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Asymmetrical Control of Fixation Durations in Scene Viewing

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Abstract

In two experiments we investigated the control of fixation durations in naturalistic scene viewing. Empirical evidence from the scene onset delay paradigm and numerical simulations of such data with the CRISP model [Psychological Review 117 (2010) 382-405] have suggested that processing related difficulties may lead to prolonged fixation durations. Here, we ask whether processing related facilitation may lead to comparable decreases to fixation durations. Research in visual search and reading have reported only uni-directional shifts. To address the question of unidirectional (slow down) as opposed to bidirectional (slow down and speed up) adjustment of fixation durations in the context of scene viewing, we used a saccade-contingent display change method to either reduce or increase the luminance of the scene during prespecified critical fixations. Degrading the stimulus by shifting luminance down resulted in an immediate increase to fixation durations. However, clarifying the stimulus by shifting luminance upwards did not result in a comparable decrease to fixation durations. These results suggest that the control of fixation durations in scene viewing is asymmetric, as has been reported for visual search and reading.

Keywords: fixation durations, eye movements, scene viewing, direct control

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1. Introduction

The study of eye guidance during naturalistic scene viewing aims to understand the processes that underlie the acquisition of vital visual information from the environment that is relevant to current tasks and goals. Described in a very general manner, investigation into the control of eye movements in scene viewing has proceeded along two primary pathways. The first seeks to address questions relating to where eye movements are directed towards, while the second addresses questions regarding when the eyes move away from currently fixated content. The first question, relating to the spatial aspects of eye movements, has received considerable attention while there is relatively less research investigating the related temporal component (Murray, Fischer & Tatler, 2013). Mean fixation durations in scene viewing are about 300 ms (Rayner, 2009) but there is considerable variability around this mean both within and across individuals. Current understanding of eye-movement programming suggests that some of the variability in the duration of individual fixations may result from factors directly related to oculomotor programming (Becker & Jürgens, 1979; Nuthmann, Smith, Engbert & Henderson, 2010; Walshe & Nuthmann, 2013), as well as global scene properties (e.g. Loftus, 1985; Henderson, Nuthmann & Luke, 2013; Nuthmann et al., 2010), and decisional processes relating to future target selection (Glaholt & Reingold, 2012).

The structure of the mechanisms that govern fixation times has been investigated in a wide variety of tasks (Rayner, 2009). Research that addresses these questions often aims to reveal the manner in which the eye-movement control system adaptively monitors and responds to environmental demands. A debate of critical importance for the understanding of the temporal characteristics of fixation times is the degree to which stimulus content that is currently under inspection influences the decision of when to terminate the current fixation (Reingold, Reichle, Glaholt & Sheridan, 2012). The hypothesis that fixations are capable of being adjusted on a moment-to-moment basis is referred to as the direct control hypothesis (reading: Rayner & Pollatsek, 1981, scene perception: Henderson & Pierce, 2008; Nuthmann et al., 2010).

This hypothesis is characterised by the assertion that when a fixation duration is under the direct control of stimulus content, there is an immediate adjustment to match the processing demands of the stimulus. In contrast, fixations may be indirectly controlled, and this occurs in the case where fixation times are governed by influences that extend beyond the locally fixated content. For instance, from studies of visual search it is known that fixation durations increase as the complexity of the search array increases (Vlaskamp & Hooge, 2006), when target-distractor similarity is increased (Hooge & Erkelens, 1998; Vlaskamp, Over & Hooge, 2005), and in order to match the difficulty of previously fixated items (Hooge & Erkelens, 1998). These results imply that the eye-movement control system is sensitive, at least in some part, to the global characteristics of the task.

A variety of direct-control mechanisms have been proposed to account for the moment-to-moment adaptation of fixations to current stimulus processing. Concepts related to the structure of direct control mechanisms have seen the most development in theories of fixation times in reading. In reading, a debate exists regarding how the lexical properties of the currently fixated word impacts the time course of that fixation. Mechanisms used to account for such lexical effects may be contrasted as those that implement what is known as a *cognitive trigger*, and those that implement *interference* mechanisms (see Reingold et al., 2012). Cognitive trigger theories postulate that the decision to terminate a fixation is made once the stimulus under inspection has been processed to a sufficient degree, and when this occurs a saccade programme is then triggered. One implementation of such a mechanism is incorporated in the E-Z Reader model, in which an eye-movement programme is triggered once a superficial stage of lexical processing has been accomplished (Reichle, Pollatsek, Fisher & Rayner, 1998; Reichle, Pollatsek & Rayner, 2012). In contrast to the triggering mechanisms just described are those that suggest that the variability in the termination of a fixation is a result of difficulties in lexical processing that interfere with the saccade initiation processes. A model that instantiates a variety of direct control along these lines is the SWIFT model (Engbert, Nuthmann, Richter & Kliegl, 2005). In the SWIFT model, the decision to initiate a saccade programme is achieved by an autonomous random timer, and the duration of this timing process may be modulated by the difficulties encountered during lexical processing. Therefore, moment-to-moment difficulties in lexical processing results in increased random timing intervals, and consequently, longer fixation durations.

Although less is known about the mechanisms that govern eye-movement control in scene perception, a model that incorporates an interference mechanism to explain fixation times in this domain is known as the CRISP model (Nuthmann et al., 2010). In this model, an autonomous random walk timer accumulates towards a fixed threshold value and when this threshold is reached, a saccade program is initiated. In the case in which processing difficulties are encountered during scene viewing, the rate at which the timer accumulates to the threshold is reduced. A consequence of such a reduction in the rate of the timer is that the initiation of saccades may be delayed, and therefore longer fixation durations will be observed. An assumption that was made in the original formulation of the CRISP model was that modulations to the timer result exclusively from unidirectional modulations (timer slowdown) (Nuthmann et al., 2010).

