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Illusory motion induced by the offset of stationary luminance-defined gradients

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Abstract

An illusory motion induced by the offset of a stationary gradient stimulus is characterized. When a gradient stimulus, whose luminance contrast ranges gradually from white on one side to black on the other, is made to disappear all at once so that only the uniform white background remains visible, illusory motion is perceived. This motion lasts ~700 ms, as if the stimulus moves from the low to the high luminance contrast side. This gradient-offset induced motion does not occur for equiluminant color-defined gradient offsets, suggesting that it relies mainly on the magnocellular pathway. Our data are consistent with the hypothesis that this illusion is caused by the difference of decay rates within the gradient afterimage.

Keywords: Motion; Illusion; Luminance-defined gradients

1. Introduction

When a gradient stimulus, whose luminance contrast ranges gradually from low on one side to high on the other side, is abruptly made to disappear so that only the white background remains visible, illusory motion is perceived. Naor-Raz and Sekuler (2000) noticed this motion upon the offset of stationary gradient wheels (that themselves can generate illusory motion; Faubert & Herbert, 1999; Fraser & Wilcox, 1979), but only mentioned this phenomenological observation in passing in their article. To our knowledge, no authors have characterized this illusion psychophysically or tried to determine its cause. In this article, we characterize the basic properties of this gradient-offset induced motion and test three hypotheses concerning potential causes of this effect. Three hypotheses about the possible cause of this phenomenon are tested by experiments here:

Hypothesis 1. First, it is possible that the illusory motion is due to apparent motion between the original image and its afterimage. Because the brighter side of the original image becomes the darker side of the afterimage and vice versa, it is possible that the illusory motion is the result of apparent motion between this flipping of gradient profiles.

Hypothesis 2. The second possibility is that this gradient-offset induced motion is a variant of a previously reported illusion called the complementary afterimage (CAI) (Hunter, 1915; MacKay, 1957; Pierce, 1900; Purkinje, 1823; Wade, 1996). After fixating on a vertical bar grating for at least 30 s and then looking at a blank sheet, horizontal lines can be perceived to shimmer and move horizontally. Although CAI induced by a vertical bar grating whose bars are all uniformly black, can be perceived as moving horizontally, the perceived motion does not have a preferred direction toward the left or right. However, it has been shown recently (Kim & Francis, 2000) that the offset of a vertical bar grating, whose bars vary in contrast against a

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white background with the highest contrast in the leftmost bar and the lowest contrast in the rightmost bar, can induce CAI with motion apparently moving to the left. Therefore, it is possible that gradient-offset induced motion is just a variant of CAI because a gradient is somewhat similar to such a bar grating whose bars have been pushed together so that they abut.

Hypothesis 3. The third hypothesis is that the fading of the afterimage causes the illusory motion. It may be that an afterimage is seen after the stimuli is turned off. Since the original stimuli are composed of gradients, the afterimage of the stimuli would also look like a gradient, with a brighter (darker) side corresponding to the original darker (brighter) side. As the afterimage fades with time, the luminance maxima and/or minima of this afterimage gradient might shift with time, creating an illusory percept of motion.

2. Experiment 1: The perceived direction of the illusory motion is determined by the luminance polarity

In Experiment 1a, we tested the relationship between the perceived direction of the illusory motion and the direction of the gradient. We also recorded how long the illusory motion lasts after the stimuli were turned off. In Experiments 1b and 1c, we tested the effect of background luminance on the perceived direction of the illusory motion.

Although the offset of a single luminance gradient is sufficient to induce the illusory motion, we used multiple gradients concatenated together to induce a stronger effect. The contiguous gradient squares comprised a ramp grating whose luminance profile is depicted in Fig. 1A. In the experiment, four ramp gratings were presented together to further enhance the effect (Fig. 1B).

2.1. Method

2.1.1. Observers

Four observers (two naïve Dartmouth students and two authors) carried out Experiment 1a. Three observers (two naïve Dartmouth students and one author) carried out Experiments 1b and 1c. All of them had normal or corrected-to-normal vision.

2.1.2. Stimulus displays

The stimulus configuration used in Experiment 1a is shown in Fig. 1B. The fixation spot was a red (luminance: 21.41 cd/m^2; CIE, $x = 0.628$, $y = 0.341$) square that subtended 0.05° of visual angle on a white (luminance: 102.79 cd/m^2) background. The luminance of each gradient square ranges from white (luminance: 102.79 cd/m^2) on one side to black (luminance: 1.68 cd/m^2) on the other side, subtending 1° in height and 1° in width. Each ramp grating was composed of five gradient squares connected together, subtending 1° in height and 5° in width. Two of the ramp gratings were centered 7° of visual angle above and below the fixation spot. The other two ramp gratings were rotated 90° and centered 7° of visual angle to the left and right of the fixation spot. The direction of the gradient (from white to black) was arranged to be either clockwise or counter-clockwise. All the stimuli were binocular and monoptic.

The stimuli in Experiments 1b and 1c were the same as those used in Experiment 1a except that the background luminances were black (luminance: 1.68 cd/m^2) and middle grey (luminance: 52.39 cd/m^2), respectively.

