OBSERVATION

Eye Movement Control During Scene Viewing: Immediate Effects of Scene Luminance on Fixation Durations

John M. Henderson
University of South Carolina

Antje Nuthmann
University of Edinburgh

Steven G. Luke
University of South Carolina

Recent research on eye movements during scene viewing has primarily focused on where the eyes fixate. But eye fixations also differ in their durations. Here we investigated whether fixation durations in scene viewing are under the direct and immediate control of the current visual input. Subjects freely viewed photographs of scenes in preparation for a later memory test while their eye movements were recorded. Using a novel scene degradation paradigm based on a saccade-contingent display change method, scenes were reduced in luminance during saccades ending in critical fixations. Results from two experiments showed that the durations of the critical fixations were immediately affected by scene luminance, with a monotonic relationship between luminance reduction and fixation duration. The results are the first to demonstrate that fixation durations in scene viewing are immediately influenced by the ease of processing of the image currently in view. These results are consistent with the CRISP (a timer-Controlled Random-Walk with Inhibition for Saccade Planning) computational model of saccade generation in scenes, proposing that difficulty in moment-by-moment visual and cognitive processing of the scene modulates fixation durations.

Keywords: eye movements, fixation duration, scene perception

During real-world scene exploration, viewers move their gaze from one scene region to another to process local visual information. Close or direct fixation on an object or scene region is necessary to perceive local visual details, to unambiguously identify objects, and to encode object and scene information into short- and long-term memory. What we see and understand about the visual world is tightly tied to our eye fixations (Henderson, 2003, 2008; Liversedge & Findlay, 2000; Rayner, 2009).

Given the importance of eye movements for perceptual and cognitive processing, a critical issue in visual perception and cognition concerns the nature of the control system that governs eye movements during scene viewing. Recent research has emphasized where fixations are placed in scenes, with a focus on how image properties and top-down factors interact to determine fixation placement (Baddeley & Tatler, 2006; Itti & Koch, 2001; Kanan, Tong, Zhang, & Cottrell, 2009; Navalpakkam & Itti, 2005; Parkhurst, Law, & Niebur, 2002; Torralba, Oliva, Castelhano, & Henderson, 2006; Zelinsky, 2008). However, far less research has focused on the factors that control how long the eyes remain fixated in a given location (Henderson, 2003, 2007; Rayner, 2009). This imbalance in emphasis on where rather than when the eyes move represents a gap in current knowledge.

Average fixation duration during scene viewing is about 300 ms, but there is substantial variability around this mean (Buswell, 1935; Henderson, 2003; Land & Hayhoe, 2001; Rayner, 1998). An important question is whether this variability is associated with ongoing perceptual and cognitive processing (Henderson, 2003, 2007). Visual quality manipulations involving image luminance, contrast, and blur have been shown to influence fixation durations (Loftus, 1985; Loftus, Kaufman, Nishimoto, & Ruthruff, 1992; Mannan, Ruddock, & Wooding, 1995). Similarly, viewing task can influence fixation durations, with longer durations during scene memorization than search (Henderson, Weeks, & Hollingworth, 1999; Mills, Hollingworth, Van der Stigchel, Hoffman, & Dodd, 2011; Nuthmann, Smith, Engbert, & Henderson, 2010). However, all of these effects could be due to changes in global fixation duration parameters. For example, fixation durations might simply be globally slowed when scene processing becomes more difficult (e.g., in low-contrast scenes). Alternatively, fixation durations
could reflect moment-to-moment changes in visual and cognitive difficulty, reacting to (and reflecting) in real time the transitory nature of the visual input. The degree to which fixations durations during scene viewing are controlled by temporally extended versus temporally immediate input is largely an open question.

Four studies have recently been reported that used a scene onset delay (SOD) paradigm to examine whether the durations of individual fixations can be controlled directly and immediately by the current stimulus (Henderson & Pierce, 2008; Henderson & Smith, 2009; Luke, Nuthmann, & Henderson, in press; Nuthmann et al., 2010). Eye movements were recorded while subjects viewed photographs of real-world scenes. Using a saccade-contingent display change technique, the scenes were occasionally (every nth saccade) removed from the display and replaced with a mask or gray field when the subject’s eyes were in saccadic movement from one location to another. In this way, the scene was not visible at the beginning of the next critical fixation. After a predetermined delay ranging from 0 to 1,200 ms, the scene returned to the display. The duration of the delay was varied, and the influence of the delay on the duration of the critical fixation was measured.