An experimental paradigm that has provided some evidence for the direct control of fixations in scene viewing is known as the scene onset delay (SOD) paradigm (Henderson & Pierce, 2008; Henderson & Smith, 2009; Luke, Nuthmann & Henderson, 2013; Nuthmann et al., 2010; Nuthmann & Henderson, 2012). In the SOD paradigm, a scene is masked during a saccade preceding a critical fixation and then restored to full view at varying delays within the critical fixation. Consistently across studies, a population of fixation durations that increased in correspondence with the length of the delay was observed. It was argued that these fixations were increased due to the immediate effects attributable to the missing stimulus. Pannasch, Schulz & Velichkovsky (2011) used a scene based free viewing task in which an irrelevant distractor was introduced either early or late within a critical fixation. Similar to the SOD paradigm, the distractors were presented for variable durations. The results demonstrated that the visual change introduced by the distractor had an immediate prolongation effect on fixation durations, regardless of whether the distractor occurred early or late in fixation, which provided additional support for the direct-control hypothesis.

Going beyond the extreme manipulations of the SOD paradigm, subsequent research has utilised a fixation-contingent scene quality paradigm (Henderson et al., 2013; Glaholt, Rayner & Reingold, 2013). During selected critical fixations, the entire scene was reduced in quality via a decrease in luminance (Henderson et al., 2013), or by filtering high or low spatial frequencies (Glaholt et al., 2013). Such manipulations are assumed to have deleterious effects on scene processing by influencing the rate at which information is extracted from scenes (Loftus, 1985) as well as impacting the fluent encoding of scene stimuli into working memory (Glaholt et al., 2013). In a study by Henderson et al. (2013), the luminance of the (colour) scene was reduced during the saccade prior to a prespecified critical fixation. During the saccade that terminated the critical fixation, the scene returned to its normal luminance. The durations of the critical fixations were immediately affected by the reduction in scene luminance, with increasing durations for decreasing luminance. Glaholt et al. (2013), on the other hand, demonstrated that fixation durations were affected on a fixation-by-fixation basis depending on the spatial frequency content of the scene stimulus. In their main experiment, during the critical fixation the (greyscale) scene was changed to a high-pass or low-pass spatial frequency filtered version. Under both conditions, fixation durations increased, and low-pass filtering produced a greater effect than high-pass filtering. In a further experiment, the authors additionally modified the orientation of the images, and using a distributional analysis of fixation durations they were able to differentiate between directly controlled extensions to fixations attributable due to higher-level cognitive influences, and transsaccadic changes resulting in a surprise effect. These results taken together, are highly suggestive that in scene viewing, as in reading, the control of fixation durations is subject to ongoing visual-cognitive processing, such that increases to processing difficulty result in extended fixation durations.

However, further questions regarding the properties of this direct-control process remain. For instance, in the studies that were previously reviewed, the observed effects on fixation durations were primarily ones in which an increase in processing difficulty resulted in an extension to fixation durations. Therefore, these studies demonstrate that there is a tendency for fixations to be immediately adjusted to match the difficulty of the stimulus. However, it is less clear whether the converse is true. That is, will a decrease to fixation durations be observed in the case in which the processing of a stimulus becomes easier and more fluent?

In reading, Kennison & Clifton (1995) investigated the impact of word frequency on two adjacent words embedded in single sentences. High and low word frequency adjectives were followed by high and low word frequency nouns. Parafoveal preview of the noun was prevented by using the invisible boundary technique. When readers first fixated a high-frequency adjective, fixation durations on the subsequent noun showed a word frequency effect, such that longer fixation durations were observed for low-frequency than for high-frequency nouns. In contrast, no such word frequency effect was observed when readers first fixated a low-frequency adjective. Thus, increasing processing demands (high $\rightarrow$ low) resulted in an immediate prolongation of fixation durations, whereas decreasing processing demands (low $\rightarrow$ high) showed no immediate facilitatory effect.

Such an asymmetry in the temporal control of fixation durations has also been observed in visual search. Hooge, Vlaskamp & Over (2007) used a search task in which participants were required to find a closed ring amongst distractor Cs. The distractors in their task varied in the size of the gap, such that small gap Cs were more difficult to distinguish from the target stimulus than were large gap Cs. They found that fixations on small gap Cs that were preceded by a fixation on a large gap C, showed increased durations. However, a fixation on a large gap C following a fixation on a small gap did not show a corresponding decrease to fixation duration. These results taken together suggest that the control of fixation durations in both reading and visual search tasks involves an asymmetrical pattern of control. While these results provide some guidance on the question of whether asymmetrical control principles generalise to scene viewing tasks, there currently exists no experimental evidence to confirm whether this is the case.

The purpose of the current study was to directly test the hypothesis that the control of fixation durations in scene viewing is asymmetric. To manipulate processing difficulty of the currently fixated stimulus, the present study employed a luminance manipulation such that increased difficulty was obtained by shifting luminance downwards, and decreased difficulty was obtained by shifting luminance upwards. The assumption that modulation of scene luminance levels may be used to control the difficulty of scene processing is derived from several sources. Past research has shown that luminance has strong effects on scene processing, with lowered recognition and recall rates of scenes when they are viewed at a lower level of luminance (Loftus, 1985; van der Linde, Rajashekar, Bovik & Cormack, 2009). These effects are paralleled by an increase in fixation durations to compensate for the increase in processing difficulty encountered due to the luminance reduction (Loftus, 1985). More recently, a control experiment conducted by Henderson et al. (2013) used a free viewing task in which scenes were viewed at 100%, 80%, or 60% original scene luminance throughout the course of the entire trial. They demonstrated that scene luminance had a clear influence on fixation durations such that longer mean fixation durations were observed when scenes were viewed at lower luminance levels. Therefore, these results taken together support the assumption that scene luminance is parametrically related to scene processing difficulty.

In order to test the hypothesis that the direct control mechanism operates in an asymmetric manner, a fixation-contingent scene quality paradigm was used (Henderson et al., 2013). With this method, the luminance shifts took place during saccades when visual transients were suppressed (Ross, Morrone, Goldberg & Burr, 2001; McConkie & Loschky, 2002). While it may be predicted from the gaze-contingent manipulations of Henderson et al. (2013), that longer fixation durations will be observed following a gaze contingent decrease in luminance, it is currently unclear how an increase in luminance will be interpreted by the eye-movement control system during naturalistic scene viewing. The prediction of an asymmetrical direct-control mechanism is that decreased luminance will result in longer fixations, while increased luminance will have no effect. In contrast, symmetrical direct control would predict that shifting luminance down will result in longer fixation durations, and clarifying the stimulus by shifting luminance up will result in shorter fixation durations.