The visual stimulator was a 2 GHz Dell workstation running Windows 2000. The stimuli were presented on a 23-in SONY CRT gamma-corrected monitor with 1600 × 1200 pixels resolution and 85 Hz frame rate. Observers viewed the stimuli from a distance of 76.2 cm with their chin in a chin rest.

2.1.3. Procedure

The stimuli were presented for 500 ms and then turned off, leaving only the fixation spot and white background visible. After stimulus offset, subjects were asked to wait until the illusory motion had totally disappeared before indicating the perceived direction of the illusory motion with a buttonpress. The direction of the gradient was either clockwise or counter-clockwise, randomized and counterbalanced across 50 trials.

The individual reaction time (RT) of each subject was measured by repeating the exact same experiment, but this time asking subjects to instead respond to stimulus offset as fast as possible. Eye movements were monitored by using a head-mounted eyetracker (Eyelink2, SR research, Ontario, Canada; Tse, Sheinberg, & Logothetis, 2002).

2.2. Results and discussion

Results show that when the direction of the gradient (from white to black) was clockwise, subjects reported seeing clockwise illusory motion 93.2 ± 6.8% of the time. When the direction of the gradient was counter-clockwise, subjects reported seeing counter-clockwise illusory motion 97.8 ± 2.2% of the time (Fig. 2A). In other words, when the stimuli were turned off, illusory motion was perceived as if the gradient had moved from the white side to the black side. On average, the RT for the determination of direction of perceived illusory motion was 980.0 ± 70.6 ms after stimulus onset. By subtracting simple RTs (227.57 ± 27.67 ms) measured in response to stimulus offset, which we assume to be equivalent to the RT to the offset of the illusory motion, we can infer that the perceived illusory motion lasted 695.4 ± 58.9 ms after stimulus offset.

Results of Experiment 1b show that when the same stimuli were turned off on a black background, illusory motion was perceived as moving in the opposite direction to that observed in Experiment 1a. When the direction of the gradient (from white to black) was clockwise, subjects reported seeing counter-clockwise illusory motion 81.3 ± 11.6% of the time. When the direction of the gradient was counter-clockwise, subjects reported seeing clockwise illusory motion 87.3 ± 7.1% of the time (Fig. 2B).

