Induced visual fading of complex images

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Visual stimuli fade from awareness under retinal stabilization or careful fixation, a phenomenon documented by Troxler more than 200 years ago. Research on visual fading during normal visual fixation typically has been restricted to discrete, simple, low-contrast shapes presented peripherally against a uniform or textured background. In four experiments, we document a striking new visual fading effect in which entire photographs of scenes fade to a uniform luminance and hue during normal visual fixation. Critically, this "scene fading" can be induced almost instantaneously by some types of visual transients but not by others. These induced fading effects are sufficiently robust that they can be experienced by most observers in a single trial. Taken as a whole, the effects are inconsistent with simple contrast adaptation, gradual Troxler fading, or transient-induced fading. They are, however, consistent with the idea that small contrast decrements can induce fading of entire scenes. The methods provide a robust tool for the exploration of visual fading, and the results could have important implications for the role of filling-in and neural adaptation in our visual awareness of natural scenes and other complex stimuli.

Keywords: scenes, Troxler fading, contrast, adaptation, visual fading

Introduction

Visual stimuli fade from awareness under retinal stabilization or careful fixation, a phenomenon documented by Troxler more than 200 years ago (Troxler, 1804) and studied intensively for decades (Clarke, 1960, 1961; Martinez-Conde, Macknik, Troncoso, & Dyar, 2006; Millodot, 1967; Sakaguchi, 2001; Spillmann & Kurtenbach, 1992; Welchman & Harris, 2001). Fading of more complex stimuli can occur under conditions of complete stabilization of the image on the retina, such as when the effects of eye movements are eliminated via compensatory image movements or by mounting images directly to the eye (Ditchburn & Ginsberg, 1952; Riggs, Ratliff, Cornsweet, & Cornsweet, 1953).

Visual fading during normal visual fixation is usually restricted to discrete, simple, low-contrast shapes presented peripherally against a uniform or textured background, and in most cases, complete fading requires prolonged and relatively stable fixation. Yet, fading also can be induced more rapidly. For example, Troxler-like fading occurs abruptly following a transient flash adjacent to a peripheral target stimulus (Kanai & Kamitani, 2003), a phenomenon known as transient-induced fading. Similar rapid fading occurs when the contrast of a peripheral target relative to the background decreases abruptly by changing the luminance of either the target or the background (May, Tsiappoutas, & Flanagan, 2003).

Other fading phenomena also appear inconsistent with a simple, bottom–up adaptation mechanism. For example, attention appears to modulate Troxler fading of peripheral stimuli (Lou, 1999), with attended stimuli fading faster than unattended ones at an equivalent eccentricity. In motion-induced blindness, bright yellow dots phenomenally disappear and reappear when presented against a background of moving blue dots (Bonneh, Cooperman, & Sagi, 2001). The dots in motion-induced blindness can fade even when they are slowly moving, and they fade faster when they are brighter than the background. These results are inconsistent with a bottom–up, local adaptation mechanism.

All of these fading phenomena examine fading of small, discrete peripheral stimuli. Yet, foveated stimuli can fade as well. For example, a central disk surrounded by an annulus can fade to a uniform hue matching the annulus, particularly

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when the relative luminance of the disk and the annulus are varied (Krauskopf, 1963). More recently, fading and filling-in have been shown for other stimuli of varying complexity, including large uniform disks centered on the fovea, large rotating windmills, and flickering random dot fields (see Pessoa & De Weerd, 2003, for a number of examples).

In this article, we present four experiments that document a new form of fading in which an entire scene fades to uniform hue and luminance. This "scene fading" can occur gradually, as in Troxler fading, but it can also be induced nearly instantaneously, as in transient-induced fading and contrast-decrement-induced fading. The gradual scene-fading effect is consistent with Troxler fading but on a grander scale than previously demonstrated. However, our induced fading effects appear inconsistent with transient-induced fading.