The main dependent variable in these experiments was the duration of the critical fixation. If fixation durations are directly controlled by the current visual input, then the durations of the critical fixations should systematically increase with the delay. If fixation durations are not under the immediate and direct control of the current scene input, then there should be no systematic relationship between delay duration and fixation duration. The results revealed two populations of fixation durations. One population had relatively short durations that ended before the scene reappeared, suggesting that these fixations were not under the direct control of the scene. Importantly, a second population of fixations increased in duration, with a strong linear relationship between delay duration and fixation duration. This second population demonstrated that the durations of a substantial number of fixations are under the direct control of the current scene.

The results from the SOD paradigm provide a compelling existence proof that scene processing during a fixation can produce an immediate and direct influence on the duration of that fixation, with moment-to-moment stimulus availability reflected in fixation duration. However, the SOD paradigm could be viewed as an extreme manipulation: It involves completely eliminating the scene during the critical fixation rather than changing scene variables that might affect how easily the scene is processed. It remains an open question whether a more subtle manipulation of quality of the scene during the critical fixation would produce an immediate and direct effect on fixation duration.

The present study introduced a new saccade-contingent scene degradation paradigm to answer this question. In this paradigm, participants freely viewed photographs of real-world scenes. During the saccade just prior to a prespecified critical fixation, the scene was reduced in quality via a decrease in luminance. In this way the luminance of the scene was lower when the eyes landed in each critical fixation. Then, during the saccade that terminated the critical fixation, the scene returned to its base luminance. In Experiment 1, three levels of luminance were used in the critical fixations: 100%, 80%, and 60% of base luminance. In the 100% condition, the software effected the saccade-contingent display change but the scene changed to an identical version of itself during the critical fixation as a control condition. In the 80% and 60% luminance conditions, luminance was reduced to those levels of base luminance during the critical fixations. Experiment 2 replicated the basic paradigm and added 40% and 20% conditions. In both experiments, luminance reduction had an immediate effect on fixation duration, with a monotonic relationship between fixation time and luminance reduction.

General Method

Subjects

Twenty members of the Edinburgh University (Experiment 1) and 20 members of the University of South Carolina (Experiment 2) communities, naïve with respect to the purposes of the study, participated for payment or course credit.

Apparatus

Eye movements were monitored with an SR Research Eyelink 1000. Eye position was sampled at 1,000 Hz and used a 9-sample saccade detection model with a 50% velocity trigger. Viewing was binocular, but only the right eye was tracked. The images were presented on a 21 in CRT monitor at a viewing distance of 90 cm with a refresh rate of 140 Hz. The experiment was controlled with SR Research Experiment Builder.

Stimuli

Stimuli were 40 unique full-color 800 × 600 pixel photographs of real-world scenes drawn from a variety of scene categories. Scenes subtended a visual angle of 25.7° × 19.4°. Base scenes were defined as 100% luminance. Scenes in the 80% and 60% reduced luminance conditions (Experiments 1 and 2) as well as the 40% and 20% conditions (Experiment 2) were created by converting the base scenes to L’a’b color space in which luminance is separated from two color channels, reducing the luminance channel to the appropriate level, and recombinining the three channels to form the reduced luminance versions of the scenes.

To ensure that the luminance manipulation was capable of affecting fixation durations, an initial control experiment was conducted in which 24 subjects freely viewed the scenes at the three levels of luminance while their eye movements were recorded. Each scene was presented at one of the three levels of luminance to each subject for the entire trial, luminance conditions were blocked, and scenes were rotated through conditions across subjects by Latin square so that each scene was shown to each subject once and appeared in each condition an equal number of times across subjects. Each scene was presented for 12 s. Analyses were restricted to the first five seconds of scene inspection as effects are known to diminish gradually with viewing time (Reinagel & Zador, 1999). The results showed a significant effect of luminance on fixation durations, \( F(2, 46) = 10.7, \text{MSe} = 266, p < .001 \), with fixation durations of 249, 258, 270 ms in the 100%, 80%, and 60% conditions respectively, validating the luminance manipulation. These results are consistent with prior reports (Loftus, 1985; Loftus et al., 1992).

Procedure

Each scene was presented for 64 fixations. Two instances of the three conditions appeared in each scene for each subject, so each
subject experienced 80 instances of each condition (two instances of each condition per scene and 40 scenes). The order of presentation of conditions within each scene was randomly determined.

Subjects were instructed to view the scenes in preparation for a later memory test and to ignore any occasional flicker they might notice. The memory test was not administered.