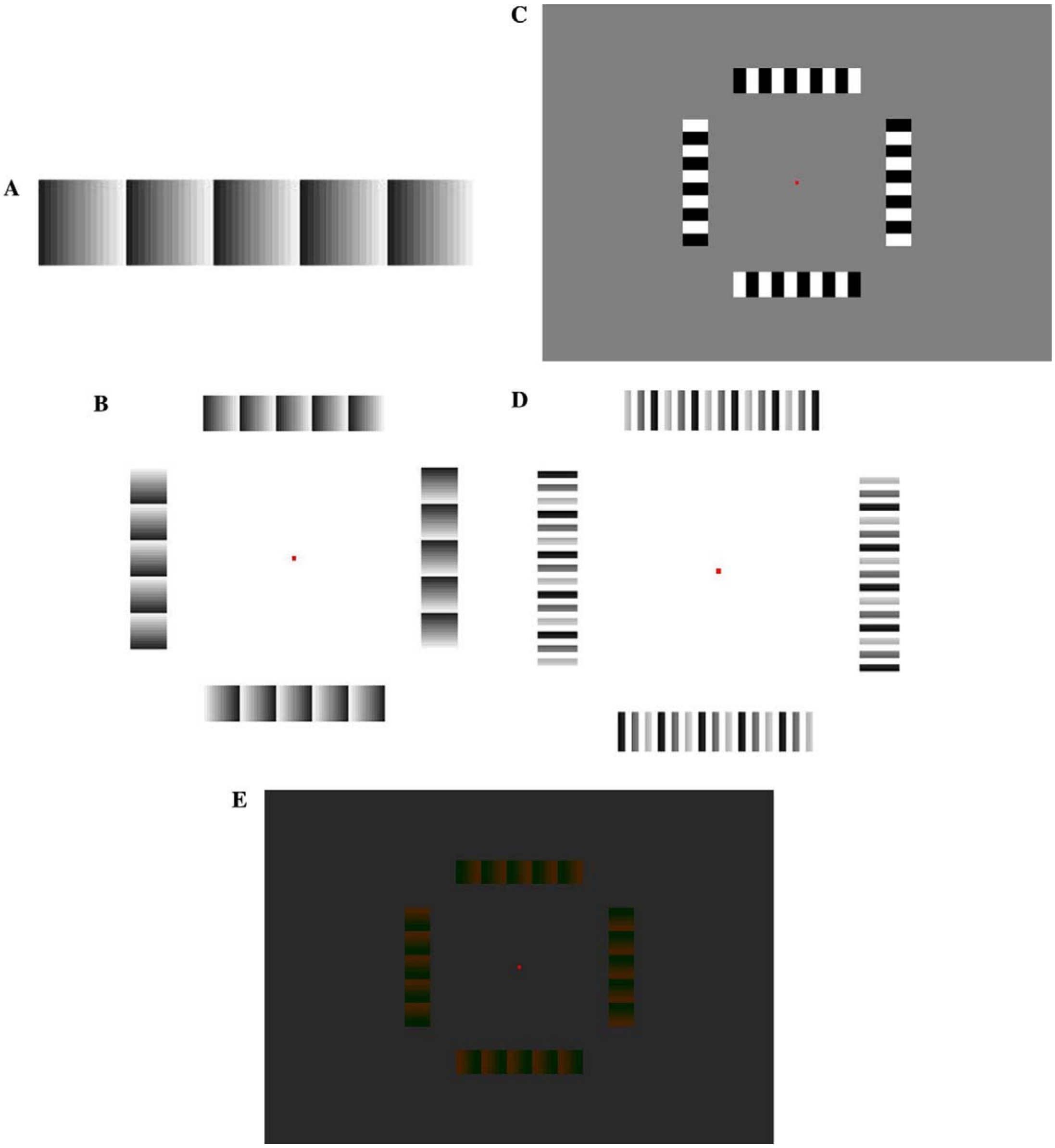

Fig. 1. Stimuli. (A) Multiple gradient squares are connected together to induce a stronger effect. The connected squares look like a ramp grating consisting of shaded stripes whose luminance profile is a repetitive ramp or a saw-tooth waveform. (B) In Experiment 1a, four ramp gratings were presented together to further induce the effect. (C) In Experiment 2, gradients were replaced with interleaved white and black rectangles. The background was grey. (D) In Experiment 3, each gradient square was disrupted by white squares so that it would look like a bar grating. (E) In Experiment 5, gradients composed of white and black were replaced with equiluminant red and green on an equiluminant grey background.

In Experiment 1c, when the same stimuli were turned off on a mid-level grey background, illusory motion was perceived as moving ambiguously. When the direction of the gradient (from white to black) was clockwise, subjects reported seeing clockwise illusory motion 53.0 ± 10.9% of the time. When the direction of the gradient was counter-clockwise, subjects reported seeing counter-clockwise illusory motion 52.4 ± 14.3% of the time (Fig. 2C).

Together, these data show that the perceived direction of the illusory motion is affected by the direction of the gradient and the background luminance. In other words, the perceived direction of the illusory motion is determined by the luminance polarity. When a gradient stimulus, whose luminance contrast ranges gradually from low on one side to high on the other side, is turned off all at once, illusory motion from low to high contrast sides is perceived.

3. Experiment 2: Gradient-offset induced motion is not due to apparent motion

Experiment 2 was conducted to test the first hypothesis. In Experiment 2a, the stimuli and procedure were identical to those in Experiment 1a except that the gradient was replaced with black and white rectangles on a grey background (Fig. 1C). Subjects were asked to answer whether they saw clockwise or counter-clockwise motion (two alternative forced choice), just as in the first experiment. If it is true that gradient-offset induced motion is due to apparent

