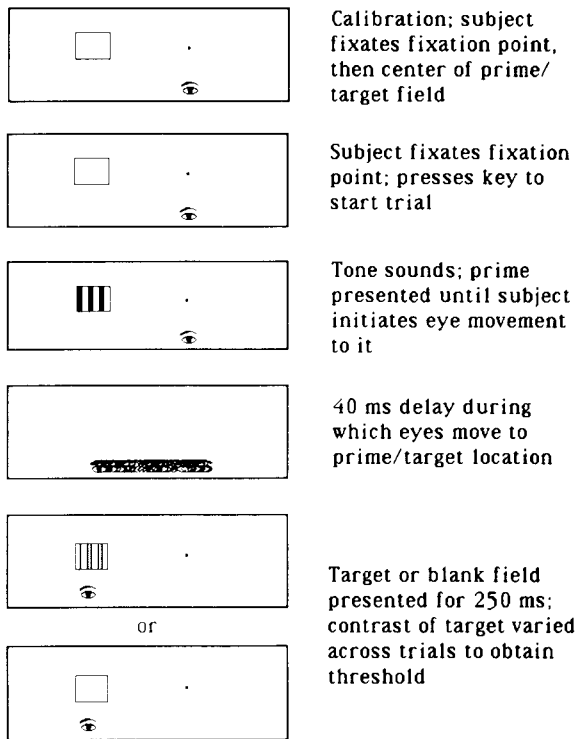Target or blank field presented for 250 ms; contrast of target varied across trials to obtain threshold

Figure 2. Schematic illustration of the procedure in each observation interval for eye-movement trials in Experiment 1. A procedure for calibrating the output of the eyetracker against spatial position was first completed, then a 2° prime grating (0, 3, or 8 cpd) was presented centered 5° from a fixation point. When a saccade to this grating was initiated, the prime disappeared and, 40 msec later, a target grating of 3 cpd or a blank field was presented in the same apparent spatial location. A two-alternative temporal forced-choice procedure was used to estimate the contrast threshold of the target.

foveally, whereas, in the peripheral no-saccade condition, the prime and the target were both presented to the peripheral retina, 4°-6° to the left of the fixation point. After the top shutter opened, the prime/target field remained blank for 1 sec (to approximate the exposure duration of this field during the calibration portion of the saccade trials), then the prime grating was presented for 250 msec (its approximate exposure duration on the eye-movement trials). The top shutter then closed, removing the prime from view. Forty milliseconds later, the target grating or the blank field was presented on the bottom display and the bottom shutter opened, revealing this stimulus in the same apparent position that the prime had occupied. The target or blank was presented for 250 msec before a tone sounded and the bottom shutter closed, leaving the viewing field in darkness. After a 1-sec delay, this sequence of events was repeated for the second observation interval, then the subject indicated on the terminal keyboard which observation interval contained the target. As in the saccade condition, no feedback was provided and the target appeared equally often in the first and second interval in a randomly ordered fashion during a block of trials.

Contrast thresholds for the target grating were estimated by a conventional staircase procedure (Levitt, 1971). In the eye-movement sessions, only trials that had acceptable eye movements in both observation intervals were used in this estimation procedure. Two correct responses in a row resulted in a decrease of the target grating's contrast, whereas each error was followed by an increase (i.e., 2:1 rule, estimating the contrast at which 71% of

responses are correct). A block of trials continued for 12 reversals of staircase direction or until 75 trials had been completed. The initial contrast for each block was based on pilot data or on the data from previous sessions; the contrast change or step size of the staircase was approximately 0.10 log units.

The spatial frequency of the prime grating (0, 3, or 8 cpd) was held constant during a block of trials. When the 3-cpd prime was used, it was presented in phase with the target grating. The contrast of the 3- and 8-cpd primes was approximately 20%. For the saccade condition, an experimental session consisted of three blocks of trials, one with each prime grating. Each subject completed three saccade sessions, with the order of prime-grating presentation counterbalanced across sessions. For the control conditions, an experimental session consisted of three blocks of foveal trials and three blocks of peripheral trials (one block with each prime grating, foveally and peripherally). Each subject completed three control sessions. Within a control session, the foveal and peripheral blocks were run separately from each other, with the order alternating over sessions. The order in which the prime gratings were presented was counterbalanced within this grouping. Data collection was spread over a period of several days, with each subject usually completing one session of trials per day. The naive subject (J.D.) completed a no-saccade practice session first, then completed the three no-saccade control sessions. Following a practice session with the saccade condition, he then completed the three saccade sessions. Subjects D.I. and J.B. completed a preliminary version of this experiment using different exposure durations and stimulus intensities before participating in Experiment 1; they received no other practice. Subject J.B. completed the three saccade sessions before completing the three no-saccade sessions; Subject D.I. intermixed saccade and no-saccade sessions.