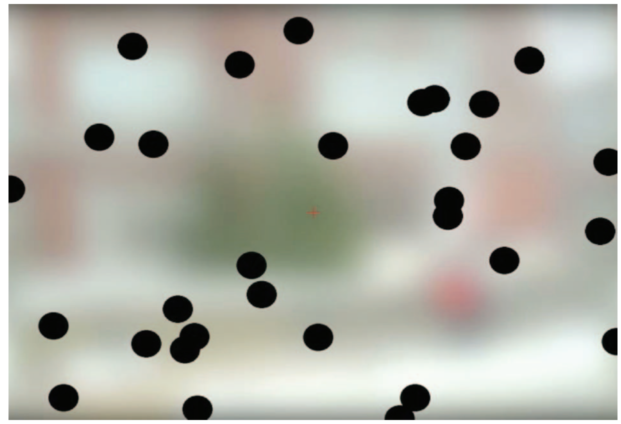

Figure 1. QuickTime movie illustrating the flickering-disks condition. Click on the image to view the movie.

Experiment 1

This experiment examines whether an unchanging, low-pass-filtered photograph of a natural scene fades under conditions of normal fixation. The experiment followed from a fortuitous experience the first author had while viewing a low-pass-filtered photograph while preparing stimuli for a different experiment. While viewing the scene, he happened to maintain careful fixation, and after a few seconds, the scene disappeared. The experience was sufficiently clear that he was convinced something about the image had changed until he saccaded and the scene returned. The effect was similar to that of Troxler fading but occurred for the entire scene. Consequently, half of the trials in this experiment were designed to document this scene-fading effect. The other half of the trials were designed to determine whether the presence of transient stimuli can enhance scene fading. To the extent that scene fading results from a gradual adaptation process, the presence of randomly positioned transient stimuli should detract from fading by providing a strong signal to the adapting neurons. Alternatively, if transients can induce fading, the presence of transient stimuli should increase fading.

Method

Observers

Eight University of Illinois undergraduates volunteered in exchange for course credit or payment. All reported normal or corrected-to-normal acuity and normal color vision.

Materials and procedure

Observers were tested simultaneously in a darkened room with dimmed incandescent lighting. Each observer was seated in front of an eMac computer (17-in. CRT monitor with 1,024 × 768 resolution) and wore sound-blocking headphones that were tethered to the monitor base to constrain the viewing distance to 57 cm. Viewing was binocular. Stimuli were 64 low-pass-filtered (5 cycles/degree) color digital photographs of natural scenes taken in Champaign and Chicago. Images subtended 30.5° × 22.9° of visual angle, and they had a mean luminance of 42.03 cd/m^2 and an RMS contrast of 29.94.

On each trial, observers maintained fixation on a small (1°) yellow cross centered on a low-pass-filtered photograph. The image remained on screen for 15 s, and observers were instructed to push a Saitek S45 joystick throttle maximally forward to indicate complete fading and to pull it maximally backward to indicate no fading. Throttle position, sampled every millisecond, provided a continuous measure of perceived fading from 0% to 100% over the course of the trial. After 15 s, the image was removed from the screen, and observers returned the throttle to the 0-fading position. They then pressed a button on the throttle to begin the next trial.

On half of the trials, 30 black disks (diameter = 1.6° of visual angle) flickered over the image repeatedly in randomly determined positions for each flash (250 ms on time, 250 ms between flashes). The other half of the trials just presented the scene image without any flickering disks. Each observer completed 32 trials with flickering disks and 32 trials without such disks (Figure 1). The assignment of images to the disk or no-disk condition was random, with the constraint that each image appeared in each condition for four participants. Each image was viewed only once by each observer, with the 64 trials presented in a different random order for each observer.

Results

All statistical analyses were based on the average across trials in a condition for each individual participant. All comparisons were repeated measures analyses, with each participant completing both conditions. The fading/second slope was calculated by finding the mean fading level at each time stamp (every 1 ms) across all participants and trials separately for each condition. A greater slope indicates faster fading. Maximum fading amounts were based on the mean maximum fading percentage across trials per condition for each individual.

