Differential detection of global luminance and contrast changes across saccades and flickers during active scene perception

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Abstract

How sensitive are viewers to changes in global image properties across saccades during active real-world scene perception? This question was investigated by globally increasing and/or decreasing luminance or contrast in photographs of real-world scenes across saccadic eye movements or during matched brief interruptions in a flicker paradigm. The results from two experiments demonstrated very poor sensitivity to global image changes in both the saccade-contingent and flicker paradigms, suggesting that the specific values of basic sensory properties do not contribute to the perception of stability across saccades during complex scene perception. In addition, overall sensitivity was significantly worse in the saccade-contingent change paradigm than the flicker paradigm, suggesting that the flicker paradigm is an imperfect simulation of transsaccadic vision.
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1. Introduction

Intuitively, we experience the visual world as continuous, stable, and rich in detail. However, this experience in some sense must be a construction. Visual input is quantized by the fixation–saccade cycle, and both acuity and color perception are limited by the extreme decrease in cone density from the fovea to the periphery. Because of these limitations, each fixation produces non-uniform input, with high acuity and color fidelity at the point of fixation and a rapid drop off in acuity and color perception into the periphery. Furthermore, each consecutive fixation is separated in time by 30–50 ms of interrupted input during which the eyes are moving in a saccade and vision is inhibited via central suppression and masking effects (Matin, 1974; Thiele, Henning, Buischik, & Hoffman, 2002; Volkmann, 1986). An important question in the study of human vision, then, is how the visual world is perceived as stable despite the dramatic changes in visual input from fixation to fixation (Bridgeman, Van der Hejiden, & Velichkovsky, 1994; O'Regan, 1992).

Contrary to our intuitions about perception, researchers have generally found little evidence that strictly visual information is accumulated across saccades (Bridgeman & Mayer, 1983; Henderson, 1997; Irwin, Brown, & Sun, 1988; Irwin, Yantis, & Jonides, 1983; McConkie, 1991; O'Regan & Lévy-Schoen, 1983; Rayner & Pollatsek, 1983; Tatler, Gilchrist, & Land, 2005). For example, simple visual patterns (e.g., Irwin, 1991; Irwin, 1992a; Irwin, 1992b) and the contours of single objects (Henderson, 1997) cannot be perceptually integrated from one fixation to the next. There is also good evidence that a change to a specific region of a scene often goes undetected when that change is synchronized to a saccade (Bridgeman, Hendry, & Stark, 1975; Bridgeman & Stark, 1979; Grimes, 1996; Henderson & Hollingworth, 1999; McConkie & Currie, 1996). Together, these results argue against a *spatiotopic fusion theory* of visual stability in which spatiotopically

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organized sensory images are aligned and integrated from fixation to fixation (Irwin, 1992a; Irwin, 1992b).

The findings that spatiotopically organized pattern information cannot be fused across saccades does not rule out the possibility that basic sensory representations such as luminance or contrast might be retained across saccades to support the perception of visual stability. That is, whereas spatiotopic pattern fusion might not be possible across saccades, global image comparison could be. For example, image comparison might still operate if the limitation on spatiotopic pattern fusion arises from an inability to precisely align visual patterns across saccades due to perisaccadic spatial compression (Ross, Morrone, & Burr, 1997), because of imperfect spatial localization across saccades (Bridgeman et al., 1975; McConkie & Currie, 1996), or because of overwriting of pattern or location information by new pattern input following a saccade (Deubel, Schneider, & Bridgeman, 1996). In contrast, comparison of global scene values (e.g., average scene luminance or contrast) across saccades may not require either precise spatial alignment nor precise pattern retention and integration.

It is currently unknown whether basic visual properties such as luminance and contrast play a role in the perception of stability across saccades in real-world scenes. These properties are computed early in the visual system and serve as important sources of input to mid- and high-level visual processes (Balboa & Grzywacz, 2000; Balboa & Grzywacz, 2003; Frazor & Geisler, 2006; Mante, Frazor, Bonin, Geisler, & Carandini, 2005; Ruderman & Bialek, 1994). They are also hypothesized to play a critical role in the guidance of attention and eye movements via saliency maps that explicitly represent regions of discontinuity in these properties or features based on them at various spatial scales (Itti & Koch, 2000; Parkhurst, Law, & Niebur, 2002; Torralba, Oliva, Castelhano, & Henderson, 2006). However, much of what we know about visual processing of these basic stimulus features derives from the study of sine wave gratings with narrow spatial frequency and orientation content presented at uniform and near threshold contrasts. In comparison to such stimuli, natural images have broad orientation and spatial frequency content, and whether the results of such studies will extend to visual processing in real-world scenes is currently a matter of much debate (Bex, Mareschal, & Dakin, 2007; Felsen & Dan, 2005; Olshausen & Field, 2005; Rust & Movshon, 2005). Of particular interest in the present study is sensitivity to changes in basic image properties across brief time intervals (Lee & Harris, 1996). The detection of differences in contrast patches overtime and space depends critically (and unexpectedly) on the number of patches presented (Scott-Brown, Baker, & Orbach, 2000; Scott-Brown & Orbach, 1998). How such data would extend to complex scenes is therefore unclear.

In the present study, we investigated whether the perception of stability across saccades in real-world scenes relies on the values of two of these basic image properties, luminance and contrast. If so, then changes in their values across a saccade should be disruptive to perceptual stability

and therefore readily detected by the viewer. On the other hand, if the specific levels of these properties are not relevant to the perception of stability from fixation to fixation, then changes to these properties should not be readily detectable when they occur across a saccade.

The present study examined this issue using a saccade-contingent global display change paradigm (Henderson & Hollingworth, 2003a). Viewers studied photographs of complex real-world scenes while their eye movements were recorded. Each time a viewer's direction of gaze crossed an invisible software-defined boundary, the display changed such that the image alternately increased and decreased in either luminance or contrast in increments of 10%, 20%, or 30% (Experiment 1), or gradually increased in 10% increments to a maximum cumulative change of 50% (Experiment 2). The display changes took place during saccades when participants' vision was suppressed, and changes were completed before the onset of the next fixation so that they could not be detected from visual transients. The global scene manipulations ensured that luminance and contrast across the entire scene changed each time a change took place, but that higher-level abstract visual properties of the scenes such as viewpoint and orientation, object shapes and details, and spatial relationships among scene elements remained constant across the changes. As a cover task, viewers were instructed to count the number of people in each scene (Torralba et al., 2006). They were also told to indicate immediately via button press each time the image changed. The exact nature of luminance and contrast changes was described prior to the study. Participants were told that more than one change would sometimes occur for a scene and that they should respond as quickly as possible to each change while withholding response when no change occurred.

It has been suggested that the saccade target plays a particularly important role in the perception of stability across saccades (Currie, McConkie, Carlson-Radvansky, & Irwin, 2000; McConkie & Currie, 1996). Attention may underlie this effect. Prior to a saccade, attention precedes the eyes to the target of that impending saccade; the eyes then move to the attended location, and attention and fixation are recoupled (Deubel & Schneider, 1996; Henderson, Pollatsek, & Rayner, 1989; Hoffman & Subramanian, 1995; Irwin & Andrews, 1996; Irwin & Gordon, 1998; Peterson, Kramer, & Irwin, 2004; Rayner, McConkie, & Ehrlich, 1978; Shepherd, Findlay, & Hockey, 1986). Localized changes in a scene may therefore not be noticed because attention (and fixation) has not been directed to the changing region (Hollingworth & Henderson, 2002). In the present study, because the scene changes took place over the entire image, they should occur wherever attention and the eyes happen to be directed.