2. Experiments

2.1. General Methods

2.1.1. Stimuli

In each of two experiments, participants viewed a total of 100 pictures of real-world scenes, in addition to 4 practice scenes. Each scene had a resolution of 800x600 pixels and was presented in full colour. Scenes were collected from online databases such as google images. They were selected to include a variety of categories such as indoor and outdoor as well as urban and nature scenes. Each scene was viewed by the participant only once over the duration of the experiment, and the experimental scenes were presented to the participants in a randomised order. Initially, scenes were presented at a baseline luminance of 80% in Experiment 1, and 60% in Experiment 2. In order to observe the effect of relative luminance shifts on fixation durations, a luminance transformation was applied. Luminance shifted stimuli were created by converting the original scene into a $L*a*b$ colour space (Oliva & Schyns, 2000), and modifying the luminance channel L by the appropriate value. This procedure allows the separation of a luminance channel from the two colour channels, and permits the transformation of scene luminance independently of scene colour. Baseline and low luminance conditions for Experiment 1 were constructed by a $L*.8$ and $L*.6$ transformation, respectively. For Experiment 2, a similar procedure was adopted, but the luminance transformation applied was $L*.6$ and $L*.2$. In both Experiment 1 and Experiment 2, the stimulus used in the high (100%) luminance condition was the untransformed scene.

2.1.2. Procedure

Participants were instructed that they would take part in an experiment in which they would see many pictures of naturalistic content and that their task was to encode the scenes for later recall. They were instructed that the recall phase would only begin once all the scenes had been viewed, but were not told how many scenes would be presented. These instructions were provided only to motivate scene encoding behaviour, and therefore the recall phase was not applied. Following the instructions, a nine-point eye-tracker calibration procedure was initiated. A trial began when the participant fixated on a cross presented at the centre of the screen. Following this fixation, the red cross and grey background were replaced with the scene presented at baseline luminance. Participants then engaged in the encoding task until a critical fixation was identified when a participant had made at least 10 saccades since the beginning of the trial. If a critical fixation had been identified, the luminance shift was made during the saccade immediately preceding the critical fixation. The luminance-shifted scene was presented for the entire duration of the critical fixation, and the luminance was then shifted back to baseline during the saccade immediately following the critical fixation. In total, four luminance manipulations were made on each trial; two manipulations resulted in an upward luminance shift, and two manipulations were made in the downward direction. After the first luminance manipulation had been completed, subsequent shifts occurred on every 10^{th} saccade since the most recent luminance shift. The order of the luminance shift direction (increase vs. decrease), was randomised within a trial. Once the fourth luminance shift had been made, and the participant terminated the resulting critical fixation, one second elapsed until the trial was terminated. The scene was then replaced with a grey background and red fixation cross. Once the participant fixated on the cross, the next trial was initiated. In the situation that the trial lasted longer than 25 seconds, the current trial was abandoned, and the participant was presented with a fixation cross to initiate the next trial. A schematic of the procedure for upward luminance shifts is presented in Figure 1. The mean trial length in Experiment 1 was 18.1 seconds and 19.2 seconds in Experiment 2. The mean number of saccades per trial was 50.3 in Experiment 1, and 48.1 in Experiment 2.

2.1.3. Apparatus

Stimuli were presented on a 21-inch CRT monitor with a refresh rate of 140 Hz. The monitor screen was at a distance of 90 cm from the participant. During stimulus presentation, participants' eye movements were recorded using an SR Research EyeLink 1000 Desktop mount system. It was equipped with the 2000 Hz camera upgrade, allowing for binocular recordings at a sampling rate of 1000 Hz for each eye. Viewing was binocular, and both eyes were tracked. A chin rest was used in order to achieve stability of a participant's head position relative to the screen. The experiment was implemented in MATLAB 2009b using the OpenGL-based Psychophysics Toolbox