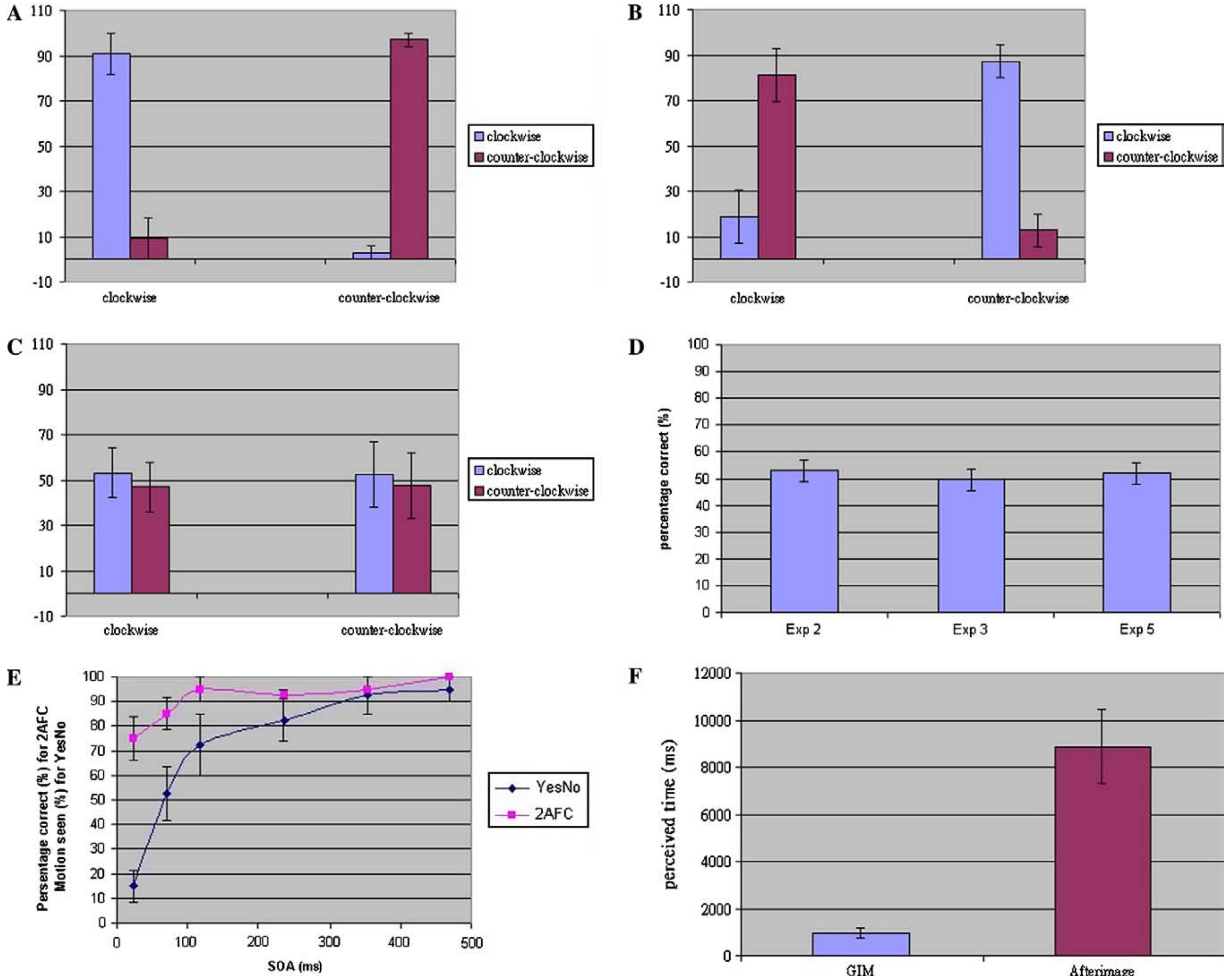

Fig. 2. Results. (A) Results of Experiment 1a show that when the direction of the gradient (from white to black) on a white background was clockwise, subjects reported seeing clockwise illusory motion 93.2% of the time. When the direction of the gradient was counter-clockwise, subjects reported seeing counter-clockwise illusory motion 97.8% of the time. (B) Results of Experiment 1b show that when the direction of the gradient (from white to black) on a black ground was clockwise, subjects reported seeing counter-clockwise illusory motion 81.3% of the time. When the direction of the gradient was counter-clockwise, subjects reported seeing clockwise illusory motion 87.3% of the time. (C) Results of Experiment 1c show that when the direction of the gradient (from white to black) on a mid-level grey background was clockwise, subjects reported seeing clockwise illusory motion 53.0% of the time. When the direction of the gradient was counter-clockwise, subjects reported seeing counter-clockwise illusory motion 52.4% of the time. (D) Results of Experiment 2 (left bar), Experiment 3 (middle bar), and Experiment 5 (right bar) all showed that no illusory motion was observed. The percentage of illusory motion direction expected from the results of Experiment 1a was about 50% (chance rate), suggesting that subjects were simply guessing. (E) Results of Experiment 4 show that, perceptually (blue curve), subjects reported (yes or no, 2AFC) that they rarely saw motion when the stimuli were presented very briefly (23.53 ms). The percentage that perceived illusory motion was below 20% at this stimulus duration. The pink curve shows that when presenting the stimuli very briefly, conditions under which subjects reported seeing no motion, the percentage of illusory motion direction expected from the results of Experiment 1a was about 75% when they were forced to answer the direction (clockwise or counter-clockwise, 2AFC). This is significantly higher than the rate expected by chance (50%). (F) Results of Experiment 6 show that, on average, gradient-offset induced motion lasted about 752.4 ms and the afterimage lasted about 7710.6 ms.

motion between the original image and the afterimage, gradient-offset induced motion should also be observed in this experiment because the flipping of images still exists. However, if gradient-offset induced motion is not cause by apparent motion between the original image and the afterimage, but instead by some factor inherent to gradients per se, then gradient-offset induced motion should not be observed, because no gradient stimuli were present in this experiment.

One might argue that, even if the results show that there is no motion seen in Experiment 2a, this alone is not sufficient to rule out the apparent motion hypothesis. It is possible that the apparent motion might occur only when luminance ramps are present. For example, assume that observers perceive a spatial feature such as a bar or edge at some point along the luminance ramp (or its afterimage), and the feature appears to be located nearer the bright end of the ramp/afterimage (Georgeson & Freeman, 1997).

When the ramp disappears and is replaced by its afterimages, observers may see apparent motion from one feature to the other in the two ramps. Therefore, even if no motion is seen in Experiment 2a, it is possibly due to the fact that ramps are required to create the appearance of a feature which is missing in Experiment 2a. In order to test this possibility, Experiment 2b was conducted by physically flipping the ramps to simulate the afterimage. In Experiment 2b, the stimuli and procedure were identical to those in Experiment 1a except that the offset of the gradient was replaced by physically flipping the ramps. The apparent motion hypothesis would predict that the perceived motion direction is consistent with that observed in Experiment 1a.

3.1. Method

3.1.1. Observers

Three observers (two naïve Dartmouth students and one author) with normal or corrected-to-normal vision carried out the experiment.