Results

An analysis of the eye-movement data showed that the spatial frequency of the prime had no effect on mean saccade latency (255 msec), mean saccade duration (31 msec), mean saccade distance (5.1°), or mean number of eye-movement errors (11.2%). Thus, it appears that the subjects' eye-movement behavior was the same in the different prime conditions, indicating that they did not adopt different eye-movement strategies for the different primes.

Contrast thresholds for detecting the 3-cpd target were calculated by taking the average contrast values of the last 8 (J.D.) or 10 (D.I. and J.B.) staircase reversals in each block of trials (i.e., the first 2–3 reversals were omitted). Thus, the contrast threshold estimates for J.D. are based on 24 reversals per condition, and those for D.I. and J.B. are based on 30 reversals per condition. Subject J.D. had fewer reversals because he was not always able to achieve 12 reversals within a block of 75 trials. Variance estimates were calculated on the basis of the variability of the reversal points. The ranges of standard errors for each subject were: J.D., 0.014 to 0.047 log units; D.I., 0.012 to 0.035 log units; J.B., 0.020 to 0.039 log units.

The results for each subject are shown in Figure 3. This figure shows the mean contrast threshold values for detecting the 3-cpd target for each type of prime (0, 3, 8 cpd) under foveal, peripheral, and saccade conditions. In the foveal no-saccade condition, when the prime had the same spatial frequency as the target (3 cpd), the contrast threshold for detecting the target was roughly 2.5 to 5 times (i.e., 0.39, 0.50, and 0.67 log units for J.B., J.D.,
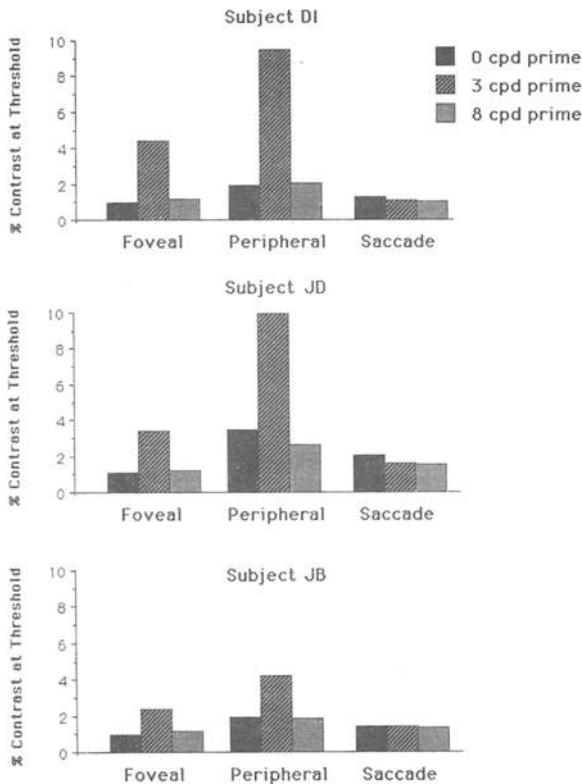
Figure 3. Experiment 1: Estimated contrast thresholds for the 3-cpd target grating as a function of the spatial frequency of the prime grating in the foveal no-saccade, peripheral no-saccade, and saccade conditions for each subject.