When maintaining normal fixation on the center of a full-screen, low-pass-filtered (5 cycles/degree) photograph of a natural scene, image elements progressively disappeared with prolonged viewing, with some participants experiencing complete fading of all image content to a uniform hue and luminance (approximately the predominant hue and mean luminance of the image). Fading typically began within a few seconds of viewing, and when complete fading occurred, it typically was after 5–15 s of viewing. This relatively slow fading process might reflect the same mechanisms underlying Troxler fading of discrete peripheral stimuli but demonstrates their operation on a large scale, with an entire scene perceived as a uniform surface. Moreover, in most cases of Troxler-like fading, the background appears to fill in the faded stimulus region. In our case, there were no distinct faded and nonfaded regions that competed with each other. Rather, fading occurred across the entire image, both in the periphery and at fixation. Phenomenally, areas of lower contrast faded quicker than higher contrast regions.

Consistent with the idea of transient-induced fading, the presence of flickering disks led to a faster rate of fading, slopes: 1.64%/s versus 2.22%/s, $t(7) = 4.67$, $p = .002$, and resulted in more complete fading, mean maximum fading: 28.29% versus 39.03%, $t(7) = 5.10$, $p = .001$. In the flickering-disks condition, 18.75% of the trials exceeded 90% fading, whereas in the no-disk condition, only 11.67% of the trials exceeded 90% fading. The flickering disks remained highly visible, but the scene faded faster and more completely. The effect is inconsistent with simple local retinal adaptation explanation because the repeated appearance and disappearance of high-contrast edges should reduce retinal adaptation (Figure 2). The strong visibility of the disks is consistent with the idea that the disks activated different sets of neurons than the underlying scene. Due to the flickering nature of the disks, neurons with receptive fields matching the various disks' locations would not adapt, thereby explaining the visibility of the disks even as the scene faded. Note, though, that this explanation does not account for the enhanced fading of the visual scene with flickering disks. If the flickering disks had reduced the amount of contrast adaptation on the overall scene, then the outcome should have been a reduction in fading.

The enhanced fading induced by the flickering disks could result from the presence of the transients themselves—transient flashes can induce Troxler fading of small peripheral stimuli (Kanai & Kamitani, 2003). Moreover, transient displays can induce invisibility during visual masking (Macknik & Livingstone, 1998; Macknik, Martinez-Conde, & Haglund, 2000). Such transient-induced fading could result from the onset of the disks, their termination, or both.

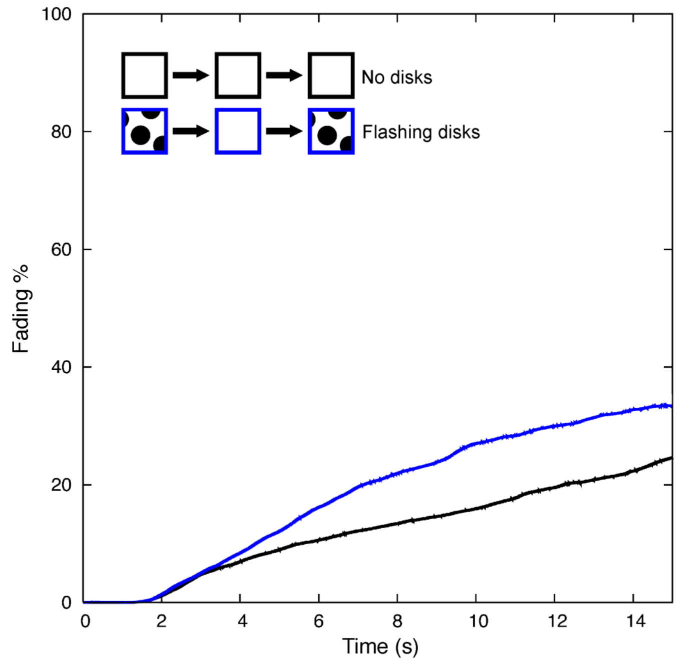

Figure 2. Influence of transient flickering black disks on perceived fading. The lines represent a continuous measure of the average extent of fading (ordinate) across images and participants during each 15-s trial (abscissa). Black, no disks. Blue, flickering disks. The flickering disks induce faster and more extensive fading.