1.1. Detecting changes across saccades versus across flickers

The present study provided an opportunity to investigate a second, related question concerning change detec-

tion in scenes. It is commonly assumed in the change blindness literature that the "flicker" paradigm reflects the same underlying processes as those that take place across saccades (Rensink, O'Regan, & Clark, 1997; see also Rensink, 2002). In fact, the flicker paradigm was originally designed to simulate the fixation–saccade–fixation cycle. If this assumption is correct, then the nature of perception as it unfolds dynamically across saccades can be investigated using the simpler flicker paradigm. However, this assumption has never been put to direct empirical test. In the present study, we directly tested the hypothesis that scene changes will be equally difficult to detect when those changes take place across a saccade and when they take place across an equivalent blank period in the flicker paradigm. To investigate this issue, we included a flicker condition in which the same luminance and contrast changes used in the transsaccadic change paradigm were used in a flicker paradigm. If the processes underlying perceptual stability in these two conditions are the same, then detection should be similar across methods for a given type or level of change. On the other hand, if change detection across saccades differs in some important way from change detection in the flicker paradigm, then change detection performance should diverge in the two conditions.

2. Experiment 1

In Experiment 1, either the global luminance or the global contrast of real-world scenes was alternately increased and decreased during extended scene viewing. In the *saccade condition*, the global changes took place during a saccadic eye movement. In the *flicker condition*, the changes were separated by an inter-stimulus interval filled by a blank gray field with a duration equivalent to the average saccade duration in the saccade condition. Finally, in the *control condition*, an upper bound on detection for these luminance and contrast changes was determined using a zero inter-stimulus interval (ISI) condition. In all three conditions, participants were instructed to press a response button immediately whenever they detected a luminance or contrast change.

2.1. Method

2.1.1. Participants

Twenty-four undergraduates (divided into three groups) with normal or corrected-to-normal vision participated after providing informed consent. All participants were naïve with respect to the experimental hypotheses and were compensated with course credit.

2.1.2. Stimuli

Stimuli consisted of 40 base full-color photographs depicting real-world scenes, digitized at 800×600 pixels $\times$ 24-bit color resolution. Examples of nine scenes are shown in grayscale in Fig. 1 (scenes were displayed in color). RGB values for the blank screen in the flicker con-

dition were 192, 192, 192 (L^* value of 78 in $L^*a^*b^*$ color space; 53.8 cd/m^2 on the display) and were based on the average luminance values for the base scenes. Three digitally edited versions of each base scene were created with a 10%, 20%, or 30% increase in luminance, and three additional versions with a 10%, 20%, or 30% increase in contrast. Manipulations to the base scenes were conducted within $L^*a^*b^*$ color space using Matlab (Oliva & Schyns, 2000). The resulting stimuli were displayed at a resolution of 800×600 pixels $\times$ 24-bit color and subtended 37 deg horizontally and 27.5 deg vertically at a viewing distance of 57 cm. The room in which the experiment was conducted was illuminated normally.

2.1.3. Apparatus

Stimuli were presented on a Dell UltraScan 991 19-in. Flat Screen CRT with a pixel pitch of 0.24 mm and operating at a refresh rate of 100 Hz set to middle brightness and contrast settings. Eye movements were monitored using an ISCAN ETL-400 pupil and corneal reflection tracking system sampling at 240 Hz with a tested accuracy to within .25 deg of visual angle both horizontally and vertically. Chin and forehead rests were used to maintain the participant's viewing position and distance. The eyetracker and display monitor were interfaced with a 2 GHz Pentium 4 microcomputer. The computer controlled stimulus presentation and maintained a complete record of eye position throughout the trial.

2.1.4. Design and procedure

Participants were shown 40 base scenes in the experiment. For each participant, 10%, 20%, and 30% alternations in global luminance occurred for 5 scenes each (15 total luminance change scenes). Similarly, 15 scenes incorporated changes in contrast, with 5 scenes each of 10%, 20%, and 30% alternations. All experimental conditions were run under the same lighting and display conditions. To establish a false alarm rate, 10 scenes appeared in catch trials with no changes. Each scene occurred equally often in each condition across participants, and the order of scene presentation and condition was determined randomly for each participant.

In the *saccade condition*, we followed the general procedure introduced by Henderson and Hollingworth (2003a). The experimental session began with a calibration routine that mapped the output of the eyetracker onto display position. Calibration was monitored throughout the experiment and adjusted when necessary. Each trial began with the participant fixating a central box on an otherwise blank screen. When the participant indicated readiness to view the stimulus, a photograph of a real-world scene was displayed for 10 s. Scenes were selected so that the search task was difficult and engaging over the entire trial period. For change trials, changes in luminance or contrast occurred during a saccade. The initial version of the scene (A) was displayed until the participant's gaze crossed one of two invisible vertical boundaries that divided the display into

Fig. 1. Examples of the scene stimuli. Images shown to participants were in full color.

equal thirds, at which point an alternate version of the scene (A') was presented. Alternations between A and A' occurred each time gaze crossed either of the two region boundaries. Participants were instructed to count the number of people in each scene, and to press a response button immediately upon detecting a change. Participants were told that on some trials more than one change would occur, and on other trials no change would occur. They were also instructed to respond as quickly as possible to each change.

Two additional conditions were included in the experiment. For participants in the *flicker condition*, scene changes occurred during a brief blank period that was inserted between successive scene displays (Rensink et al., 1997). Scene and blank screen presentation times were derived from the average elapsed time between boundary crossings and the average saccade duration observed in the saccade condition.[1] Specifically, alternations between A and A' occurred every 1337 ms, with 1300 ms of scene presentation and a 37 ms ISI of a blank gray screen between scene presentations. For participants in the *control condition*, alternations between A and A' also occurred every 1337 ms, but the ISI was set to 0 so that no blank period intervened between scene changes. The control condition was included to establish a baseline for detecting the luminance and contrast changes used in the transsaccadic and flicker change conditions. Eye movements were not monitored in the flicker or control conditions.

2.2. Results

Detection of changes in luminance and contrast were characterized in three ways: proportion of changes that were detected, proportion of trials in which at least one of the changes was detected, and number of changes in a trial prior to the first detected change. In the saccade condition, 20% of the boundary crossings were excluded from the analysis because scene changes occurred within a fixation rather than during a saccade. Each detection measure, averaged over participants, is illustrated in Figs. 2 and 3 as a function of change type (luminance and contrast), change condition (saccade, flicker, and control), and change magnitude (10%, 20%, and 30%). Because the luminance and contrast changes were not psychophysically equated, we report the results for each change type separately and caution against directly comparing them.