and D.I., respectively) higher than when the prime was a zero-contrast (i.e., 0 cpd) field. In other words, the prime with the same spatial frequency as the target caused masking. Masking occurred because the prime persisted in the visual system, so that even when the blank field was presented instead of the target, one still "saw" the prime, making the discrimination of target and blank more difficult. This result is consistent with recent work by Georgeson and Georgeson (1987) using a similar procedure. The 8-cpd prime did not differ from the 0-cpd prime (0.07, 0.05, and 0.10 log units higher for J.B., J.D., and D.I., respectively) in its effect on the contrast threshold of the 3-cpd target, consistent with other work showing little interaction between gratings whose spatial frequencies differ by an octave or more (see Olzak & Thomas, 1986, for a review). Similar results were obtained in the peripheral no-saccade condition. Contrast thresholds were higher in this condition than in the foveal condition, presumably because of the acuity limitations of the peripheral retina. Nonetheless, masking effects of approximately the same size (0.35, 0.46, and 0.69 log units for J.B., J.D., and D.I., respectively) as in the foveal condition were found for each subject when the prime and the target had the same spatial frequency, but the 8-cpd prime did not differ from the 0-cpd prime (J.B., −0.01 log units; J.D., −0.13 log units; D.I., 0.02 log units).

The results of the no-saccade control conditions demonstrate that the prime grating with the same spatial frequency as the target had, at the very least, an effect at a retinotopic level of representation; the peripheral control also shows that the prime could be resolved and could affect performance even when it was presented in the visual periphery. The main purpose of Experiment 1, however, was to determine whether or not any evidence for spatiotopic interaction across saccades could be found. In other words, was there any evidence for a masking effect when the prime and target gratings overlapped only spatially, and not retinally? Figure 3 shows that the answer to this question is negative. Contrast thresholds for detecting the 3-cpd target were the same regardless of the spatial frequency of the presaccadic prime grating. Masking effects were small (J.B., −0.02 log units; J.D., −0.10 log units; D.I., −0.07 log units) and nonsignificant for 2 of the 3 subjects [for J.B., $t(58) = 0.38$, $p > .5$; for D.I., $t(58) = 1.45$, $p > .15$]. For the third subject (J.D.), there was a significant effect [$t(46) = 2.26$, $p < .04$], but it was in the direction opposite to that predicted by the spatiotopic fusion hypothesis: The contrast threshold was actually slightly lower, rather than higher, when the prime and the target had the same spatial frequency.

Discussion

The purpose of Experiment 1 was to try to replicate the results of Wolf et al. (1978, 1980), which had provided support for the existence of a visual memory capable of summating information from successive fixations based on their spatiotopic coordinates. Using a forced-choice procedure and experimental conditions that eliminated retinal overlap of the pre- and postsaccadic gratings and artifactual contributions of phosphor persistence, we found no evidence for spatiotopic interaction across saccades. The contrast threshold for detecting a 3-cpd target grating presented after a saccade was the same regardless of the spatial frequency of a priming grating presented in the same spatial location before the saccade. Our failure to find a priming effect under these conditions is unlikely to be due to the use of an inadequate priming stimulus, because the prime had a large effect on contrast threshold when the prime and target impinged on the same region of the retina, even when that region was in the visual periphery. In sum, our results conflict with those of Wolf et al. and provide no support for the spatiotopic fusion hypothesis.

Given the acuity limitations of the peripheral retina, however, it's conceivable that only low spatial-frequency information is integrated across saccades. Thus, even though we found evidence for retinotopic integration of medium (3-cpd) spatial frequency gratings in Experiment 1 when they were presented in the visual periphery, perhaps spatial frequencies in this range do not contribute to transsaccadic integration. To solidify and extend our findings, we decided to conduct a second experiment using prime and target gratings of a lower spatial frequency (0.75 cpd).

EXPERIMENT 2

The purpose of Experiment 2 was to determine whether or not detection of a low spatial-frequency grating presented after a saccade is affected by the presaccadic presentation of a grating with the same spatial frequency in the same place in space. The contrast threshold for a 0.75-cpd grating presented after a saccade was determined for two different presaccadic primes: 0 and 0.75 cpd. For comparison, the contrast threshold for a 0.75-cpd grating presented foveally while the eyes remained still was also determined.

Method

Subjects. One of the authors (D.I.) and the naive subject (J.D.) participated as subjects in Experiment 2.

Apparatus. The apparatus used in Experiment 2 was the same as that used in Experiment 1.

Procedure. The experimental procedure was identical to that of Experiment 1, with three exceptions. First, the target consisted of a 0.75-cpd grating; second, in the saccade condition, only two priming gratings were used, 0 and 0.75 cpd; third, in the no-saccade condition, only the 0-cpd prime was used. The contrast of the 0.75-cpd prime was approximately 20%; it was presented in phase with the target grating.