Alternatively, fading could result from contrast gain control mechanisms (Ohzawa, Sclar, & Freeman, 1985; Wilson & Humanski, 1993): The visual system could change its contrast gain based on the presence of high-contrast disks and, as a result, variations within a low-pass-filtered scene would fall below the threshold for conscious perception.

Experiment 2

This experiment examined whether the enhanced fading induced by flickering disks in Experiment 1 resulted from contrast gain control or transient-induced fading. Rather than flickering disks repeatedly, in this experiment, we presented a single transient removal or addition of disks and compared those transient conditions with static conditions with and without high-contrast disks. If the presence of disks in Experiment 1 reduced the perceptibility of the contrast within the scene via contrast gain control mechanisms, then fading should be greater with static black disks than without them. In addition, contrast gain control should lead to greater fading of the scene when high-contrast disks are added and should lead to less fading when they are removed. If the transients themselves induced fading, however, then both the addition and removal of disks should enhance fading relative to the unchanging displays.

Method

Observers

Sixteen University of Illinois undergraduates volunteered in exchange for course credit or payment. All reported normal or corrected-to-normal acuity and normal color vision.

Materials and procedure

Except as noted, the stimuli and procedure were identical to Experiment 1. All participants completed a total of 16 trials in each of the following four conditions: (a) the scene by itself for all 15 s of the trial; (b) the scene with static black disks superimposed for all 15 s of the trial; (c) the scene by itself for the first 10 s, at which point black disks appeared abruptly and remained for the final 5 s; and (d) the scene with static black disks for the first 10 s, at which point the disks disappeared abruptly and remained absent for the final 5 s (Figure 3). On each trial, observers maintained fixation on a yellow cross and used the joystick to indicate the extent of fading. All trials ended after 15 s.

A

B

Figure 3. QuickTime movies illustrating the added-disks (A) and removed-disks (B) conditions. Click on the images to view the movies.

Results

As in Experiment 1, to determine the rate of fading, we calculated a fading/second slope across all trials and participants in each condition. When the trial involved a stimulus change, separate slopes were calculated for the first 10 s (at which point the transient occurred) and for the period after 10 s. An increased average slope indicated more rapid fading because of the event. For some participants, average fading during the first 10 s of the trial (before the critical event) was sufficiently rapid that increased fading would be limited due to ceiling effects. When the average fading rate for the first 10 s in either condition for an individual was greater than 5%/s, we excluded that participant's data from all analyses (n = 2, which left us with data from the remaining 14 participants). This arbitrary criterion was chosen to allow detection of a rapid increase in fading following the stimulus change. The overall pattern of results was comparable with and without these participants.

Surprisingly, neither contrast gain control nor transient-induced fading could account for the pattern of results (Figure 4). First, in the static displays, the presence of black disks produced *less* fading (mean slope = 0.988%/s) than the control condition with no disks (mean slope = 1.47%/s), $t(13) = 2.96$, $p = .0098$. Second, the transient *disappearance* of the black disks immediately increased fading, mean pretransient = 0.90%/s, mean posttransient = 6.42%/s, $t(13) = 3.90$, $p = .0014$, but the transient appearance of the disks had no significant effect, mean pretransient = 1.21%/s, mean posttransient = 2.28%/s, $t(13) = 1.50$, $p = .153$ (see Figure 2). The difference between the removed-disks condition and all of the other conditions was readily experienced by most participants; for the removed-disks condition, 12.38% of trials showed greater than 90% fading, whereas for the added-disks, constant-disks, and no-disk conditions, fewer than 2% of trials showed 90% or greater fading. Some participants falsely believed that the scene had been replaced with a uniform gray screen when they experienced complete fading in the removed-disks condition.