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[1] Given this averaging, trial duration was 955 ms longer in the flicker condition compared to saccade condition. However, the frequency of scene changes was equated. In the saccade condition, boundary crossings occurred, on average, 6.7 times per trial; in the flicker condition, 7 changes occurred on each trial.
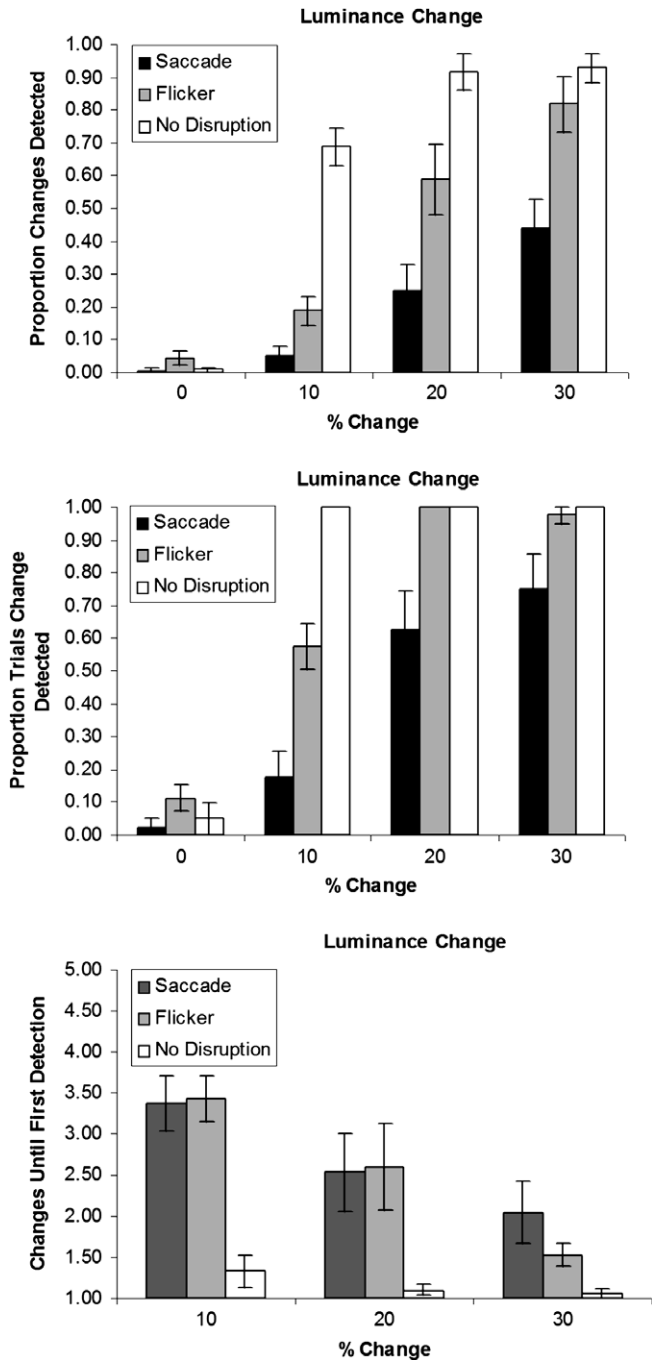
Fig. 2. Luminance change detection performance, Experiment 1, in the saccade-contingent, flicker, and control change conditions, for 0%, 10%, 20%, and 30% changes. Data shown are proportion of all changes detected (top panel), proportion of trials on which at least one change was detected (middle panel), and the number of changes before a change was first detected (bottom panel).
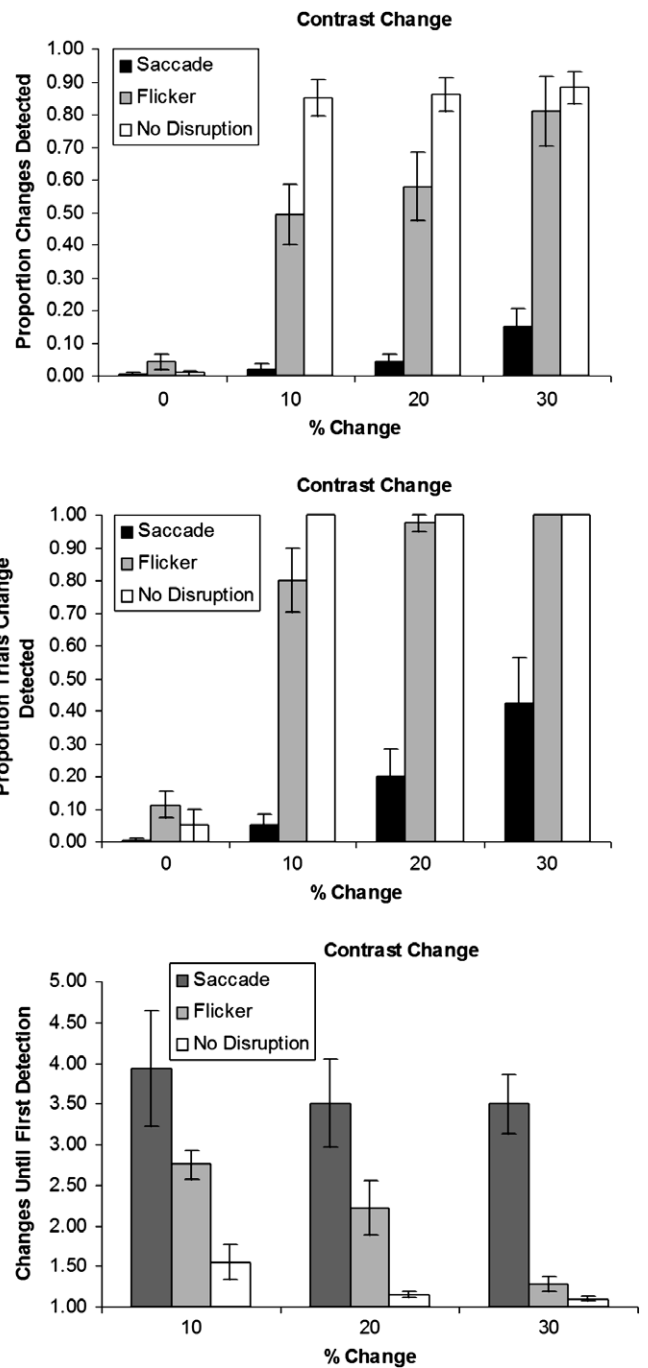
Fig. 3. Contrast change detection performance, Experiment 1, in the saccade-contingent, flicker, and control change conditions, for 0%, 10%, 20%, and 30% changes. Data shown are proportion of all changes detected (top panel), proportion of trials on which at least one change was detected (middle panel), and the number of changes before a change was first detected (bottom panel).

2.2.1. Luminance

2.2.1.1. Proportion of changes detected. Detection rates in all cells of the experimental design were greater than their respective false alarm rates, with the exception of the 10% change in the saccade condition (see Fig. 2). The proportion of changes detected was subjected to a 3 (change magnitude) × 3 (change condition) mixed model analysis

of variance. A main effect of change magnitude was observed, $F(2, 42) = 70.1$, $p < .001$, with all pairwise comparisons reliable. Changes of 10%, 20%, and 30% were detected 36%, 57%, and 71% of the time, respectively. In addition, a main effect of change type was observed, $F(2, 21) = 28.3$, $p < .001$, with all pairwise comparisons reliable. In the control condition where no visual disruptions

(either by saccadic suppression or an artificial flicker) occurred, luminance changes were detected 86% of the time. In contrast, changes in the flicker and saccade conditions were detected, on average, 53% and 24% of the time, respectively. These factors also interacted, $F(4,42) = 5.47$, $p < .001$. As can be seen in Fig. 2, in the control condition, although the 10% luminance change was not always perceptible (69% detected), the 20% and 30% changes approached ceiling performance (93% detected). When luminance changes were separated by visual disruptions, the detection rate increased more as a function of change magnitude in the flicker condition than in the saccade condition. In fact, with 30% luminance changes, the detection rate in the flicker condition was at ceiling and did not differ reliably from the control condition, $t(14) = 1.18$, $p = .26$, whereas the detection rate for 30% luminance changes in the saccade condition was well below that of the control condition, $t(14) = 5.22$, $p < .001$.