Subject D.I. completed two experimental sessions, and Subject J.D. completed three sessions. Each session began with a block of 50 no-saccade trials, followed by two blocks of saccade trials (60 trials/block). The order of prime presentation alternated over sessions. The subjects dark-adapted for 5-10 min before beginning each session.

Results

Contrast thresholds for detecting the 0.75-cpd target were calculated by taking the average contrast values of the last 6 (J.D.) or 10 (D.I.) staircase reversals in each block of trials. Thus, the contrast threshold estimates for J.D. are based on 18 reversals per condition, and those for D.I. are based on 20 reversals per condition. Variance estimates were calculated on the basis of the variability of the reversal points. Standard errors ranged from 0.019 to 0.023 log units for J.D., and from 0.018 to 0.021 log units for D.I.

The results for both subjects are shown in Figure 4. This figure shows the mean contrast threshold value for detecting the postsaccadic 0.75-cpd target grating when a presaccadic prime of 0 or 0.75 cpd appeared in the same spatial location. Also shown is the contrast threshold for an unprimed (i.e., preceded by the 0-cpd prime) foveal target when no saccade occurred. The contrast thresholds were higher here than in Experiment 1, but this is expected given the lower spatial frequency of the target used in this experiment. A comparison of the foveal condition with the 0-cpd saccade condition shows that making an eye movement had a small (0.08 to 0.15 log unit) deleterious effect on contrast threshold, presumably because of saccadic suppression (a similar result also occurred in Experiment 1).

The results of Experiment 2 nicely replicate the saccade condition results of Experiment 1. For D.I., the contrast threshold for the target was 0.02 log units higher
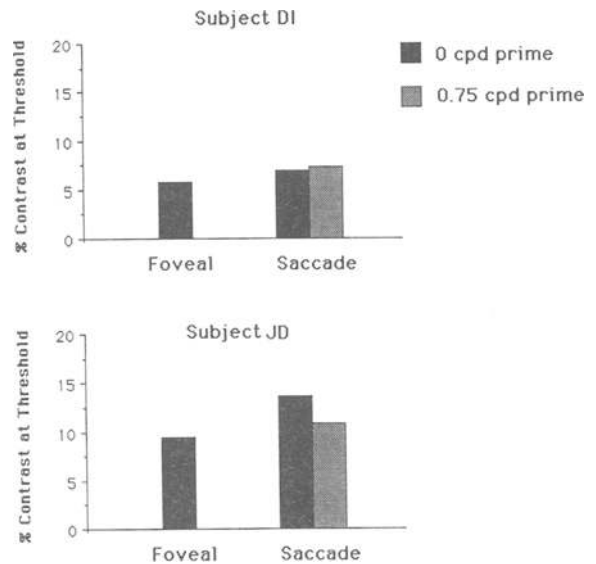

Figure 4. Experiment 2: Estimated contrast thresholds for the 0.75-cpd target grating as a function of the spatial frequency of the prime grating in the foveal no-saccade and saccade conditions for both subjects.

when the prime had the same spatial frequency as the target than when the prime was a zero-contrast field (i.e., 0 cpd). This difference is very small and not statistically significant [$t(38) = 0.77, p > .2$]. For J.D., the contrast threshold for the target was 0.10 log units lower when the prime and the target had the same spatial frequency than when the prime was 0 cpd; this difference, though small, is statistically significant [$t(34) = 3.26, p < .005$], but it is in the direction opposite to that predicted by the spatiotopic fusion hypothesis. The cause of this small facilitation (also found in Experiment 1 for this subject) is unknown. The subject reported at debriefing that it seemed more difficult to make saccades in the 0-cpd-prime condition because no visual stimulus appeared in the periphery to serve as a saccade goal (i.e., the field remained blank). There was no evidence in his eye-movement records to support this introspection, however; his saccade latencies were actually slightly faster in the 0-cpd-prime condition than in the 0.75-cpd-prime condition, and there was no difference in saccade duration, saccade distance, or saccade accuracy. Because the effect was small and in the direction opposite to that predicted by the spatiotopic fusion hypothesis, we decided not to pursue it any further.