3.1.2. Stimulus displays and procedures

The stimulus layout in Experiment 2a was the same as that used in Experiment 1a except that the gradient was replaced with interleaved squares (half black and half white) on a grey background (Fig. 1C). The order of the rectangles was either clockwise or counter-clockwise. If it was clockwise, the leftmost rectangle in the upper stimulus bar was white. If it was counter-clockwise, the leftmost rectangle in the upper stimulus bar was black. The two stimulus configurations were randomized and counter-balanced across 50 trials. In Experiment 2b, the stimuli were identical to those in Experiment 1a except that the offset of the gradient was replaced by physically flipping the ramps.

3.2. Results and discussion

Results show that no illusory motion was observed in Experiment 2a. The percentage of illusory motion direction expected from the results of Experiment 1 was about 50% (chance rate) (left bar in Fig. 2B), implying that subjects were guessing. During debriefing all subjects reported that they saw no motion in the experiment. Therefore, we can conclude that gradient-offset induced motion is not due to apparent motion between the original image and its afterimage, ruling out Hypothesis 1 above.

Results of Experiment 2b show that, when the ramps were physically flipped, illusory motion was perceived as moving in the opposite direction to that observed in Experiment 1a. In Experiment 1a, illusory motion was perceived from low to high luminance contrast sides when ramps were turned off. However, in Experiment 2b, illusory motion was perceived from high to low luminance contrast sides. Therefore, the apparent motion hypothesis is unlikely to be correct because the result is contradictory to its prediction.

In addition, we believe the gradient-offset induced motion is not due to apparent motion for two other reasons. First, gradient-offset induced motion is phenomenally different than apparent motion. Apparent motion is "apparent" in the sense that subjects have the impression of movement without really perceiving continuous motion of an object that occupies all intermediate positions. Gradient-offset induced motion, in contrast, creates the impression that luminance energy is continuously moving through all positions of space occupied by the afterimage. Second, apparent motion is fast and transient, but gradient-offset induced motion lasts much longer (about 700 ms).

4. Experiment 3: Gradient-offset induced motion is not a variant of CAI

Experiment 3 was conducted to test the second hypothesis. In this experiment, the stimuli and procedure were identical to those in Experiment 1a except that each gradient square was interrupted by three white rectangles so that each gradient square would look approximately like the luminance-varying bar grating of Kim and Francis (2000) described above (Fig. 1D). Subjects were asked to answer whether they saw clockwise or counter-clockwise motion (two alternative forced choice), just as in the first and second experiments. If it is true that gradient-offset induced motion is a variant of CAI, we would expect to see illusory motion upon stimulus offset. The bar gratings in this experiment consist of portions of the original gradient stimulus. If motion is perceived upon stimulus offset, this would suggest that CAI can account for the present effect. However, if gradient-offset induced motion is not a variant of CAI, but instead depends crucially on the presence and disappearance of a continuous gradient, then gradient-offset induced motion should not be observed, because the continuous gradient stimuli were disrupted.

4.1. Method

4.1.1. Observers

Three observers (one naïve Dartmouth students and two authors) with normal or corrected-to-normal vision carried out the experiment.

4.1.2. Stimulus displays and procedures

The stimulus was the same as that used in Experiment 1a except that each gradient square was disrupted by three white rectangles so that it would look like a bar grating whose bars varied in contrast against a white background with the highest contrast bar on one side and lowest contrast bar on the other side (Fig. 1D). Each bar was 0.167° of visual angle in width and 1° of visual angle in height. The experimental procedure was identical to that used in Experiments 1a and 2.

4.2. Results and discussion

Results showed that no illusory motion was observed. The percentage of illusory motion direction expected from the results of Experiment 1a was 50% (chance rate, implying that subjects were guessing; middle bar in Fig. 2D) after replacing the gradient stimuli with bar gratings. During debriefing all subjects reported that they saw no motion in the experiment. This result is contradictory to the CAI hypothesis, which predicts that subjects should perceive illusory motion. Therefore, we can conclude that gradient-offset induced motion is not a variant of CAI. Further evidence suggesting that gradient-offset induced motion is not a variant of CAI comes from the fact that the stimulus durations required to induce perceived motion are different for the two illusions. For CAI, subjects are required to fixate on the stimuli for approximately 30 s (Kim & Francis, 2000). However, only 0.5 s of stimulus presentation is sufficient to generate gradient-offset induced motion (Experiment 1a). Moreover, CAI persists for several seconds, which is much longer than gradient-offset induced motion (only about 700 ms). Together, these lines of evidence suggest that: (1) gradient-offset induced motion is not a variant of CAI, and (2) continuous gradient stimuli are necessary for gradient-offset induced motion.

5. Experiment 4: Gradient-offset induced motion can be perceived despite short presentation times

Experiment 4 was conducted to show the minimum stimulus duration necessary to perceive gradient-offset induced motion and to test the third hypothesis. In this experiment, the stimuli and procedures were identical to those in Experiment 1a except that the gradient was presented for different durations. If the gradient-offset induced motion were caused by the decay of the afterimage, we would expect that the illusion would go away or become weaker for very short stimulus durations because afterimages take time to develop, and are weaker following a brief stimulus presentation.

5.1. Method

5.1.1. Observers

Four observers (two naïve Dartmouth students and two authors) with normal or corrected-to-normal vision carried out the experiment.