2.2.1.2. Proportion of change trials in which at least one change was detected. So far we have examined change detection for each individual change. These data showed a clear difference in change detection for the transsaccadic and flicker versions of the change paradigm. However, in the standard flicker paradigm (e.g., Rensink et al., 1997), the trial ends when a change is first detected. It is possible that performance in the saccade and flicker conditions would be more similar if an equivalent measure were examined. To test this possibility, we analyzed the proportion of change trials in which at least one of the changes in that trial was detected.

Detection rates in all cells of the experimental design were greater than their respective false alarm rates, with the exception of the 10% change in the saccade condition (see Fig. 2). In the control condition, luminance changes were detected on 100% of the trials, disallowing inferential statistics involving this condition. Note however that these data, combined with the percentage of changes analysis reported above, suggest that although individual changes were sometimes missed, all changes (including the 10% changes) in the control condition were above perceptual threshold when repeated.

The proportion of trials on which at least one change was detected in the saccade and flicker conditions were submitted to a 2 (change condition) × 3 (change magnitude) mixed model ANOVA. The main effect of change condition was reliable, $F(1,14) = 15.9$, $p < .01$. Whereas 52% of trials containing a change were identified in the saccade condition, 85% of trials were identified in the flicker condition. The main effect of change magnitude was also reliable $F(1,14) = 52.6$, $p < .01$. Alternating luminance changes of 10% were detected at least once on 38% of trials, whereas changes of 20% and 30% were detected at least once on 81% and 86% of trials, respectively. The interaction of these factors was not reliable, $F(1,14) < 1$. These data again suggest that changes in the saccade condition were less detectable than in the flicker condition.

2.2.1.3. Number of changes to first detection. Several changes typically occurred in the saccade and flicker conditions before an observer first responded that the scene was changing. The number of changes prior to detection (or equivalently, the time to first detection) is often used as a measure of change detection in the flicker paradigm (e.g., Rensink et al., 1997). We therefore measured this lag as another indicator of the difficulty of change detection. The number of changes to first detection was undefined for one participant in the saccade condition because that participant did not detect any of the changes. This participant was therefore removed from the analysis. Removal of this participant works against the hypothesis that change detection is more difficult in the saccade than flicker condition.

The number of changes to first detection were subjected to a 3 (change magnitude) × 3 (change condition) mixed model analysis of variance. A main effect of change magnitude was observed, $F(2,40) = 11.1$, $p < .001$, with all pairwise comparisons reliable. The average number of changes to the first detection for changes of 10%, 20%, and 30% were 2.68, 2.06, and 1.52, respectively. In addition, a main effect of change type was also observed, $F(2,20) = 21.2$, $p < .001$. In the control condition, collapsing across participants, the average number of changes to the first detection was 1.16. Ninety-five percent confidence intervals indicated that this rate of detection was not reliably different from 1.00. In the saccade and flicker conditions, alternations of luminance were first detected, on average, after 2.65 and 2.52 changes, respectively. Planned comparisons indicated that these rates of detection were not reliably different from each other, but both were reliably different from the control condition. The experimental factors did not interact, $F(4,40) = 2.01$, $p = .11$.

2.2.2. Contrast
2.2.2.1. Proportion of changes detected. Detection rates in all cells of the experimental design were greater than their respective false alarm rates, with the exception of the 10% and 20% changes in the saccade condition (see Fig. 3). The proportion of changes detected was subjected to a 3 (change magnitude) × 3 (change condition) mixed model analysis of variance. A main effect of change magnitude was observed, $F(2,42) = 18.8$, $p < .001$. Changes of 10% and 20% were detected 46% and 49% of the time, respectively, and did not reliably differ from each other. Changes of 30% were detected 61% of the time. In addition, a main effect of change type was also observed, $F(2,21) = 56.6$, $p < .001$, with all pairwise comparisons reliable. In the control condition, contrast changes were detected 86% of the time. Changes in the flicker and saccade conditions were detected, on average, 63% and 7% of the time, respectively. These factors also interacted, $F(4,42) = 5.11$, $p < .01$. As can be seen in Fig. 3, in the control condition, all contrast changes were detected equally well and performance approached ceiling. When visual disruptions occurred between contrast changes, the magnitude

of the change had a greater effect on detection in the flicker condition. The difference in conditions was particularly striking in the 30% contrast change condition, where 15% of changes were detected across a saccade but 81% were detected across an equivalent blank period.

2.2.2.2. Proportion of change trials where at least one change was detected. Detection rates in all cells of the experimental design were greater than their respective false alarm rates, with the exception of the 10% change in the saccade condition (see Fig. 3). In the control condition, contrast changes were detected on 100% of the trials in the control condition, disallowing inferential statistics involving this condition. In addition, contrast changes in the flicker condition of 10%, 20%, and 30% magnitude were detected on 80%, 98%, and 100% of trials, respectively. Because of the lack of variability in the 30% change condition and the ceiling effect in the 20% condition, it was also not possible to conduct inferential statistics involving the flicker condition. We therefore conducted a one-way repeated-measures ANOVA on the saccade condition. The rate of detection depended on the magnitude of the change, $F(2, 14) = 6.08$, $p < .05$. Contrast changes of 10% were detected at least once on 5% of the trials. Changes of 20% and 30% magnitude were detected at least once on 20% and 42% of trials. To compare this level of performance with the control and flicker conditions, we computed independent 95% confidence intervals around the means for each level of change magnitude in the saccade condition. None of these confidence intervals included the level of performance in the equivalent flicker and control conditions, suggesting that detection was poorer in the saccade condition.

2.2.2.3. Number of changes to first detection. In the saccade condition, one participant did not identify any of the contrast changes at any level and was excluded from the analyses. Three of the remaining 7 participants never detected a 10% contrast change and thus in all of the following analyses we excluded the 10% change condition. The number of changes to first detection were therefore subjected to a 2 (change magnitude) × 3 (change condition) mixed model analysis of variance. A main effect of change magnitude was observed, $F(1, 17) = 11.7$, $p < .001$. The average number of changes to the first detection for changes of 20% and 30% were 2.24 and 1.89, respectively. In addition, a main effect of change type was also observed, $F(2, 17) = 13.54$, $p < .001$, with all pairwise comparisons reliable. In the control condition, the average number of changes to the first detection was 1.12. Ninety-five percent confidence intervals indicated that this rate of detection was not reliably different from 1.00. In the saccade and flicker conditions, alternations of contrast were first detected, on average, after 3.50 and 1.75 changes, respectively. The experimental factors did not interact, $F(2, 17) = 1.36$, $p = .28$. That is, given that a contrast change was detected, more changes were required to first

detect it when the change occurred across a saccade than across a flicker.