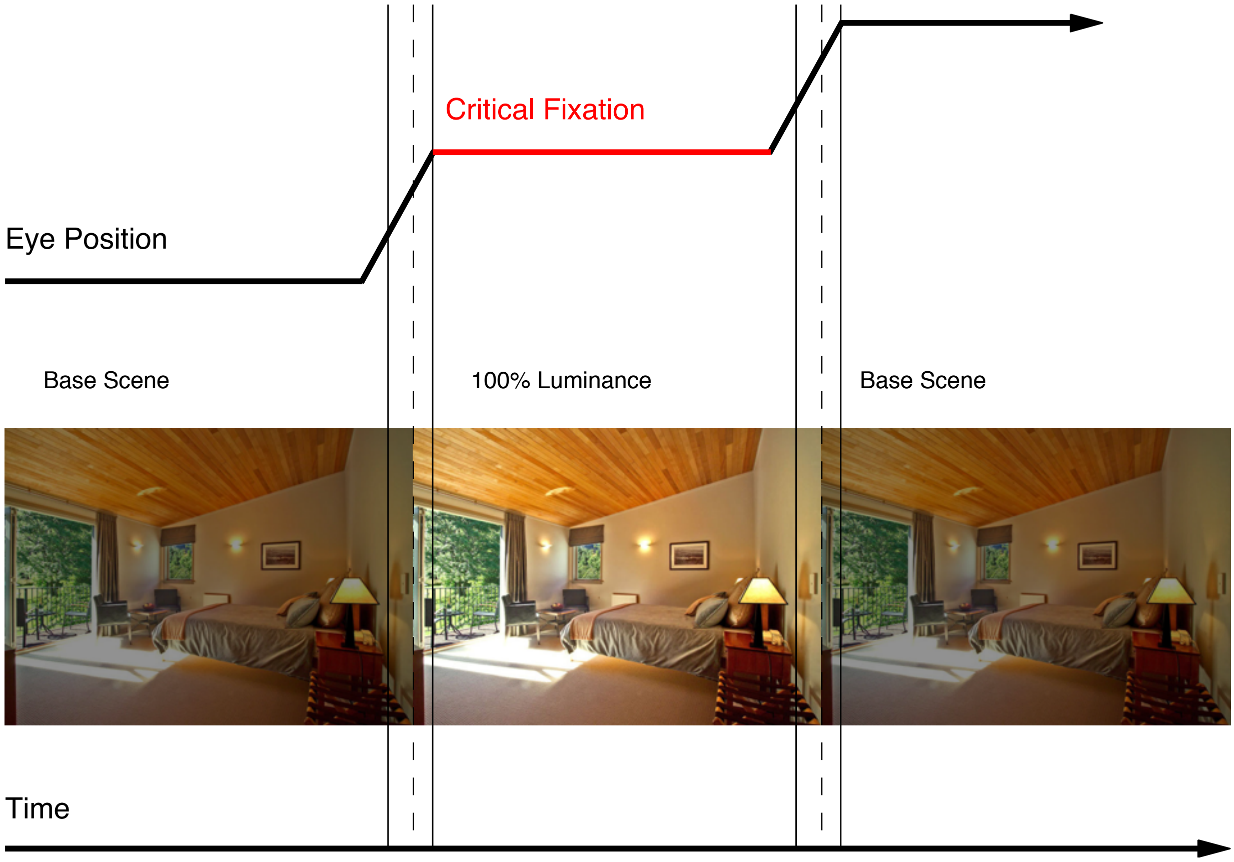

Fig. 1. A schematic of the paradigm used to create gaze contingent luminance shifts. Base scenes represent the image that is viewed during the fixation immediately preceding a critical fixation. A critical fixation is defined to occur on the 10^{th} fixation since the previous luminance manipulation. The oblique lines represent saccadic eye movements. During a saccadic eye movement, the scene is either increased or decreased in luminance. A critical fixation is terminated upon detection of a saccadic eye-movement, and the scene is restored to base scene luminance during this saccade.

3 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007), which incorporates the EyeLink Toolbox extensions (Cornelissen, Peters & Palmer, 2002). The software allowed precise control over the timing of display changes.

Online detection of saccades involves a speed-accuracy trade off, such that incorporating more samples reduces the noise in the signal. However, by increasing the number of samples, measurement lag is increased, which decreases the temporal precision with which saccades are detected. We implemented a 9-sample online velocity detection algorithm in MATLAB that aimed to mimic Data Viewer's offline saccade detection procedure (SR Research Ltd., 2006). Saccades were identified when gaze data from the right eye reached a two-dimensional velocity threshold of $85°/s$. Raw data was post-processed utilising SR Research Data Viewer to parse the gaze samples into sequences of fixations and saccades.

Several data exclusion criteria were applied to remove critical fixations that had been misidentified. Prior to any data exclusion, 97.9% of the luminance manipulations were executed in Experiment 1 and 95.7% were executed in Experiment 2. This number is less than 100%, as a trial would occasionally timeout before all luminance shifts had been completed. Critical fixations on which the display change did not complete prior to fixation onset were discarded. This criteria was validated by comparing the saccades detected online with saccades identified by the post-processed Data Viewer output. Comparison with the post-processed data represents an objective measure, as this data incorporates acceleration and velocity of both prior and future eye-position samples, in detecting current saccadic activity. This resulted in retention of 85.4% of the data in Experiment 1, and 86.4% in Experiment 2. Critical fixations that co-occurred with blinks were also excluded from the analysis. Removing blinks resulted in 67.5% of the critical fixations being retained in Experiment 1, and 68.4% in Experiment 2. A final criteria was applied that excluded critical fixations that had durations of less than 50 ms or greater than 1200 ms, on the assumption that they are not determined by cognitive level processes under investigation in this study (Inhoff & Radach, 1998). As a result of the application of all criteria, 65.8% of the critical fixation were retained in Experiment 1 and 65.1% were retained in Experiment 2.

2.1.4. Analysis

Data were analysed with linear mixed-effects (LME) models, using the `lmer` programme of the `lme4` package (Bates, Maechler & Bolker, 2012) implemented in the R statistical computing software (R Core Team, 2012). To evaluate the effect of the downward and upward luminance shifts on fixation duration, we used treatment contrasts in which the baseline condition, where no luminance change occurred, served as the reference group. Consequently, the intercept for the fixed effect "luminance shift", estimates the mean value for the no-shift condition. The two slopes estimate the difference between downward luminance shift and no shift (DOWN) and between upward luminance shift and no shift (UP). The effect of luminance is assessed in the LME model by observing regression coefficients for the luminance shift conditions that are significantly different from 0; a two-tailed criterion of $t = 1.96$ was used to assess statistical significance. The LME models included random intercepts and random slopes for participants and items (Baayen, Davidson & Bates, 2008).

Additional ex-Gaussian distributional analyses of fixation durations were conducted by employing a generalised additive model location, scale and shape (GAMLSS) framework, using the `gamlss` package (Rigby & Stasinopoulos, 2005) implemented in R. GAMLSS is a regression framework that allows the response variability to be modelled by skewed distributions such as the ex-Gaussian distribution. Regression coefficients of the ex-Gaussian parameters contrasted the two treatment conditions (DOWN and UP) with the baseline condition. A two-tailed criterion of $t = 1.96$ was used to assess statistical significance.

2.2. Experiment 1

2.2.1. Methods

Stimuli. The stimuli used in Experiment 1 were presented at a baseline level of 80% of original scene luminance throughout the trial. Upon detection of a saccade preceding the critical fixation, the stimulus was replaced with a scene which had the luminance raised or lowered by a margin of 20%. This meant that in the DOWN condition, participants viewed a stimulus at 60% original luminance, and in the UP condition participants viewed a stimulus at 100% original luminance. During the saccade that terminated the critical fixation, the scene returned to its base luminance.

Participants. Four males and 18 females were recruited from the University of Edinburgh student population. The mean age of the participants was 21 years. Each participant was paid £7 per hour of participation in compensation for their time.

2.2.2. Results

The goal of the analysis was to assess the impact that gaze-contingent luminance shifts have on fixation durations. Therefore, our analysis was restricted to critical fixations that began following the termination of a saccade and ended with the initiation of a subsequent saccade. In all cases, the critical fixation was defined such that a luminance manipulation had been made during the saccade immediately preceding the fixation. A baseline measure was constructed in order to detect differences between luminance shifted fixations and fixations in which no luminance shift took place. For each luminance manipulation that survived the exclusion criteria, we measured the duration of the fixation immediately preceding the critical saccade. Since the participant was unaware that a luminance manipulation was to take place during the subsequent saccade, this fixation duration represents an accurate measure of fixation on the unmodified image. It is important to note that a baseline condition with a greater number of observations than were present in either the UP or the DOWN condition was used (cf., Glaholt et al., 2013). A strength of the linear mixed-effects modelling approach adopted in the present study is that it can deal with unbalanced designs (Baayen et al., 2008).