Discussion

Experiments 1 and 2 provide no evidence for the spatiotopic fusion hypothesis. Contrast threshold for detecting a postsaccadic grating was unaffected by having a prime grating with the same spatial frequency as the postsaccadic grating appear in the same spatial location before the saccade. When prime and target overlapped on the retina, a large effect of the prime on contrast threshold

was found, even when this overlap occurred in the visual periphery; but no effect of the prime was found when prime and target overlapped only spatially, and not retinally.

Our results conflict with those of Wolf et al. (1978, 1980). We can only conclude that some nonoptimal aspect of their experimental situation (e.g., phosphor persistence, retinal overlap of prime and target across the saccade, possible criterion shifts across prime conditions) was responsible for their results; when we eliminated these potential problems, we found no evidence for spatiotopic interaction across saccades. It is possible that some other difference in experimental procedure is responsible for the different pattern of results, but we believe that our procedure should have found evidence for spatiotopic visual fusion across saccades if such fusion exists. It is also worth mentioning at this point that Subjects D.I. and J.B. completed additional blocks of trials in the saccade condition with different target-exposure durations (150–500 msec) and different stimulus intensities, with no change in results. Subject D.I. also completed a version of the saccade condition without using the optical system; in this version, the prime and the target were presented on the same display in the same spatial location, with the prime viewed presaccadically and the target viewed postsaccadically. As in the experiments reported above, contrast threshold for detecting the target was unaffected by the spatial frequency of the prime. Thus, our failure to find spatiotopic interaction across saccades was not due to some interfering effect of the optical system (e.g., shutters opening and closing, prime and target being presented on separate regions of the display).

Although inconsistent with the results of Wolf et al., our results are consistent with numerous studies (mentioned in the introduction) that also have failed to find evidence for spatiotopic fusion across saccades. A potential weakness of those studies was that they required subjects to integrate material that changed during the saccade, which may have inhibited the hypothetical fusion mechanism. The results of the present studies demonstrate, however, that even when one uses a procedure that requires the subject to integrate the same stimulus across a saccade, no evidence for spatiotopic fusion is found. We conclude that humans' perception of a stable and continuous visual world across changes in eye position is not caused by the spatiotopic fusion of successive fixations in memory.

But if successive "snapshots" of the world are not fused in memory across saccades, why does the world look stable and continuous across eye movements? Perhaps some detailed memory for the contents of a presaccadic fixation does exist, but its function is to *compare* the contents of successive fixations, rather than to fuse them into a composite whole. Such a memory could indicate whether, and how, the environment changed during an eye movement, signaling stability if no change occurred. This possibility was investigated in the next experiment.

EXPERIMENT 3

In Experiment 3, the subjects were asked to make *same/different* judgments about random-dot patterns viewed in successive fixations. Our procedure was similar to one used by Phillips (1974) to study visual memory within a single fixation. In our experiment, one pattern was presented while the subjects were fixating one part of a display, and then a second pattern was presented following a saccade to a new location. Sometimes the second pattern was identical to the first pattern, and sometimes it was different by the displacement of one dot. The subject's task was to judge whether the patterns were identical or different. Because the two patterns were presented in separate fixations, accurate performance of this task required the existence of a transsaccadic memory capable of comparing the contents of successive fixations.

Method

Subjects. Four students, who were naive as to the hypotheses of the experiment, and two of the authors (D.I. and J.B.) participated as subjects. One of the naive subjects (B.H.) was highly experienced, having participated in previous eye movement experiments. The other 3 subjects had little or no previous experience.

Apparatus. The stimuli in Experiment 3 consisted of random-dot patterns constructed by randomly choosing seven locations from a 5 × 3 array of locations. The dot patterns were presented on a Hewlett-Packard 1340A X-Y oscilloscope equipped with P31 phosphor. The microcomputer used in Experiments 1 and 2 controlled stimulus presentation by means of digital-to-analog converters. The computer also recorded the output from the scleral reflectance eyetracker used in the previous experiments. The eyetracker was configured to record horizontal movements of the right eye only. During the experiment, the subjects were seated 36 cm from the display and they used a bite bar with dental impression compound to keep their heads steady. At this viewing distance, the display field subtended 20° of visual angle horizontally and 15° vertically. The experimental area was dimly illuminated (approximately 0.5 cd/m²), so a red filter and a blue filter were lowered over the face of the display scope to reduce phosphor persistence visibility; shutter tests similar to those described by Irwin et al. (1983) and Sun and Irwin (1987) confirmed that no phosphor persistence was visible 5 msec after stimulus offset. The optical system used in Experiments 1 and 2 was not used in Experiment 3.