2.3. Discussion

The results of Experiment 1 indicate that above-threshold global luminance and contrast changes to real-world scenes are very difficult to detect, and often are not detected at all, when they occur across a saccadic eye movement. For example, considering only the largest (30%) changes in this experiment, participants detected fewer than half (44%) of all luminance changes and only 15% of all contrast changes across saccades. Furthermore, although on average 6.7 changes occurred on each trial, these changes were completely missed over all alternations on 25% of the luminance change trials and 58% of the contrast change trials. In comparison, changes of the same magnitude were never missed over an entire trial in the control condition. Furthermore, when luminance changes were detected across a saccade, over twice as many alternations were needed before an alternation was detected than in the control condition; for contrast changes, over three times as many changes were required for first detection.

The results in the transsaccadic change condition demonstrate substantial perceptual insensitivity to global changes in luminance and contrast across saccadic eye movements. These results suggest that these basic image properties play little role in the perception of stability across saccades. Furthermore, because the changes took place globally over the scenes, the detection failures could not be due to a failure to attend to the changing region of the image, as has been the case for object changes in scenes (Henderson & Hollingworth, 1999, 2003a, 2003b; Hollingworth & Henderson, 2002). These results thus provide strong evidence against the hypothesis that perceptual stability is due to consistency of these basic image properties across saccades.

A second important finding from Experiment 1 is that, when equated for viewing time and for intervening blank time, detection of global scene changes is qualitatively worse across a saccade than across an equivalent blank period in the flicker paradigm. Considering again the maximum (30%) change condition, participants detected 44% of luminance changes and 15% of contrast changes across saccades, but detected 82% and 81% of the same changes in the flicker paradigm. The results of the trial data were even more striking: In the saccade condition participants completely missed multiple alternations of luminance on 25% of trials and multiple alternations of contrast on 58% of trials, whereas in the flicker condition multiple alternations of luminance were missed on only 2 trials across all participants, and alternations of contrast were never missed over an entire trial for any trial by any participant. Finally, for those trials in which a change was eventually detected, although a similar number of luminance alternations was required to detect the change in the saccade and flicker conditions, almost three times as many

contrast alternations were needed to first detect the change across a saccade (3.50) than across a flicker (1.28). Note that because the display durations in the flicker paradigm were determined by the durations in the saccade condition, these differences cannot be due to simple differences in encoding time or memory delay. The differences in results in the saccade and flicker conditions challenge the generally held assumption that these two paradigms are equivalent and that the study of perception over multiple fixations can be simulated by the flicker paradigm.

3. Experiment 2

In Experiment 1, we demonstrated that global alternations of up to 30% in luminance and contrast are very difficult to detect when they take place across a saccade during real-world scene viewing. In Experiment 2, we examined whether substantial changes to these basic image properties remain undetected if the changes are generated incrementally over several fixation–saccade cycles. Hollingworth and Henderson (2004) demonstrated in a flicker paradigm that global scene rotations can be very difficult to detect when they take place in small incremental steps rather than all at once. In Experiment 2, we investigated whether incremental changes to basic sensory properties are difficult to detect across saccades, and if so, whether such changes are also more difficult to detect than the same incremental changes in the flicker paradigm. Specifically, we tested viewers' sensitivity to increases of up to 50% in luminance and contrast when those increases occurred in 10% increments, with each increment occurring across a saccade or a flicker.

If the initial levels of luminance or contrast in a scene are important in the perception of stability across saccades, then we would expect that following a given level of change, the change should be detected whether it takes place all at once or incrementally. In other words, if image properties from the present fixation are 30% different from those in the initial fixation, then as long as the initial view contributes to the perception of stability, detection of that difference should be the same whether the 30% increase occurs incrementally or in one shot. Alternatively, if perceptual stability is mostly a function of two immediately consecutive fixations, with the visual system essentially ignoring image properties from earlier fixations, then change detection at a given cumulative level of change should be less than when that same level of change takes place all at once. At the extreme, if perceptual stability is completely a function of the last and the present fixation, then detection rates for incremental changes should be no different than detection for single-shot changes equal to the level of the individual increment, regardless of the total amount of change that has taken place up to that point in time. That is, if a change is not perceived between fixations 1 and 2, then image properties from fixation 1 will not be functional in detecting a change between fixations 2 and 3.

3.1. Method

3.1.1. Participants

Twenty-four undergraduates with normal or corrected-to-normal vision participated after providing informed consent. All participants were naïve with respect to the experimental hypotheses and were compensated with course credit. Participants were randomly assigned to control, saccade, and flicker conditions. None of the observers tested in Experiment 2 had participated in Experiment 1.

3.1.2. Stimuli

The scene photographs were the same as those used in Experiment 1, with additional versions of each photograph incorporating 40% and 50% increases in luminance and contrast over the base scenes.

3.1.3. Apparatus

The same apparatus was used as in Experiment 1.

3.1.4. Design and procedure

The design and procedure were the same as in Experiment 1, with the following exceptions. First, scene changes occurred on every trial (i.e., no catch trials were included). Of the 40 presented scenes, 20 incorporated changes in luminance and 20 incorporated changes in contrast. Assignment of scene to change condition was counterbalanced across participants. Second, rather than alternating between two versions of each scene (A and A'), luminance or contrast increased by 10% each time a saccade crossed a region boundary. That is, the initial scene (A) was followed by scene A' with luminance or contrast increased by 10%, scene A'' with an additional 10% increase (now 20% greater than A), scene A''' with another 10% increase, and so on until a maximum of 5 changes occurred in the 10 s viewing period, yielded a maximum total increase of 50%.

3.2. Results

In the saccade condition, 14% of the boundary crossings were excluded from the analysis because scene changes occurred within a fixation rather than during a saccade. As in Experiment 1, change detection was measured in terms of the percentage of changes detected and the percentage of trials in which a change was detected at least once. Due to extremely low detection rates (described below), it was not possible to analyze the number of changes that occurred prior to first detecting the change as was done in Experiment 1. Results are summarized in Figs. 4 and 5.