The contrast gain control explanation fails because it predicts greater fading in the presence of black disks than in their absence and greater fading with the addition of black disks than with their removal. The opposite was found in each case. Transient-induced fading also cannot explain this pattern because the addition of high-contrast disks failed to induce fading. This finding suggests that other demonstrations of transient-induced fading might result not from the presence of a transient but from the removal of a high-contrast element. In prior studies of transient-induced fading, the transient was induced by "blinking" an inducing stimulus near the target stimulus. Our findings suggest that it was the disappearance of this inducing stimulus that led to fading, not the presence of a transient per se.

Although contrast gain control and transient-induced fading cannot account for the entire pattern of results, the pattern is consistent with the idea that an abrupt reduction of luminance contrast for the display as a whole induces fading.

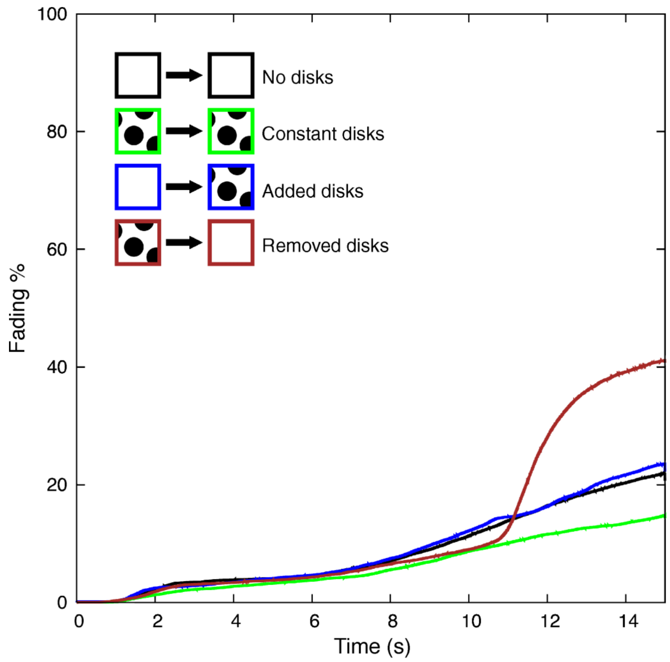

Figure 4. Influence of transient onset and disappearance of black disks on perceived fading. In the no-disk condition, the unaltered scene appeared for 15 s (black). In the constant-disks condition, the scene appeared with 30 black disks superimposed on it for 15 s (green). The added-disks condition initially was identical to the no-disk condition, but after 10 s, black disks were added for the remainder of the trial (blue). The removed-disks condition initially was identical to the constant-disks condition, but after 10 s, the black disks were removed from the display (brown). All conditions showed a gradual increase in perceived fading over time, but only the removed-disks condition showed a sharp increase in fading. Note that prior to 10 s, the removed-disks condition was equivalent to the constant-disks condition.

The black disks constitute a high-contrast stimulus relative to the scene background, and their removal causes an abrupt contrast decrement for the display as a whole in the frequency range corresponding to the disk edges. This contrast decrement might lead to scene-wide fading, in much the same way that local contrast decrements lead to Troxler-like fading of small peripheral stimuli (May et al., 2003). We calculated the local contrast change caused by removing the black disks by measuring the local band-limited contrast before and after removing the disks (Peli, 1990). This measure gives contrast values for each pixel in the image, which are then averaged to give a contrast value for the whole image. The contrast value for each pixel is calculated as the ratio of its value in the band-pass-filtered luminance map to its value in the low-pass-filtered luminance map. When using a one-octave pass band centered on 2 cycles/degree, the local band-limited contrast dropped by 99.99%.

Experiment 3

This experiment examined whether the effect of removing the disks varied as a function of the size of the resulting decrement in luminance contrast. Does fading result from any decrement in contrast or does the extent of fading depend on the magnitude of the contrast drop? If fading depends on the magnitude of the contrast decrement, the removal of gray disks should induce less fading than the removal of black disks (as the gray disks are, on average, closer in luminance to the mean luminance of the scenes).