Procedure. The sequence of events for a typical trial is depicted in Figure 5. Each trial began with a calibration routine during which a calibration point (+) stepped across the display at five locations separated by 1.5°. 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 1000 Hz) for 100 msec near the middle of this interval. These recordings served to calibrate the output of the eyetracker against spatial position.

Following calibration, the first fixation point was presented. On rightward-movement trials (as shown in Figure 5), this point was presented where the second calibration point (hereafter, Location 2) had appeared, whereas on leftward-movement trials, it was presented where the fourth calibration point (Location 4) had appeared. The subject was instructed to fixate this point carefully. After 1.5 sec, the first fixation point disappeared and a saccade target (another +) appeared in the visual periphery. On rightward-movement trials, the saccade target appeared at Location 4; on leftward-movement trials, it appeared at Location 2. The subject was instructed to saccade to this target when it was presented. Sampling of eye position (at 1000 Hz) began with the presentation of the saccade target.

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

First fixation point presented for 1.5 sec

Saccade target presented; First matrix shown for 10 ms

Delay until subject initiates eye movement

40 ms delay during which eyes move to saccade target

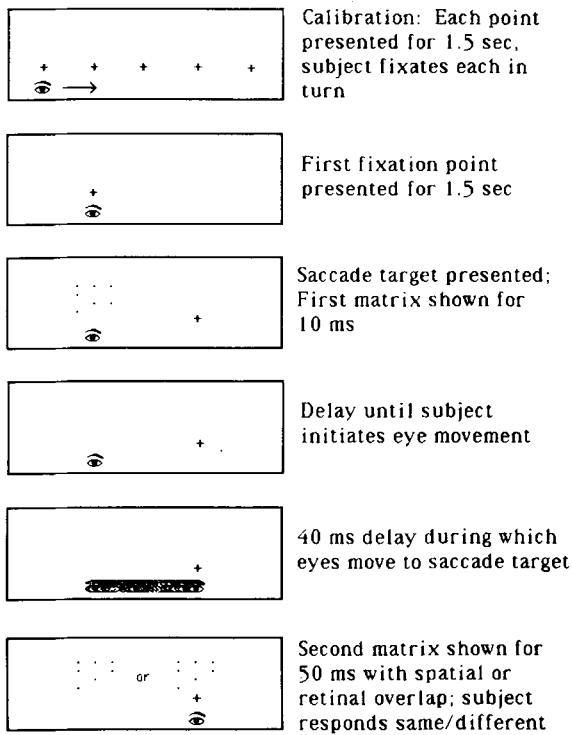Second matrix shown for 50 ms with spatial or retinal overlap; subject responds same/different

Figure 5. Schematic illustration of the procedure for eye-movement trials in Experiment 3. Following a calibration routine, a matrix of dots was presented foveally simultaneous with the onset of a saccade target. Following the saccade, a second matrix was presented either in the same spatial area as the first matrix or to the same part of the retina; the subject reported whether the two matrices were identical or different. In this trial, the correct response is "different."

Simultaneous with the onset of the saccade target, the first dot pattern was presented. This pattern consisted of seven dots randomly chosen from a 5 row × 3 column dot matrix. It was presented for 10 msec at the location of the first fixation point. The 5 × 3 dot matrix subtended 3° of visual angle horizontally and vertically (i.e., the matrix columns were separated by 1.5°).

Following the offset of the first pattern, there was a delay until the saccade toward the saccade target was detected; this delay averaged 225 msec. An additional 40-msec delay ensued to allow the saccade to reach its destination. Finally, the second dot pattern was presented for 50 msec, centered either at the location of the first fixation (so that the pre- and postsaccadic patterns appeared in the same place in space, but at different regions of the retina) or at the location of the saccade target (so that the two patterns appeared at different spatial locations, but were presented to the same [foveal] region of the retina). On half of the trials, the second pattern was identical to the first pattern; on the other half, one of the dots from the original pattern was moved to a previously unoccupied location. The subjects made their same/different response by pressing one of two keys on the terminal keyboard; no feedback was provided.