The mean pattern of critical fixation durations is presented in Figure 2. To reiterate, the intercept for the fixed effect of luminance shift estimates the mean value for the no-shift condition ($b = 297.30, SE = 9.20, t = 32.30$). As expected, downward luminance shifts were associated with critical fixations that were significantly longer than in the no-shift condition ($b = 44.92, SE = 6.07, t = 7.40$). In addition, there was also a significant increase in fixation durations for upward luminance shifts ($b = 13.28, SE = 4.21, t = 3.15$). The effect of the UP condition is contrary to predictions by both the asymmetric control hypothesis (no change) and symmetric control hypothesis (decrease). When translating the estimated effects of luminance shift into a % increase relative to baseline, it becomes apparent that the effect was much smaller in the UP condition (4.5% increase) than in the DOWN condition (15.1% increase). Comparing the between condition means is informative for the asymmetrical control hypothesis under investigation in the current study. However, changes in mean fixation duration (or the lack thereof) may reflect distinct patterns at the level of underlying distributions. More specifically, previous work on eye guidance in reading and scene perception has argued that applying an ex-Gaussian distributional analysis to fixation durations allows inferences about the time course of effects by quantifying whether effects may be attributed to a shift in central tendency or tail of the distribution (Glaholt & Reingold, 2012; Reingold et al., 2012; Luke et al., 2013; Staub, White, Drieghe, Hollway & Rayner, 2010). The ex-Gaussian is a three-parameter distribution that is derived by a convolution of the Gaussian distribution with the exponential distribution. The parameters contributed by the Gaussian distribution are μ and σ, and describe the central tendency and the spread of the distribution. The τ parameter contributed by the exponential distribution provides a measure of the skewness of the distribution and is useful for describing effects that specifically impact the tail of the distribution.

Figure 3a and c plot the empirical distribution and ex-Gaussian fitted distributions for Experiment 1. Consistent with the findings from the analysis of means, the distributions for both the

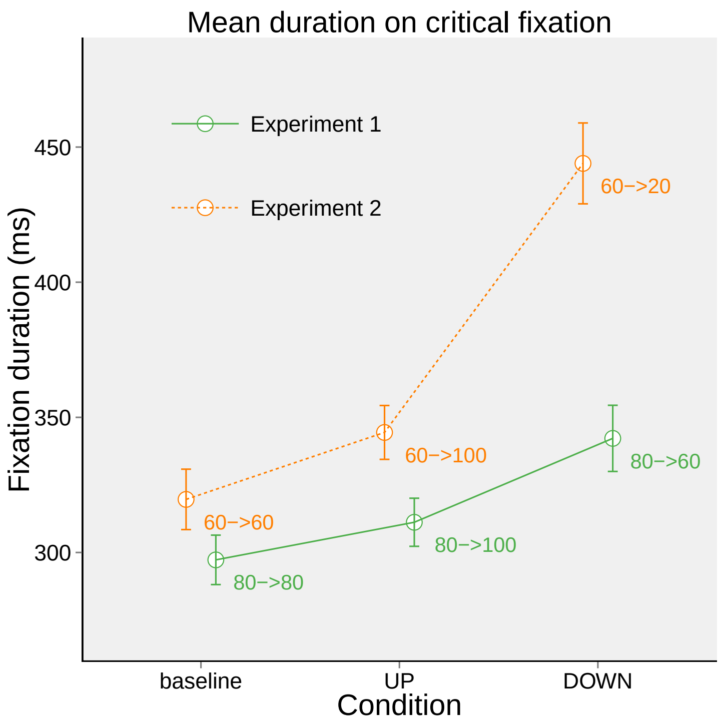

Fig. 2. Mean fixation durations on critical fixations following gaze-contingent luminance shifts. Fixation durations are plotted as a function of the direction of luminance shift. Data is plotted for Experiment 1 (solid line) and for Experiment 2 (dashed line). Error bars represent the standard error of the mean.

DOWN and UP condition are shifted to the right relative to the baseline condition, indicating a higher probability of observing longer fixation durations in these conditions. Accordingly, there was a significant effect of DOWN on μ in the ex-Gaussian fit ($b = 50.06, SE = 2.87, t = 17.40$). There was also a significant effect of UP on μ ($b = 32.04, SE = 2.64, t = 12.11$). A statistically significant effect of DOWN on σ was observed ($b = 10.29, SE = 2.11, t = 4.87$), indicating that the spread of the distribution was larger than in the no-shift control condition. In contrast, there was no effect on σ for the UP condition ($b = 1.59, SE = 1.99, t = 0.79$). An analysis of the τ parameter of the ex-Gaussian fit revealed that the increase in fixation durations in the DOWN and UP conditions does not result from increases that are specifically attributable to the tails of the distributions. Rather, the fixation duration distribution in the UP condition was significantly less skewed than the baseline condition, evidenced by a significant negative effect on τ ($b = -19.92, SE = 3.86, t = -5.13$). DOWN had a small, marginally significant, negative effect on τ ($b = -8.08, SE = 4.14, t = -1.94$).

2.2.3. Discussion

A 20% luminance reduction of the entire scene during critical fixations was associated with an immediate lengthening of those fixations' duration. The pattern of mean fixation durations for a fixation-contingent downward shift in luminance is consistent with results by Henderson et al. (2013). Thus, we provide a replication of their results with a different base luminance level (80% rather than 100%), different scene stimuli and participants, and statistical evaluation that controlled for variability introduced by participants and items. In addition, the current experiment included a condition in which processing was made easier by shifting luminance upwards (from 80% to 100%). There was no facilitatory effect of shortened fixation durations observed in this condition, which is consistent with research in visual search (Hooge et al., 2007) and in reading (Kennison & Clifton, 1995). On the contrary, in the UP condition we observed a significant lengthening of fixation durations, but the magnitude of the increase to fixation durations was considerably smaller than in the DOWN condition. Taken together, the results are indicative of an asymmetrical pattern of control such that difficulties in scene processing are directly incorporated and result in longer fixation durations, whereas processing facilitation does not lead to a comparable decrease in fixation durations.