Method

Observers

Sixteen University of Illinois undergraduates volunteered in exchange for course credit or payment. All reported normal or corrected-to-normal acuity and normal color vision. Data from 3 participants were excluded because their average rate of fading was greater than 5%/s in one of the conditions. Results were comparable with and without these participants.

Materials and procedure

Except as noted, the stimuli and procedure were identical to Experiment 2. On each trial, a scene appeared with randomly positioned static disks superimposed. After 10 s, the disks disappeared abruptly and remained absent for the final 5 s of the trial. All participants completed a total of 16 trials at each of four different disk luminance levels (black: 0.70 cd/m^2, dark gray: 9.27 cd/m^2, light gray: 54.21 cd/m^2, and white: 140.48 cd/m^2), with a different randomly generated trial order for each observer. Observers maintained fixation on the yellow fixation cross throughout each trial and used the joystick to indicate the extent of fading. All trials ended after 15 s.

Results

Removing disks produced fading, regardless of the luminance of the disks, $F(1,12) = 7.89$, $p = .016$. Strikingly, the effect of removing the disks did not vary significantly as a function of the luminance of the disks, $F(3,36) = 1.93$, $p = .142$ (Figure 5). In fact, the magnitude of the increase in fading was only minimally related to the signed magnitude of the luminance change resulting from removing disks of different luminance, $r(240) = .108$, $p = .0936$ (for the absolute magnitude of the luminance change, $r = .010$), with a mean slope increase of 4.74%/s. In all conditions, between 14% and 21% of trials showed greater than 90% fading. The drop in local contrast caused by removing the disks was greatest for the black (99.99%) and white (97.63%)

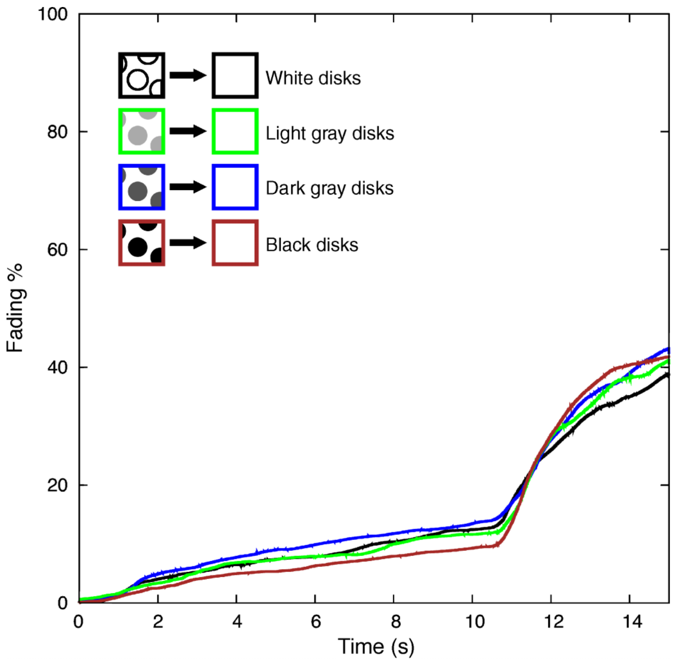

Figure 5. Scene fading induced by the removal of disks of different luminances. Lines depict the average extent of fading over time as well as the increase in fading resulting from removing the disks after 10 s. All conditions (white disks, light gray disks, dark gray disks, and black disks) showed an abrupt increase in fading following the removal of disks, with relatively little difference between conditions.

disks and slightly less for the dark gray (88.81%) and light gray disks (87.52%). Fading was comparable across conditions, though, suggesting that fading does not depend critically on the magnitude of the contrast change. The finding is consistent with the hypothesis that the contrast decrements produced by the transient removal of disks induce fading.