The subject's eye movement had to satisfy two criteria in order for the trial to be acceptable: First, it had to land within 1° of the saccade target; second, it had to have a latency of 100 to 300 msec. Approximately 30% of the trials failed to satisfy these criteria; they were repeated later in the block of trials. Each subject completed eight blocks of 16 acceptable trials each; these blocks were balanced for eye-movement direction (left and right), pattern overlap (spa-

tial and retinal), and response type (same and different). The first block of trials was discarded as practice.

In addition to these eye-movement trials, each subject completed two no-saccade control conditions. In one condition, the two dot patterns were presented foveally, while the subject maintained fixation at the initial fixation point. In this condition, the two patterns overlapped retinally and spatially, so accuracy should have been at its highest. This condition thus serves as an upper reference point for accuracy in the retinal overlap and spatial overlap eye-movement conditions. In the second control condition, the first dot pattern was presented foveally and the second dot pattern was presented 3° to the side as the subject maintained fixation. In this condition, the two dot patterns overlapped neither retinally nor spatially, so it served as a lower reference point for accuracy in the eye-movement conditions. Note that the first control mimicked the retinal layout of the retinal overlap eye-movement trials, whereas the second control mimicked the retinal layout of the spatial overlap eye-movement trials.

To become familiar with the same/different matching task, each subject completed 100 trials in each control condition before participating in the eye-movement condition. These data were discarded as practice. Following the eye-movement trials, the subjects completed 50 additional trials in each control condition; these data were collected in a single block of 100 trials, with condition type (overlap vs. no overlap) randomly varying from trial to trial. The exposure duration of the first pattern was 10 msec, and the second pattern was presented for 50 msec. The interpattern interval was set equal to the individual subject's saccade latency.

Results

Table 1 shows the results for each subject on retinal overlap and spatial overlap eye-movement trials, and on the retinal + spatial overlap and no-overlap control trials. These data were analyzed in a one-way ANOVA with condition (four levels) as the sole factor.

The ANOVA revealed a significant effect of condition [$F(3,15) = 12.5, MS_e = 68.2, p < .001$]. Post hoc comparisons revealed that accuracy on the retinal + spatial overlap trials was significantly higher than was accuracy in the other three conditions, which did not differ from each other. Inspection of Table 1 reveals that the three inexperienced subjects performed very poorly on the eye-movement trials; in retrospect, we should have given these

Table 1
Percentage Correct for Each Subject in
Each Condition of Experiment 3

	Conditions			
Subject	Retinal Overlap	Spatial Overlap	Retinal + Spatial Overlap	No Overlap
	Experienced Subjects			
D.I.	78.6	85.7	92.0	74.0
B.H.	82.1	75.0	96.0	86.0
J.B.	67.9	71.4	88.0	66.0
Mean	76.2	77.4	92.0	75.3
	Inexperienced Subjects			
R.M.	57.1	58.9	88.0	74.0
R.N.	51.8	57.1	90.0	76.0
C.C.	42.9	60.7	90.0	80.0
Mean	50.6	58.9	89.3	76.7
	All Subjects			
Mean	63.4	68.1	90.7	76.0

subjects much more practice in the eye-movement condition before we collected experimental data from them. An analysis of just the experienced subjects (D.I., J.B., and B.H., who was naive) yielded the same results, however. For these subjects, the effect of condition was significant [$F(3,6) = 7.0$, $MS_e = 26.6$, $p < .025$], with only accuracy in the retinal + spatial overlap condition differing from accuracy in the other three conditions. Accuracy in these 3 conditions was significantly higher than chance, however, averaging 76.3%.