In the saccade condition, because increments in luminance and contrast were linked to the behavior of the eyes, specifically requiring that the eyes cross the invisible boundaries, the maximum of 5 changes did not occur on every trial. Two percent of trials included one or two changes and therefore these trials were not analyzed further. Three, four, and five changes (cumulative changes of 30%, 40%, and 50%
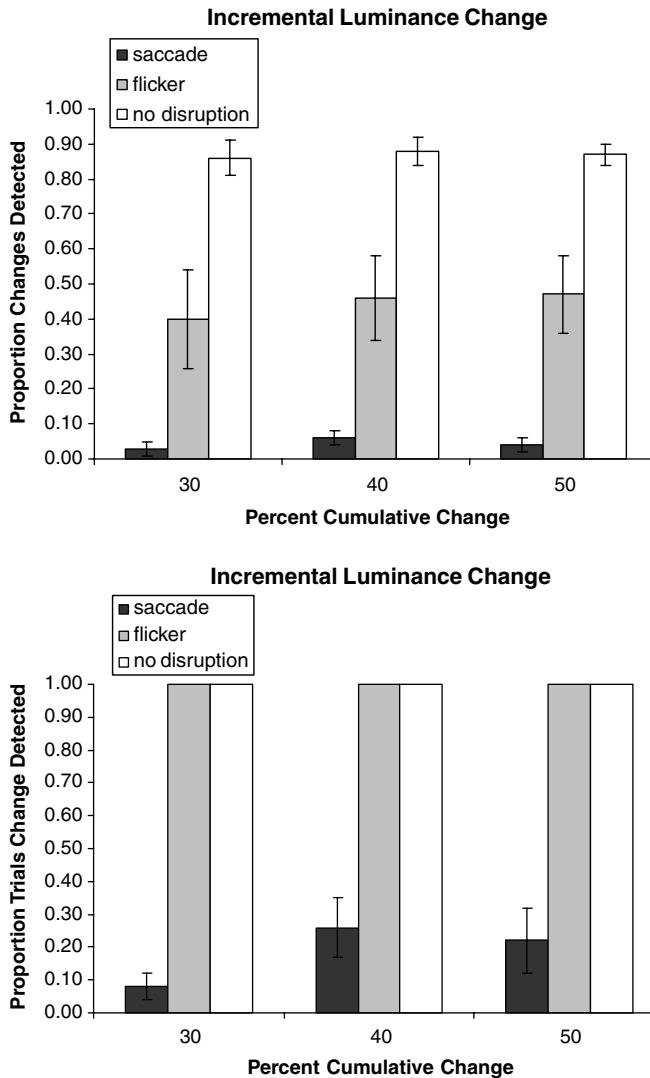
Fig. 4. Luminance change detection performance, Experiment 2, in the saccade-contingent, flicker, and control change conditions for the 3-change, 4-change, and 5-change bins (i.e., cumulative changes of 30%, 40%, and 50%). Data shown are proportion of all changes detected (top panel) and proportion of trials on which at least one change was detected (bottom panel).

over the base scenes) occurred on 16%, 36%, and 46% of trials, respectively, and the analyses focused on these cases. In the control and flicker conditions, however, all 5 increments occurred on every trial. To compensate for this inequality, for each type of change in the control and flicker conditions, 1 trial (5%) was excluded from the analysis, 3 trials (15%) were analyzed through the third change, 7 trials (35%) were analyzed through the fourth change, and 9 trials (45%) were analyzed through the fifth change. For each participant, trials in each pseudo-condition were chosen randomly. We will refer to these as the 3-change, 4-change, and 5-change bins, respectively.

3.2.1. Luminance
3.2.1.1. Proportion of changes detected.
The proportion of changes detected was subjected to a 3 (change magni-
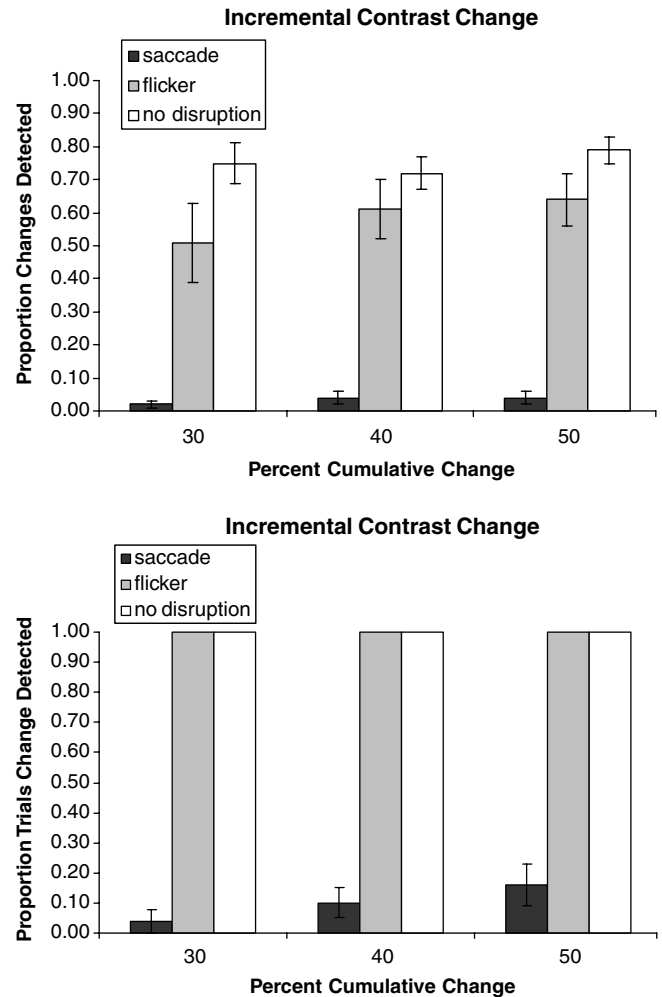

Fig. 5. Contrast change detection performance, Experiment 2, in the saccade-contingent, flicker, and control change conditions for the 3-change, 4-change, and 5-change bins (i.e., cumulative changes of 30%, 40%, and 50%). Data shown are proportion of all changes detected (top panel) and proportion of trials on which at least one change was detected (bottom panel).

tude) × 3 (change condition) mixed model ANOVA. The main effect of change magnitude was not reliable, $F(2, 42) = 1.91$, $p = .16$. This result indicates that change detection was constrained by the magnitude of the incremental change rather than the magnitude of the cumulative change. A main effect of change type was observed, $F(2, 21) = 34.7$, $p < .001$, with all pairwise comparisons reliable. In the control condition, luminance changes were detected 87% of the time. In comparison, changes in the flicker and saccade conditions were detected, on average, 44% and 4% of the time, respectively. These factors did not interact, $F(4, 42) < 1$, indicating that there was no effect of cumulative change magnitude in any change condition.

3.2.1.2. Proportion of trials change detected.
In both the control and flicker conditions, luminance increments were detected on 100% of trials. Whereas some individual incremental changes were missed (as indicated by the above

analyses), all changes were above perceptual threshold when repeated.

In comparison, in the saccade condition luminance changes were detected at least once on only 8% of the trials with 3 changes (30% cumulative change), 26% of the trials with 4 changes (40% cumulative change), and 22% of the trials with 5 changes (50% cumulative change). These detection rates did not reliably differ, $F(2, 14) = 2.72$, $p = .10$. By way of comparison, in Experiment 1, 30% luminance alternations were detected at least once on 75% of the trials.

Because of the lack of variance in the flicker condition, the flicker and saccade conditions could not be contrasted with an ANOVA model. Constructing 95% confidence intervals around the detection rates in the saccade condition, however, indicated that detection in the saccade condition was reliably worse than in the flicker condition at all levels of cumulative change.

3.2.2. Contrast
3.2.2.1. Proportion of changes detected.
In a 3 (change magnitude) × 3 (change condition) mixed model ANOVA, the main effect of change magnitude was marginally reliable, $F(2, 42) = 3.07$, $p = .07$. Across change conditions, 43%, of changes were detected in the 3-change bin, 46% were detected in the 4-change bin, and 49% were detected in the 5-change bin. This growth of 6% is modest compared to the 35% growth in change detection observed in Experiment 1 from the 10% change trials to the 30% change trials. Thus, in Experiment 2, change detection was more strongly related to the magnitude of the incremental change rather than the magnitude of the cumulative change. A main effect of change type was also observed, $F(2, 21) = 39.5$, $p < .001$, with all pairwise comparisons reliable. In the control condition, contrast changes were detected 75% of the time, while changes in the flicker and saccade conditions were detected, on average, 59% and 3% of the time, respectively. These factors did not interact, $F(4, 42) = 1.34$, $p = .27$.