Experiment 4

If the removal of disks induces fading due to a contrast decrement, then a contrast decrement alone might induce scene fading, even without the transient disappearance of high-contrast elements. This experiment tested this possibility by reducing the contrast of the scene following 10 s of viewing.

Method

Observers

Twenty-four University of Illinois undergraduates volunteered in exchange for course credit or payment. All reported normal or corrected-to-normal acuity and normal color vision. Eight participants failed to return the throttle to the "0" position prior to each trial, and their data were discarded. An additional 3 participants showed rates of fading exceeding 5%/s during the first 10 s of one of the conditions, and their data were excluded, which left us with a total of 13 participants in the analyses. Results were comparable with and without the excluded participants.

Materials and procedure

Except as noted, the stimuli and procedure were identical to Experiment 3. On each trial, observers viewed a scene for 10 s, followed immediately by the same scene that was either unchanged or changed (increased or decreased) in contrast by approximately 20% relative to the original image. (The average drop in RMS contrast was 22.32%. The contrast decremented version of each image was created by introducing a 20% drop in contrast in Photoshop. To create the contrast-incremented version, we just reversed the presentation order of the two stimuli.) All participants completed a total of 16 trials in each of the following conditions: (a) a "high-contrast" condition in which the scene remained constant at the original contrast level used in the previous experiments; (b) a "low-contrast" condition in which the scene remained constant with reduced contrast relative to the scenes used in previous experiments; (c) an "increased-contrast" condition in which the scene was initially contrast reduced and then reverted to its original contrast after 10 s; and (d) a "decreased-contrast" condition in which the scene was initially shown at its original contrast and then the contrast was reduced after 10 s (Figure 6). As in previous experiments, observers maintained fixation on the yellow fixation cross throughout each trial and used the joystick to indicate the extent of fading. The trials were presented in a different random order for each observer, and each trial ended after 15 s.

Figure 6. QuickTime movie illustrating the decreased-contrast condition. Click on the image to view the movie.

Results

Following a contrast decrement, scene fading increased dramatically, mean slopes: 1.83%/s (before) and 8.32%/s (after), $t(12) = 6.22$, $p = .00002$, with the mean maximum fading ($M = 68.71\%$) exceeding that for an unchanging low-contrast scene ($M = 29.65\%$), $t(12) = 6.68$, $p < .00001$ (Figure 7). In some cases, observers reported that the change induced the complete disappearance of all scene content, resulting in a display of uniform luminance and hue. Observers experienced greater than 90% fading on 36.92% of trials in the contrast decrement condition. None of the other conditions had more than 5% of trials with 90% or more fading. This effect must be attributed to the change from high to low contrast rather than to generally better fading of low-contrast scenes; prior to 10 s, the extent of fading did not differ significantly for the high-contrast ($M = 1.98\%$/s) and low-contrast ($M = 1.70\%$/s) trials, $t(12) = 1.32$, $p = .205$. Whereas contrast decrements induced fading, contrast increments slightly reduced fading, mean slope: 2.05%/s (before) and 2.01%/s (after), making the original scene slightly more visible, $t(12) = .112$, $p = .912$. Although the results of Experiment 4 could be explained by contrast adaptation mechanisms (Blakemore & Campbell, 1969; Blakemore, Muncey, & Ridley, 1973), they are also consistent with the idea that a contrast decrement alone can induce fading.