One possibility for the lack of a speedup in the UP condition is that the magnitude of the luminance difference between the baseline and increase in luminance was insufficient to provide enough processing facilitation to elicit shorter fixation durations. That is, the possibility remains that while a luminance shift from 80% to 60% is sufficient to create scene processing difficulties, a shift from 80% to 100% is insufficient to create a context for processing facilitation. This hypothesis is strengthened by the results of the distributional analyses. This analysis showed that in the UP condition, an overall shift in the distribution occurred due to a significant positive effect on μ. However, we also observed a significant negative influence on the tail of the distribution (decrease in τ), indicating a significantly less skewed distribution in the UP condition. Therefore, we hypothesise that a more extreme luminance enhancement may result in a diminished impact on the central tendency of the distribution than was observed in Experiment 1, but that the influence on the tail of the distribution will remain. Experiment 2 was designed to address this possibility by lowering the baseline luminance of the scene to 60% and further lowering the luminance to 20% in the DOWN condition and raising it to 100% in the UP condition.

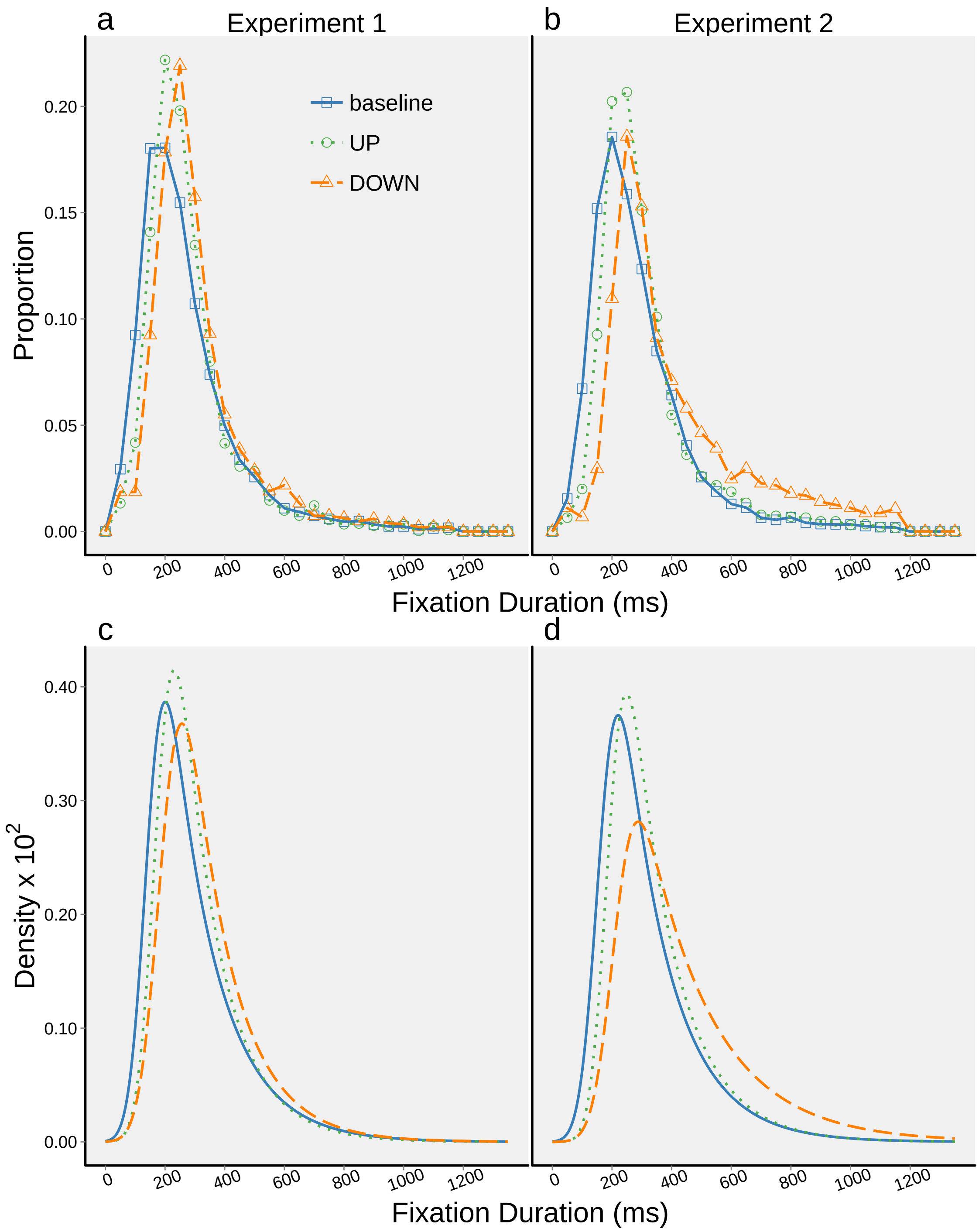

Fig. 3. Fixation duration distributions. Empirical distributions for the three luminance conditions in Experiments 1 (Panel a) and Experiment 2 (Panel b), and their respective ex-Gaussian fitted distributions plotted in (Panel c) and (Panel d).

2.3. Experiment 2

2.3.1. Methods

Procedure and Stimuli. The procedure and stimuli for Experiment 2 were identical to that of Experiment 1 in all aspects other than the magnitude of the luminance change. During the saccade immediately preceding a critical fixation, the luminance was either shifted up to 100% or down to 20% luminance, from a 60% luminance baseline. During the saccade immediately following the critical fixation, the luminance of the scene was changed back to the 60% baseline level.

Participants. 13 females and 4 males who did not participate in Experiment 1 were tested in Experiment 2. The mean age of the participants was 24 years. Each participant was paid £7 per hour of participation in compensation for their time.

2.3.2. Results

Experiment 2 sought to complement the results observed in Experiment 1 by testing whether similar effects would be observed when a different baseline luminance level was used, and when the magnitude of the luminance shifts was increased. The observed pattern of mean durations is plotted in Figure 2. In the LME model, the intercept for the fixed effect of luminance shift estimates the mean value for the no-shift condition ($b = 319.47, SE = 11.09, t = 28.79$). Experiment 2 used a lower baseline level of original scene luminance than Experiment 1 (60% vs. 80%). Accordingly, the mean fixation duration in the no-shift baseline luminance condition was longer in Experiment 2 than in Experiment 1 (319 ms vs. 297 ms, Figure 2). Following the default prediction, downward luminance shifts were associated with critical fixations that were significantly longer than in the no-shift condition ($b = 124.28, SE = 13.15, t = 9.44$). Experiment 2 used a greater magnitude of luminance shifts than Experiment 1 (40% as opposed to 20%). Therefore, downward shifts in luminance resulted in a larger relative increase in fixation duration in Experiment 2 as compared to Experiment 1 (Figure 2). In addition, there was again a significant increase in fixation durations for upward luminance shifts ($b = 24.55, SE = 7.92, t = 3.10$). Relative to the no-shift baseline condition, fixation durations increased by 38.9% in the DOWN condition but only 7.7% in the UP condition.