5.1.2. Stimulus displays and procedures

The stimuli were the same as those in Experiment 1a except that the gradient was presented at different durations (2 frames ≈ 23.53 ms, 6 frames ≈ 70.59 ms, 10 frames ≈ 117.65 ms, 20 frames ≈ 235.29 ms, 30 frames ≈ 352.94 ms, or 40 frames ≈ 470.59 ms) that are randomized and counter-balanced across 60 trials. Subjects were first asked to answer whether they saw motion in a two alternative forced choice (2AFC) paradigm, and then answer the direction of the motion (clockwise or counter-clockwise, 2AFC). They were forced to answer the direction of motion even when their first answer was no.

5.2. Results and discussion

Results of Experiment 4 are shown in Fig. 2E. The blue curve shows that, perceptually, subjects reported that they did not see any motion when the stimuli were presented very briefly (23.53 ms). The percentage of perceived illusory motion was below 20% at this stimulus duration. Assuming that a 2AFC methodology reflects subjects' true motion perception, this result is consistent with the prediction of the third hypothesis, namely that the illusion should disappear under very short stimulus durations (because no afterimage is generated under short stimulus presentation). Therefore, this result suggests that the illusory motion might be due to the decay of the afterimage. Note also that when subjects were forced to answer the direction of motion while they alleged not to be perceiving any, the percentage of illusory motion direction expected from the results of Experiment 1a was about 75% (pink curve in Fig. 2E), which is significantly higher than the chance rate (50%). This phenomenon might reveal a type of unconscious perception (Kanwisher, 2001; Merikel, Smilek, & Eastwood, 2001). Alternatively, this result could also mean that subjects define a conservative threshold for what counts as 'seeing motion.' However, we believe this is less likely to be true because verbal reports from subjects reveal that the percentage of perceived motion dropped dramatically at short stimulus durations. Another possibility is response bias. Observers tended to report clockwise (counter-clockwise) after seeing the clockwise (counter-clockwise) stimulus when the illusory motion was perceived with the long durations. A simple stimulus–response association would cause the observers to report clockwise after seeing the short-duration clockwise stimulus (even without seeing any illusory motion). This issue will be settled by future experiments.

6. Experiment 5: Gradient-offset induced motion cannot be perceived using equiluminant stimuli

To determine whether this illusory motion results from processing in the magnocellular or the parvocellular pathway, Experiment 5 was conducted by using equiluminant stimuli. This experiment also tested the third hypothesis (afterimage hypothesis) because an equiluminant stimulus creates an equiluminant afterimage (Kelly & Martinez-Uriegas, 1993), which should not induce illusory luminance-defined motion. In this experiment, the stimuli and procedure were identical to those used in Experiment 1a except that the gradient composed of white and black was replaced with equiluminant red and green on a grey background (Fig. 1E). Subjects were asked to answer whether they saw clockwise or counter-clockwise motion (two alternative forced choice), just as in the first experiment. If gradient-offset induced motion is an effect occurring in the magnocellular pathway that relies on luminance differences, this illusory motion should disappear because the gradient stimuli were equiluminant in this experiment.

6.1. Method

6.1.1. Observers

Three observers (one naïve Dartmouth students and two authors) with normal or corrected-to-normal vision carried out the experiment.

6.1.2. Stimulus displays and procedures

The stimuli were the same as that in Experiment 1a except that the gradient composed of white and black was replaced with red and green on a grey background (Fig. 1C). The luminances of the red, green, and grey were adjusted to become subjectively equal for each subject using the minimal flicker technique (Anstis & Cavanagh, 1983). The averaged color/luminance for red, green, and grey was: red (CIE, $x = 0.457 \pm 0.003$, $y = 0.488 \pm 0.006$; luminance: $1.78 \pm 0.03\,\text{cd/m}^2$), green (CIE, $x = 0.280 \pm 0.003$, $y = 0.640 \pm 0.003$; luminance: $1.61 \pm 0.01\,\text{cd/m}^2$), and grey (R: 41 ± 0.01; G: 41 ± 0.01; B: 41 ± 0.01; luminance: $2.06 \pm 0.04\,\text{cd/m}^2$). The experimental procedure was identical to that of Experiment 1a.

6.2. Results and discussion

Results showed that no illusory motion was observed. The percentage of illusory motion direction expected from the results of Experiment 1a was about 50% (chance rate) (right bar in Fig. 2D), suggesting that subjects were simply guessing. During debriefing all subjects reported that they saw no motion in the experiment. Therefore, this result supports the afterimage hypothesis. Moreover, we can also conclude that gradient-offset induced motion is a magnocellular effect.

7. Experiment 6: Gradient-offset induced motion is observed only at the beginning phase of the afterimage

Experiment 6 was conducted to further test the third hypothesis. In this experiment, the stimuli were identical to those in Experiment 1a, but were presented for a longer duration to generate a stronger afterimage. Subjects were asked to answer both how long the illusory motion lasted and how long the afterimage lasted using two separate buttonpresses. If the afterimage hypothesis is correct, we would expect that the illusory motion should last as long as the afterimage lasts.