Discussion

Experiment 3 shows that there is some memory for the contents of a fixation, which persists even after an eye movement to a new location has occurred: experienced subjects were able to judge at better-than-chance levels whether or not a pattern viewed before a saccade was identical to a pattern presented after the saccade. But this memory is far from perfect; performance in the eye-movement conditions was significantly worse than performance in a condition in which the two patterns were presented with retinal and spatial overlap within a single fixation, and it was not significantly better than performance in a condition in which the two patterns did not overlap. Also of interest is the fact that there was no accuracy difference between spatial overlap and retinal overlap eye-movement trials; whatever the memory is that operates across saccades, it apparently is not tied to specific spatial coordinates. Displacing the entire pattern during the eye movement (as we did in the retinal overlap condition) led to performance no different from that found when the two patterns occupied the same spatial location across a saccade. This suggests that some location-independent pattern memory is used to combine or compare information across eye movements. The fact that performance in the no-overlap control condition was identical to that in the two eye-movement conditions suggests that the same pattern memory may be used within fixations, as well as across them. There does, in addition, seem to be another memory component that contributes to even higher accuracy when the patterns overlap both spatially and retinally, but this is of little interest to us here, given our emphasis on integration across eye movements. Rather, the most important finding of Experiment 3 is the demonstration that some schematic visual information is retained across saccades in a location-independent representation.

GENERAL DISCUSSION

Why does the visual world appear stable and continuous across changes in eye position? The experiments reported above tested two hypotheses about how this might occur. The first, the spatiotopic fusion hypothesis, claims that the contents of successive fixations are fused in memory according to environmental coordinates. Experiments 1 and 2 failed to support this hypothesis. They showed that one's ability to detect a grating presented af-

ter a saccade is unaffected by the presentation of a grating with the same spatial frequency in the same spatial location before the saccade. In other words, there appears to be no position-specific summation of visual information across eye movements.

The second hypothesis we investigated claims that visual information about the contents of a fixation can be maintained across an eye movement for purposes of comparison with the contents of a succeeding fixation, allowing one to determine whether the world has changed during the saccade. Experiment 3 provided some support for this hypothesis. It showed that experienced subjects could accurately determine whether two patterns viewed in successive fixations were identical or different, even when the two patterns appeared in different spatial positions across the saccade. Thus, it appears that what subjects remember from one fixation to the next is the spatial relationships internal to a pattern as a whole, independently of the pattern's absolute location in space. This kind of memory is usually called *exocentric* (e.g., Howard, 1986) or *reatopic* (Potter, 1983). Of course, it's possible that some specifically spatiotopic memory exists in addition to this exocentric store; however, given our inability to demonstrate spatiotopic fusion or a spatiotopic advantage in pattern comparison across saccades, if such a memory exists, it must store successive fixations independently, so that the contents of new fixations do not interact with the contents of previous fixations.[1]

Generalizing from dot patterns to scenes, the results of Experiment 3 suggest that our perception of a stable visual environment across eye movements may be due to the fact that the relative positions of objects in the world defined with respect to one another do not change when the eyes change position. In other words, the global "pattern" that an arrangement of objects in the world makes on the retina does not change when the eyes change position—a chair that is midway between a table and a bookcase in one fixation on the scene will still be midway between the table and the bookcase when the eyes change position. Because the relative positions of objects with respect to one another do not change during the saccade, we do not see any change; in some sense, then, the world looks stable across saccades because it *is* stable. This view of perceptual stability across saccades is consistent with the ecological theories of perception proposed by Gibson (1966, 1979) and by Haber (1985), which claim that object overlap and visual continuities across successive fixations constitute stimulus invariants that allow the viewer to properly apprehend the world as stable and continuous.

Another important implication of the results of Experiment 3 is that there appears to be no specifically "transsaccadic" memory. The results in the eye-movement conditions were identical to those of the no-overlap control condition in which the two dot patterns were presented in separate spatial locations while the eyes remained still. This suggests that some of the same memory processes that operate within fixations also serve to integrate information across fixations; there is no need to postulate the

existence of a special buffer whose only function is to combine information across eye movements. This conclusion is consistent with research by Rayner et al. (1980) and Pollatsek et al. (in press). Rayner et al. found that a word presented in the visual periphery of one fixation facilitated naming latency for a word viewed in a subsequent fixation if the two words shared the same beginning letters, regardless of letter case; significantly, the same pattern of facilitation was found when the first word was presented peripherally and the second word foveally, with no intervening eye movement. This result suggests that the integrating memory they were studying operates within fixations, as well as across them, consistent with our argument. Pollatsek et al. (in press) obtained similar results using pictures as stimuli. Thus, the results from several studies point to the conclusion that perceptual stability and information integration across saccades is accomplished by general-purpose object- and pattern-recognition processes that are location-independent, rather than by a specific transsaccadic memory buffer that attends to the absolute positions of objects in space.

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