The approach to analysing the distributional effects in Experiment 2 was conducted along analogous lines to Experiment 1. Figure 3b and d show the empirical and ex-Gaussian fitted distributions. A similar pattern was found to Experiment 1 in that the distributions showed a general rightward shift consistent with the increased mean durations observed in both luminance shift conditions. The GAMLSS model yielded a significant positive effect on μ for both the DOWN and UP conditions relative to the no-shift baseline condition (DOWN: $b = 51.63, SE = 3.65, t = 14.13$; UP: $b = 31.11, SE = 3.02, t = 10.28$). In the DOWN condition, there was a significant positive effect on σ ($b = 7.42, SE = 2.71, t = 2.73$), indicative of an increase in the variance in this condition. As in Experiment 1, there was no effect on σ in the UP condition ($b = -2.77, SE = 2.28, t = -1.21$). With regard to the τ parameter, a different pattern of results was observed than in Experiment 1. In the DOWN condition, there was a substantial increase in long fixation durations, which is manifested as a more positively skewed distribution. This late influence on the tail of the distribution was substantiated by a statistically significant positive effect of DOWN on the τ parameter ($b = 70.14, SE = 6.32, t = 11.08$). No statistically significant effect of the UP condition on τ was observed ($b = -6.51, SE = 4.62, t = -1.40$).

2.3.3. Discussion

A possible explanation for the observation that no facilitatory effect was observed in Experiment 1 is that the magnitude of the luminance increase was too small to result in benefits in processing to the degree required in order to observe shortened fixation durations. Experiment 2 directly tested this hypothesis by increasing the magnitude of the luminance shift from baseline in both the UP and DOWN condition. Mean fixation durations observed in Experiment 2 showed a similar pattern to Experiment 1. Further decreasing the luminance of the scene during selected critical fixations was associated with an immediate and substantial increase in fixation duration. Furthermore, we did not observe a decrease in fixation durations following a facilitation in stimulus processing, as was assumed to occur following the increase in scene luminance. By inspecting the parameters of the ex-Gaussian distribution in Experiment 1, we speculated that if the more extreme luminance shift in the UP direction diminished the influence on the central tendency of the distribution then a facilitation effect may have been observed. The results from the analysis of means and parameter of the ex-Gaussian fit suggest that this is not the case. These results complement Experiment 1 and provide further support for the hypothesis that fixation durations are controlled in an asymmetric manner. The results from Experiment 1 and 2 show that a fixation-contingent increase of overall scene luminance was not sufficient to elicit a speedup in processing as observed through decreased fixation durations.

3. General Discussion

Two experiments were conducted to test whether the adjustment of fixation durations in naturalistic scene viewing is unidirectional (slow down), or bidirectional (speed up and slow down). A saccade-contingent display change method was used to make the scene more difficult or easier to process during prespecified critical fixations. In Experiment 1, a luminance baseline of 80% was presented to participants and the luminance was shifted to either 60% (DOWN) or 100% (UP). Experiment 2 extended these results by reporting a similar pattern for a 60% baseline with shifts to 20% (DOWN) and 100% (UP). If the direct-control process was asymmetric or unidirectional, decreasing the luminance of the scene should make processing more difficult and result in longer fixations, while clarifying the scene by increasing the luminance should have no effect on the duration of critical fixations. In contrast, if fixation durations were controlled in a symmetric or bidirectional manner, shifting luminance down should result in longer fixation durations, and shifting luminance up should result in shorter fixation durations. In both experiments, a pattern consistent with the asymmetrical hypothesis was observed such that decreases to luminance resulted in longer fixation durations, but increases to luminance did not result in an immediate decrease in fixation durations.

Downward luminance shifts were associated with increases in fixation durations in both Experiment 1 and Experiment 2. This was reflected in a difference in elevated mean durations relative to the baseline luminance. The overall effect of decreasing luminance on fixation durations is broadly a replication of results reported by Henderson et al. (2013) with different baseline conditions (60% and 80% compared to 100%) and novel stimuli. Additional distributional analyses using GAMLSS regression models qualified the time course of the observed effects. The results from the distributional analysis for Experiment 1 revealed that the increased durations in the DOWN condition occurred due to an overall shift in the distribution (increase in μ) as well as a significant increase in σ, the latter indicating the presence of greater variability in fixation durations in this condition. By comparison, the comparatively larger increase in durations in Experiment 2 was again associated with an overall shift in the distribution (increase in μ) and an increase in σ, but also with a longer tail (increase in τ). The specific influence on the tail of the distribution in Experiment 2 may be partially informed by a recent study conducted by Glaholt et al. (2013). In their study, the authors used a fixation-contingent scene quality paradigm to modify scenes under a variety of conditions such as spatial frequency filtering, and changes to the orientation of the image. In order to observe the differential effects of these modifications on fixation durations, they reported ex-Gaussian fitted distributions for the various conditions. They found that effects on the tail of the distributions were observed primarily for conditions in which the manipulation was hypothesised to result in a change that presented challenges to the later stages of stimulus encoding. In Experiment 2 of the current study, the extreme luminance manipulation ($60\% \rightarrow 20\%$) is likely to lead to difficulties in integrating the lowered-luminance stimulus into existing working memory structures and may partially account for the overall increase in fixation durations and the effects observed on the tail of the distribution.

Upward luminance shifts were associated with a small but reliable increase in fixation durations, which is contrary to predictions by both the asymmetric control hypothesis (no change) and symmetric control hypothesis (decrease). The distributions revealed that in both experiments the increase was attributable to an increase in the central tendency (increased μ); there was no increase in τ in either experiment (rather a significant negative effect in Experiment 1), and no effect of UP on σ.