7.1. Method

7.1.1. Observers

Four observers (two naïve Dartmouth students and two authors) with normal or corrected-to-normal vision carried out the experiment.

7.1.2. Stimulus displays and procedures

The stimuli were the same as those in Experiment 1a, except that the direction of the gradient was always clockwise across 25 trials. In this experiment, the stimuli were presented for 2500 ms and turned off all at once by replacing them with the uniform white background. After stimulus offset, subjects were asked to wait until the illusory motion had completely disappeared before pressing a button to record the perceived time of the illusory motion. Subjects were also asked to press another button when the afterimage had totally disappeared to record the perceived duration of the afterimage.

7.2. Results and discussion

Results show that, on average, the gradient-offset induced motion lasted 831.6 ± 176.6 ms before motion was perceived to cease, while the afterimage was perceived to last 7710.6 ± 1443.6 ms, after subtracting simple RTs (Fig. 2F). Since the afterimage lasts much longer than gradient-offset induced motion, it would seem that the fading of the afterimage does not cause gradient-offset induced motion. However, a variant of the afterimage hypothesis is still possible. Even though the timecourse of afterimage decay is not the same as that of gradient-offset induced motion, given an alternative mechanism, the afterimage could still be the cause of gradient-offset induced motion. One possible explanation is that the decay rate of the afterimage may be faster in the beginning phase and slower in the later phase, as would occur in cases of exponential decay, and gradient-offset induced motion may only be observed when the decay rate of the afterimage is high. It has been shown that the afterimage decays exponentially with a ($1/e$) time constant of 4–8 s (Kelly & Martinez-Uriegas, 1993). Therefore, it is possible that gradient-offset induced motion lasts shorter than the afterimage because gradient-offset induced motion is only observed during the beginning phase of the afterimage during which the decay rate of the afterimage is high. Further experiments are required to test this possibility.

8. General discussion

Results from Experiment 1a show that gradient-offset induced motion can be perceived upon stimulus offset for about 700 ms. The perceived direction of the illusory motion is determined by the luminance polarity. When a gradient stimulus, whose luminance contrast ranges gradually from low on one side to high on the other side, is turned off all at once, illusory motion from low to high contrast sides is perceived.

In Experiments 2 and 3, our data successfully rule out the possibility that gradient-offset induced motion is due to apparent motion between the original image and the afterimage (Hypothesis 1), and the possibility that gradient-offset induced motion is a variant of CAI (Hypothesis 2). Results from Experiment 3 also reveal that continuous gradient stimuli are necessary for gradient-offset induced motion. It is therefore some property of gradients per se, presumably a continuous change in luminance values over space, which is crucial to the generation of this effect.

In Experiments 4 and 5, our results show that both short presentation of the stimuli and equiluminant stimuli fail to induce gradient-offset induced motion. Since a luminance-defined gradient afterimage is missing in both cases, these results suggest that such an afterimage is a necessary condition for generating gradient-offset induced motion. Therefore, these data are consistent with the possibility that gradient-offset induced motion arises because of afterimage decay. Results from Experiment 5 also suggest that gradient-offset induced motion is a magnocellular effect because the illusory motion disappeared when the luminance-defined gradient was removed.

In Experiment 6, results show that gradient-offset induced motion lasts much shorter than the afterimage, seeming to suggest that gradient-offset induced motion may not be due to the decay of the afterimage. However, an alternative explanation is that gradient-offset induced motion might be related to the decay rate of the afterimage. It is possible, for example, that gradient-offset induced motion can only be observed at the beginning phase of the afterimage during which the decay rate of the afterimage is high. This possibility is actually supported by the finding that the afterimage decays exponentially with a (1/*e*) time constant of 4–8 s (Kelly & Martinez-Uriegas, 1993), which necessarily leads to the consequence of faster decay rate at the beginning phase of the afterimage. Indeed, the subjective speed of gradient-offset induced motion appears to be fastest in the beginning, and to slow down with time.

A possible simple model is shown in Fig. 3. Assume that a single gradient square, whose luminance ranges gradually from white on the left side to black on the right side, is turned off. This would generate an afterimage whose luminance ranges gradually from black on the left side to white on the right side (red line, Fig. 3). Based on the finding that the afterimage decays exponentially with a (1/*e*) time constant of 4–8 s (Kelly & Martinez-Uriegas, 1993), we modeled the decay of the afterimage. The blue line shows the afterimage luminance profile 700 ms after the stimulus was turned off. The following black lines show the consequent luminance profiles every 700 ms later. Notice that the center of luminance energy shifts with time. It is obvious that the decay rate for the first 700 ms time interval is faster than in subsequent time intervals. We hypothesize that the faster decay rate in the beginning phase of the afterimage might be the cause of this illusory motion.