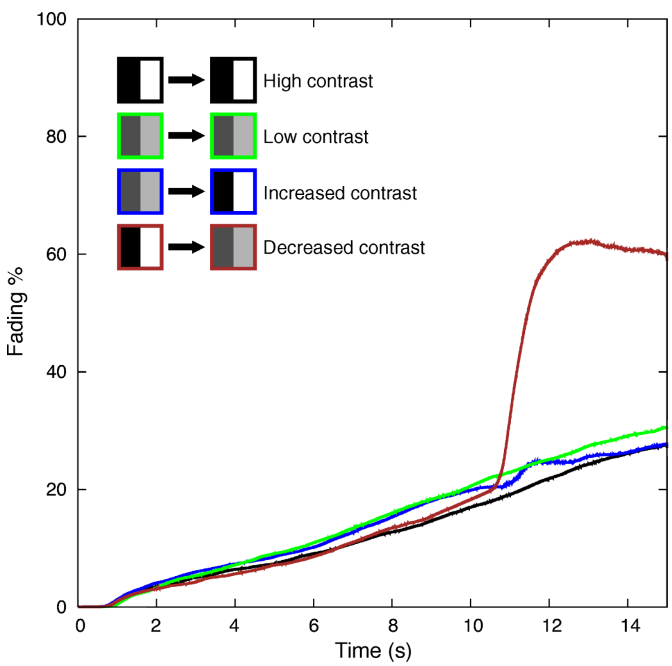

Figure 7. Extent of scene fading as a function of scene contrast and contrast change. High-contrast (black) and low-contrast (green) scenes showed comparable extents of fading when unchanged throughout the trial. A contrast increment after 10 s (blue) led to slightly reduced fading. A contrast reduction (brown) led to a substantial increase in fading, exceeding fading levels for the low-contrast condition.

Discussion

Together, these experiments provide striking new examples of perceptual failures on a larger scale than previously demonstrated (Bonneh et al., 2001; Kanai & Kamitani, 2003; Lou, 1999; May et al., 2003; Troxler, 1804). Entire scenes disappear from awareness instantaneously because of the contrast decrement of a superimposed image, such as disks. Contrast decrements can be small in magnitude but uniform across the entire image (Experiment 4), or they can be large and highly localized (as with the disks in Experiments 1, 2, and 3).

Critically, induced fading by the removal of high-contrast disks is inconsistent with simple contrast gain control accounts. The visual system may interpret a global change in contrast that affects all parts of a scene equally to indicate the disappearance of the stimulus. Lighting or other environmental changes that affect the relative luminance of scene elements typically do not apply uniformly across an entire display. Ongoing research extends these effects to other types of displays (e.g., gratings) and examines how contrast decrements that do not uniformly affect the entire scene influence fading.

In addition to providing a robust new example of a perceptual failure that occurs even for foveated locations, induced scene fading provides a useful tool to study filling-in processes more generally (Ramanchandran & Gregory, 1991). As for most examples of visual fading, studies of filling-in typically examine cases in which a uniform visual texture is completed across the target area. However, with induced scene fading, filling-in operates across an entire heterogeneous image and multiple surfaces simultaneously, resulting in a percept akin to the average hue and luminance of the scene. A better understanding of this "averaging" process (see Arrington, 1994; Grossberg & Todorovic, 1988) may yield a clearer understanding of visual perception of uniform surfaces in the absence of visual input, and it might also provide a tool for studying the nature of visual processing in the absence of a visual percept (Mitroff & Scholl, 2004). In sum, these visual fading effects are robust, spatially extended, and temporally sustained. As such, they could also significantly enhance the study of the "filling-in" processes and perceptual completion in complex, natural images.

Conclusion

We documented a striking new visual fading effect in which entire photographs of scenes fade to a uniform luminance and hue during normal visual fixation. To our knowledge, these experiments are among the first to examine fading of complex, naturalistic stimuli under normal fixation. This scene fading can be induced almost instantaneously by transients that produce a contrast decrement but not by those that increase the overall contrast of the display, and the effects, particularly those in Experiment 4, can be experienced by most observers in a single trial. Although several distinct mechanisms (e.g., Troxler fading, contrast adaptation, and contrast-reduction-induced fading) could contribute to these scene-fading effects, the results are entirely consistent with a mechanism in which a sudden contrast decrement leads to scene fading. The purpose and origin of this mechanism are unclear, but uniform and instantaneous contrast decrements might be interpreted by the visual system as the disappearance of the stimulus. Further research is needed to explore the limits and generality of this scene-fading phenomenon and to better understand the mechanisms underlying it.

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