Luminance reduction was implemented using a saccade-contingent display change technique: The luminance of the displayed scene was reduced during the saccade just prior to the critical fixation (see Figure 1). With this method the display change took place during the saccade when visual transients were suppressed, and the luminance was already reduced on the CRT when the critical fixation began. The luminance manipulation occurred every five saccades, but because in the 100% control condition luminance did not actually change, luminance reductions occurred following a variable number of fixations. When the eyes moved to terminate a critical fixation, the scene returned to the base luminance level.

An experimental trial took place as follows. First, calibration was checked. A central fixation point was then presented. Once the participant had fixated the point, the experimenter initiated the trial and the scene was presented for free viewing. Following 64 fixations, the scene was terminated and calibration was checked for the next trial.

Results

Critical fixations were excluded from analysis if they were preceded by or co-occurred with blinks, were the first, second, or last fixation in a trial, had durations less than 50 ms or longer than 1,200 ms, or if the display change was not completed during the prior saccade.

If fixations are under real-time control of the properties of the currently viewed scene, then fixation durations should immediately be related to the luminance of the scene in the critical fixation, with increasing durations for decreasing luminance. Consistent with this prediction, average critical fixation duration was significantly affected by luminance in both Experiment 1 \(F(2, 38) = 18.4, p < .001\) and 2 \(F(2.77, 52.68) = 13.52, p < .001\). In Experiment 1, fixation durations were 304, 346, and 399 ms in the 100%, 80%, and 60% conditions, respectively. In Experiment 2, fixation durations were 306, 332, 360, 396, and 445 ms in the

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1 Mauchly’s test indicated that the assumption of sphericity was violated. Therefore, degrees of freedom were adjusted using Greenhouse–Geisser correction.
100%, 80%, 60%, 40%, and 20% conditions, respectively. These data are shown in Figure 2.

Discussion

The present study introduced a new saccade-contingent scene degradation paradigm to investigate whether fixation durations are under the immediate control of the currently visible scene. In this paradigm, participants freely viewed photographs of real-world scenes. During the saccade just prior to a prespecified critical fixation, the image of the scene was changed so that its luminance was lower when the eyes landed. Then, during the saccade that terminated the critical fixation, the scene returned to its base luminance. If fixation duration during scene viewing reflects the difficulty of scene analysis taking place during that fixation, then critical fixation durations should increase as luminance decreases. On the other hand, if fixation duration is independent of immediate scene analysis, or reflects more temporally distributed scene properties, then critical fixation durations should not be influenced by momentary luminance level. Consistent with the first hypothesis, fixation durations increased monotonically as luminance decreased.

How can we account for the real-time control of fixation durations during scene viewing? We have proposed CRISP, a timer-Controlled Random-Walk with Inhibition for Saccade Planning computational model, to account for saccade timing and programming and so for variations in fixation durations during scene viewing (Nuthmann & Henderson, 2012; Nuthmann et al., 2010). The model architecture can be summarized with three main principles. First, timing signals for saccades are modeled as random walks. The random walk timing signal accumulates toward a threshold. Once the threshold is reached, a new saccade program is initiated. Second, saccade programming is completed in two stages (Becker & Jürgens, 1979). The saccade program first enters a labile stage where it can still be modified or even cancelled. The program then enters a nonlabile stage, which inevitably leads to saccade execution. Fixation durations are derived from the model as the time intervals between successive saccades. Third, difficulties arising from perceptual and cognitive analysis can inhibit and thus, modulate saccade timing and programming, leading to longer fixation durations. The CRISP model was initially tested using the stimulus onset delay paradigm (Nuthmann & Henderson, 2012; Nuthmann et al., 2010). In the context of those simulation studies, we proposed and tested two mechanisms by which saccade timing

2 The common data points across experiments (100%, 80%, 60% conditions) did not statistically differ. However, this null effect should be treated with caution given that the experiments were not designed for direct comparison.

Figure 2. Fixation durations in the fixation-contingent scene quality paradigm: average critical fixation duration as a function of luminance level in Experiment 1 (circles, connected by solid line) and Experiment 2 (triangles, connected by broken line). Error bars and shaded areas represent the standard error of the mean.
and programming can be modulated by visual-cognitive processing. Current processing demands immediately modulate the random walk’s transition rate and thus, affect the speed at which new timing signals are generated. Processing difficulties can further lead to saccade cancellation.

In the present study, the durations of critical fixations were immediately lengthened when scene luminance was reduced, with a monotonic relationship between fixation durations and luminance reduction. These data lend support to a core assumption of CRISP, that the immediate difficulty of scene analysis can exert real-time influence on fixation durations. The results more generally support the view that real-time control is a general property of eye movement programming during scene viewing.

References


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