One explanation for this small increase comes from an effect of surprise that may accompany the shift of luminance that participants encounter on critical fixations. The analysis provided by Glaholt et al. (2013) is informative of why this might be the case. They found that fixation durations were increased in all conditions, but that the effects on the tail were absent for the conditions in which no encoding difficulty was to be expected. These contrasting effects were explained by suggesting that the fast-acting effect that influences the central tendency is a result of surprise due to a detected mismatch between transsaccadic stimulus content. The small but significant increase in fixation durations in the UP condition of both experiments reported here is consistent with the fast-acting effect of surprise that is hypothesised to occur following transsaccadic changes to the scene. Their study included another control experiment that is relevant to the interpretation of the present results. During critical fixations, colour information was added to the greyscale scene. By clarifying the stimulus with a colour enhancement, stimulus processing should be facilitated. According to the symmetric control hypothesis, adding colour should lead to an immediate decrease in fixation duration. However, an increase in the durations of critical fixations was observed, which resulted from an increase to μ, but not from τ. These results are consistent with the results reported here.

Our presentation of the distributional effects that further qualify the inferences made by assessing differences in mean fixation durations is in keeping with recent analyses in reading (e.g., Glaholt, Rayner & Reingold, in press; Luke et al., 2013; Reingold et al., 2012; Staub et al., 2010) and scene viewing (Glaholt & Reingold, 2012; Glaholt et al., 2013; Luke et al., 2013). Such analyses are highly informative in that they reveal the specific components of the distributions that contribute to the observed mean effects. As has been previously discussed, these results contribute to a growing body of research demonstrating consistent distributional effects within a variety of viewing tasks.

The pattern emerging from the present study, as well as recent empirical results, is that the direct control mechanism operates in an asymmetric manner, in both scene viewing and other visual-cognitive tasks. For instance, Glaholt et al. (in press) reported an asymmetrical control pattern in a reading task in which the contrast of the sentence text was either increased or decreased in a gaze-contingent manner. During the saccade immediately preceding a critical fixation the contrast of the sentence text with the background was either increased, decreased, or was left unchanged. The authors found that upon landing on a sentence that had decreased contrast, fixation durations were increased relative to the no change baseline condition, whereas fixation durations remained the same when contrast was increased. Such results complement previous results observed in both reading (Kennison & Clifton, 1995) and in visual search (Hooge et al., 2007).

The results reported here have direct theoretical consequences for models of eye-movement control generally, but most specifically for accounts of fixation behaviours in scene perception. A computational framework that has had considerable success in modelling the temporal aspects of eye-movement control in scene viewing is known as the CRISP model (Nuthmann et al., 2010; Nuthmann & Henderson, 2012). The CRISP model is a stochastic timing model such that a random walk timing process accumulates to a fixed threshold value. Once this threshold is reached, the programming of a saccade is initiated. The variability of fixation durations predicted from the model are generated from three primary sources, a) the inherent stochasticity of the random walk timer, b) modulation of the random walks transition rate due to difficulties encountered during stimulus processing, and c) cancellation and reprogramming of current saccade programmes. In the original formulation of the CRISP model it has been assumed that eye-movement control operates in a manner consistent with what we have here called asymmetric control. That is, modulations to the timer could only occur due to processing difficulty that is expressed as a timer slowdown. With regards to the present results, the CRISP model captures such behaviour by assuming that difficulties in processing due to the decrease in luminance, result in a slowdown of the random walk timer rate and a temporal increase in the interval between successive saccade programmes. However, the results reported here with respect to the condition in which luminance is increased suggest that the default timer slowdown implemented in the CRISP model is sufficient to capture the effects of both degrading and enhancing stimulus processing.

A relevant question for future studies is how the adaptation of fixation durations to immediate changes in processing difficulty changes over the course of viewing. One possibility is that fixation durations may adapt with an immediate increase when processing difficulty increases but may decrease more gradually, say on the second or third fixation, following a decrease in difficulty. Trukenbrod & Engbert (2014) have investigated this issue using a task that required participants to scan sequences of horizontally arranged symbols from left to the right to search for a target stimulus. The target was always a ring, and Landolt-Cs were used as distractors. Processing difficulty of the stimulus elements was manipulated by increasing or decreasing the size of the gap in the Landolt-Cs. Fixations durations upon first encountering a change of difficulty, as well as fixation times on subsequent elements were measured. The authors reported an asymmetrical pattern of control of fixation durations such that increasing difficulty resulted in an increase to fixation durations upon first encountering the change, while a decrease in difficulty resulted in no immediate impact. However, they reported a delayed adjustment to fixation durations in the decreasing difficulty condition, as fixation durations showed evidence of a decrease for later fixations. The time course of the adjustment to changes in processing difficulty within scene viewing is currently an open empirical question.

4. Conclusion

In summary, this study used a luminance manipulation in order to vary the scene processing difficulty in a gaze-contingent fashion on critical fixations. We predicted that if the control of fixation durations operates in a symmetric manner, then shifting luminance down would result in increased fixation durations, while shifting luminance up would result in decreased fixation durations. On the other hand, if control is asymmetric we predicted that decreasing the luminance would result in fixation duration increases and that luminance increases would result in no change to fixation durations. The pattern of results observed in the two experiments provides support for the asymmetric control hypothesis.

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Figure Captions

Figure 1. A schematic of the paradigm used to create gaze-contingent luminance shifts. Base scenes represent the image that is viewed during the fixation immediately preceding a critical fixation. A critical fixation is defined to occur on the 10^{th} fixation since the previous luminance manipulation. The oblique lines represent saccadic eye movements. During a saccadic eye movement, the scene is either increased or decreased in luminance. A critical fixation is terminated upon detection of a saccadic eye-movement and the scene is restored to base scene luminance during this saccade.

Figure 2. Mean fixation durations on critical fixations following gaze-contingent luminance shifts. Fixation durations are plotted as a function of the direction of luminance shift. Data is plotted for Experiment 1 (solid line) and for Experiment 2 (dashed line). Error bars represent the standard error of the mean.

Figure 3. Fixation duration distributions. Empirical distributions for the three luminance conditions in Experiments 1 (Panel a) and Experiment 2 (Panel b), and their respective ex-Gaussian fitted distributions plotted in (Panel c) and (Panel d).