3.2.2.2. Proportion of trials change detected.
In both the control and flicker conditions, contrast increments were ultimately detected on 100% of trials. In comparison, in the saccade condition contrast increments were detected at least once on only 4% of the trials with 3 changes (30% cumulative change), 10% of the trials with 4 changes (40% cumulative change), and 16% of the trials with 5 changes (50% cumulative change). These detection rates did not reliably differ, $F(2, 14) = 2.28$, $p = .14$. By way of comparison, in Experiment 1, when contrast alternations of 30% occurred, a change was detected at least once on 42% of trials. Again, 95% confidence intervals around the detection rates in the saccade condition indicated that detection was reliably worse across saccades than across equivalent flickers.

3.3. Discussion

The results of Experiment 2 support two general conclusions. First, detection rates for cumulative incremental changes to luminance and contrast across saccades are far more similar to those of the incremental level of change than to the cumulative level of change. For example, when a 30% cumulative change took place in 10% increments, 3% of luminance and 1% of contrast changes were detected. In Experiment 1, when 30% changes luminance or contrast occurred in "one shot," the detection rates were 44% and 15%, respectively. These results demonstrate substantial insensitivity to global changes in luminance and contrast across saccadic eye movements. In addition, these results suggest that perceptual stability is driven by at most a "one-back" operation whereby the primary relevant information comes from the immediately previous fixation. Had the initial fixation (or just two or more prior fixations) been considered in determining perceptual stability, detection rates should have increased as more change occurred to the scene, a result that was not observed. Second, replicating Experiment 1, detection rates were far lower for transsaccadic changes than for changes across an equivalent blank period in the flicker paradigm. This result is particularly clear when looking at the proportion of trials in which any change was detected (bottom panels of Figs. 4 and 5). In these cases a change was detected on 100% of trials in the flicker and control conditions, but the changes were missed in the majority of trials in the transsaccadic change condition. These results are difficult to reconcile with the assumption that transsaccadic perception can be directly simulated by the flicker paradigm.

4. General discussion

In the present study, we investigated the degree to which two fundamental image properties, luminance and contrast, are functional in producing the perception of stability across saccades during real-world scene viewing. We examined this issue using a saccade-contingent global display change paradigm. Participants viewed photographs of real-world scenes while their eye movements were recorded, and each time a saccade crossed a pre-defined boundary, the display changed. In Experiment 1, the scene alternately increased and decreased in luminance or contrast in increments of 10%, 20%, or 30%. In Experiment 2, luminance or contrast gradually increased in 10% increments to a maximum cumulative change of 50%. The display changes took place during saccades, and each change was completed before the onset of the next fixation so that it could not be detected from visual transients. Participants were instructed to count the number of people in each scene and to indicate immediately via button press each time the image changed.

The results of both experiments demonstrated that above-threshold global changes to luminance and contrast in real-world scenes were very difficult to detect, and indeed were often not detected at all, when those changes occurred across a saccadic eye movement. In Experiment 1, increments and decrements of up to 30% of luminance and contrast levels were missed more often than they were detected

when they took place across a saccade. In Experiment 2, luminance and contrast increases of up to 50% of the initial levels in a scene were almost never detected across a saccade when the changes took place over gradual 10% increments. Furthermore, the detection rates in Experiment 2 for the transsaccadic changes were similar to those observed for the individual 10% increments in Experiment 1. These results strongly suggest that the precise values of these basic image properties are not functional in the perception of stability during real-world scene perception.

Prior studies have demonstrated that change detection across saccades during scene viewing is strongly influenced by the location of the change with respect to eye position and saccade direction. For example, changes to individual objects in scenes (e.g., a coffee cup in a kitchen) are detected much more easily (approaching 100%) if the changing object is the target of the saccade that triggers the change (Henderson & Hollingworth, 1999, 2003b; see also McConkie & Currie, 1996). This change detection advantage for saccade targets is likely due to the dynamics of attention and eye movement control, with attention preferentially allocated to the target of the impending saccade. In the present study, because image changes took place globally across the scenes, detection failure could not be due to a failure to attend to a changing region of the image. Together with the results of change detection and memory for higher-level structural scene properties, these results are consistent with the hypothesis that only more abstracted visual representations play a role in transsaccadic perception.

4.1. Saccade-contingent versus flicker change paradigms

A second important finding to emerge from this study involves the comparison of the saccade-contingent and flicker versions of the paradigm. Specifically, changes that were relatively easy to detect in the flicker paradigm were much more difficult to detect across saccadic eye movements. The data across both experiments and all of the reported analyses support this conclusion. For example, consider the 30% contrast changes in Experiment 1. Here, contrast alternately increased and decreased 30% in both the flicker and transsaccadic change conditions. Yet less than 20% of these changes could be detected when they took place across a saccade compared to over 80% across an equivalent flicker (refer to top panel of Fig. 3). Because the display durations in the flicker paradigm were determined by the durations in the saccade condition, these differences cannot be due to simple differences in encoding time or memory delay.

Comparing against the no-flicker control condition also highlights the difference in results across the saccade-contingent and flicker paradigms. In Experiment 1, participants' ability to detect the largest changes in luminance and contrast in the flicker paradigm and the control condition were statistically equivalent (refer to top panels of Figs. 2 and 3). These results suggest that participants were

detecting the changes in the flicker paradigm at ceiling level and in most cases close to 100% of the time. In contrast, detection of the same changes in the saccade-contingent condition was always much poorer, with only 44% and 15% of the largest luminance and contrast changes detected across saccades, respectively.

Interestingly, when we examine the measures that are more similar to those typically reported for the flicker paradigm, the differences between the saccade-contingent and flicker conditions are not quite as extreme (refer to bottom panel of Fig. 3). For example, when the number of changes before detection is used as the dependent measure, the data in the saccade and flicker conditions are relatively similar for luminance changes, at least for the 10% and 20% conditions. However, even using these measures, differences do still emerge favoring detection in the flicker paradigm. For example, as can be seen in the bottom panel of Fig. 3, there were clear differences in detecting contrast changes in the flicker and saccade conditions, and these differences became larger as the degree of change increased. Nevertheless, these measures clearly only tell part of the story, with the more fine-grained measures revealing the increased difficulty of detecting changes across saccades.

Taken together, the different results for the saccade and flicker paradigms call into question the generally held assumption in the literature that the flicker paradigm taps into the same perceptual processes as those that are engaged during natural active vision involving a sequence of fixations and saccades. The present results indicate, instead, that a flicker is not necessarily a good approximation of a saccade; clear and large quantitative differences in the level of detection can be observed across the saccade and flicker paradigms for the same level of stimulus change and the same duration of blanking. It may be that detecting changes to visual properties that are computed in the first stage of cortical analysis is easier when detection can be based directly on retinotopic representations (possible in the flicker paradigm) than when it requires spatiotopic representations (as in the transsaccadic paradigm). This possibility is consistent with related findings in visual fusion. For example, when two dot patterns forming a matrix of dots are presented with a brief inter-stimulus interval at the same retinal position within an eye fixation, a single fused pattern is perceived and performance (e.g., identification of a missing dot from the matrix) can be based on this percept (Di Lollo, 1977; Di Lollo, 1980; Eriksen & Collins, 1967; Irwin, 1992a; Phillips, 1974). However, when the two patterns are viewed with similar timing parameters at the same environmental position but different retinal positions across a saccade, no such fused percept is experienced and performance is dramatically reduced (Bridgeman & Mayer, 1983; Irwin, 1991; Irwin et al., 1983, 1988; Irwin, Zacks, & Brown, 1990; O'Regan & Lévy-Schoen, 1983; Rayner & Pollatsek, 1983). The visible and informational persistence that is available retinotopically within a fixation but is not available spatiotopically across saccades (Coltheart, 1980; Irwin, 1992a; Irwin & Brown, 1987; Irwin & Yeomans,

1986) may at least partially underlie the better detection rates in the flicker paradigm.

In summary, the differing results for the flicker and the transsaccadic change detection paradigms challenge the generally held assumptions that these two situations are equivalent and that the study of perception over multiple fixations can be simulated by the flicker paradigm.

4.2. Overt versus covert change detection

Although overt responses to image changes have sometimes been taken to reflect completely the degree to which viewers perceptually notice changes, more recent evidence has demonstrated that overt responses can underestimate change sensitivity across saccades (Hayhoe, Bensinger, & Ballard, 1998; Henderson & Hollingworth, 2003a; Hollingworth & Henderson, 2002; Hollingworth, Williams, & Henderson, 2001). Therefore, it is possible that although global changes were not always overtly reported in the present experiments, they may still have been covertly detected. Fixation duration has been shown to be a sensitive measure of covert (i.e., unreported) change detection in saccade-contingent change experiments (Hayhoe et al., 1998; Henderson & Hollingworth, 2003a; Hollingworth & Henderson, 2002; Hollingworth et al., 2001). In a previous study, we found that global scene changes induced by hiding and revealing alternating sections of a scene were neither overtly reported nor covertly revealed in fixation durations (Henderson & Hollingworth, 2003a). To investigate this issue in the present study, separate repeated measures ANOVAs for luminance and contrast changes compared fixation durations immediately following undetected changes and fixation durations in the equivalent no-change condition in Experiment 1. Neither analysis indicated that a fixation following an undetected change was any different from an equivalent fixation in the no-change condition (luminance: $F(3, 21) = 1.23$, $p = .31$; contrast: $F(3, 21) = 1.33$, $p = .29$). Thus, consistent with prior global-change results (Henderson & Hollingworth, 2003a), we have no evidence in this study that covert (unreported) change detection was taking place.

4.3. When are changes in scenes detected?

The global change-blindness effect reported here is particularly striking because viewers were informed about the nature of the changes beforehand and were presented with multiple changes on each trial. These results thus likely provide an upper bound on perceptual sensitivity to the global changes investigated in these experiments. The present results contrast with evidence demonstrating that changes to the orientation or specific instance of an object concept in a scene (e.g., rotating a chair by 90 deg or changing one coffee cup into another) can be readily detected when the object is attended before and after the change (e.g., Henderson & Hollingworth, 2003b; Hollingworth & Henderson, 2002; Hollingworth, Schrock, & Hen-

derson, 2001). These latter results suggest that more abstract visual properties of objects in scenes do play a role in the perception of stability. Furthermore, direct memory probes demonstrate that the relatively detailed memory representations needed to support detection of these object changes are retained in longer-term memory (Hollingworth & Henderson, 2002; see Hollingworth, 2006), even when the viewer is not aware that memory will be tested following scene viewing and so has no reason to memorize object details (Castelhano & Henderson, 2005; see also Williams, Henderson, & Zacks, 2005). The difference in change-detection results for these past object-change experiments and the current global scene-change experiments is even more striking when one considers that the objects used in the object-change experiments occupied only about 3% of the area of each scene on average but were detected quite easily (e.g., Henderson & Hollingworth, 2003a; Hollingworth & Henderson, 2002), whereas the global image changes used in the present study took place across the entire image yet were often impossible to detect.

The change detection results are consistent with evidence from other paradigms in suggesting that some visual information, such as pattern structure and spatial relationships, can be retained from fixation to fixation (e.g., Brockmole & Irwin, 2005; Carlson-Radvansky, 1999; Carlson-Radvansky & Irwin, 1995; Irwin, 1991; Irwin, 1992a; Irwin, 1992b; Pollatsek & Rayner, 1992; Verfaillie & De Graef, 2000). In addition, relatively detailed visual representations of meaningful objects in real-world scenes can be retained across saccades, particularly for the saccade target (Currie et al., 2000; Henderson & Hollingworth, 1999, 2003b; Hollingworth & Henderson, 2002; McConkie & Currie, 1996). The object representations retained across saccades are visually precise enough to support discrimination of object orientation and to distinguish one member of an object category (e.g., a coffee cup) from another (e.g., Henderson & Hollingworth, 2003b; Hollingworth & Henderson, 2002; Williams et al., 2005; see also Henderson & Siefert, 1999). These results suggest that visual representations of meaningful objects in real-world scenes can be retained across saccades, albeit in a non-sensory format, and that the integration of these higher-level representations might underlie in part the perception of stability across saccades.

The global perceptual insensitivity to change reported here, together with recent demonstrations of good change detection across saccades for token substitutions and orientation changes (for attended objects), can be accommodated by a theory of dynamic scene perception in which sensory representations coding specific values of basic visual properties such as luminance and contrast are available only within the fixation in which they are acquired. These iconic representations are highly volatile, are encoded in retinotopic coordinate space, survive only short periods of time after the stimulus is removed from view, and are susceptible to visual masking (Irwin, 2006). For all of these reasons, they are not functional across saccadic eye movements (Irwin, 1991; Irwin, 1992a; Irwin, 1992b).

Instead, perceptual stability is supported by visual representations that have been abstracted away from an initial sensory format but that nonetheless code visual information (Henderson, 1994; Henderson & Hollingworth, 1999, 2003a, 2003b; Henderson & Siefert, 2001; Hollingworth & Henderson, 2002). These abstract visual representations are consistent with functional accounts of more anterior visual areas of cortex, such as medial and inferior temporal cortex, where detailed and orientation-specific object representations seem to be stored (e.g., Kreiman, Koch, & Fried, 2000; Logothetis & Sheinberg, 1996; Tanaka, 1996; Vuilleumier, Henson, Driver, & Dolan, 2002).

Because sensory properties from one fixation are not available during the next fixation, detecting changes to those properties from fixation to fixation will be very difficult, even if attention is directed to the changing scene region, as demonstrated here. On the other hand, because visual representations coding higher-level visual properties are retained across saccades, changes to those properties can be detected if the changing object is attended before and after the change (Henderson and Hollingworth, 2003b; Hollingworth and Henderson, 2002; Hollingworth, Schrock, & Henderson, 2001; Hollingworth et al., 2001). These results suggest that it is these more abstract visual representations that support the perception of visual stability, contribute to the perception of an integrated scene representation, and that linger to support visual memory and dynamic visually guided action.

Acknowledgments

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