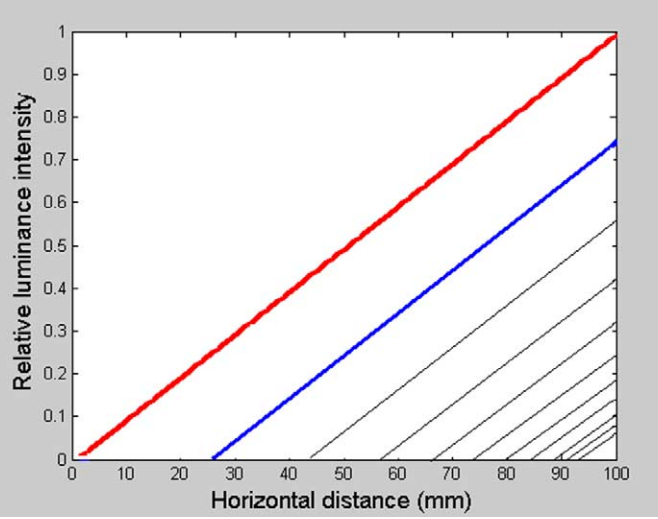

Fig. 3. A simple model of the decay of afterimage. When a single gradient square (100 mm × 100 mm) presented on a white background, whose luminance ranges linearly from white on the left side to black on the right side, was "turned off" so that the whole visual field becomes white as the background, we assume that this would generate an afterimage whose luminance, relative to the background (*y*-axis), increases linearly from the left side to the right side (*x*-axis) as indicated by the red line. We modeled the decay of the afterimage based on the finding that the afterimage decays exponentially with a (1/*e*) time constant of 4 s (Kelly & Martinez-Uriegas, 1993). The blue line shows that the afterimage luminance profile 700 ms after the stimulus was turned off. Black lines show subsequent luminance profiles every 700 ms later. It is obvious that the decay rate for the first 700 ms time interval is faster than for any of the subsequent time intervals. The trend that the decay rate for the first 700 ms time interval is faster than the consequent time intervals remains regardless of what time constant we chose (between 4 and 8 s) as long as decay was exponential. In all instances, the location of the center of luminance energy shifts to the right over time, with the biggest shift occurring in the initial period of afterimage decay.

Anstis (1967) has reported an apparent movement illusion that is perceived over gradient stimuli after visual adaptation to gradual changes of intensity (i.e., after exposure to a light that grows gradually lighter, a steady gradient stimulus would appear to grow dimmer and move gradually). The effect, perhaps related to gradient-offset induced motion, may be related to shifts in the apparent location of features in brightening/darkening ramp, whether the ramp is real or an afterimage. When the ramp disappears in our stimulus, any gradual fade-out of the stimulus may induce the apparent movement reported by Anstis. Differences between the present findings and those of Anstis include: (1) the apparent movement is observed on a real gradient in Anstis' finding, and is observed on the afterimage of a gradient in ours; and (2) the apparent movement is due to adaptation to gradual change of intensity in Anstis' finding, and is probably due to a faster decay rate in the beginning phase of the afterimage in the case of gradient-offset induced motion. Despite these differences, both motion effects suggest that apparent movement can be observed on a brightening/darkening ramp, whether the ramp is real or an afterimage, whatever the cause of the brightening/darkening is.

An alternative explanation for the gradient-offset induced motion is the adaptation of 'motion streak' detectors. Geisler (1999) theorized that motion streaks provide a potential motion cue that could be exploited by the visual system. Motion streaks arise because of the finite decay time in the responses of retinal cells, creating a 'blur' signal behind a moving stimulus (Carello, Rosenblum, & Grosofsky, 1986; Kim & Francis, 1998). Gradient stimuli could possibly activate motion streak detectors, because a gradient resembles the streak that a bar would leave upon the retina when moving along the direction of the gradient. If gradient stimuli activate such motion detectors, this could lead to their relative fatiguing in the absence of any conscious experience of motion. Therefore, it is possible that gradient-offset induced motion is perceived because the gradient stimulus we used in our experiment resembles a motion streak. The gradients we used would resemble the streaks left by black bars moving on a white background. However, this hypothesis would predict that, after the stimulus was turned off, motion should appear to go from the dark side to the bright side of the original stimulus because the bright side of the original stimulus was interpreted as the "tail side" of a motion streak. Since the results are opposite to this prediction, we conclude that this explanation is incorrect.

Another hypothesis is that the gradient-offset induced motion might arise from the differential response latencies of motion detectors that are sensitive to luminance cues within static gradient stimuli. Kitaoka and Ashida (2003) proposed that higher contrast would produce faster responses in the visual system. This contrast-based difference in response timing has been observed in visual neurons (Conway, Kitaoka, Yazdanbakhsh, Pack, & Livingstone, 2005; Maunsell & Gibson, 1992; Sestokas & Lehmkuhle, 1986; Shapley & Victor, 1978). Thus, it is possible that motion detectors are activated on the higher-contrast side (black side) before being activated on the lower-contrast side (white side) and thus respond as if there were real motion in the image. In our case, the original gradient stimuli should generate motion signal from the black side to the white side upon gradient onset, since the black side has highest contrast, and in the same direction upon stimulus offset, because the component of the afterimage that has highest contrast is where the black side was. This prediction is the exact opposite of what we observed. We therefore reject this hypothesis as well.

To conclude, we report properties of a new type of illusory motion, which we call "gradient-offset induced motion." When a gradient stimulus, whose luminance ranges gradually from white on one side to black on the other side, is "turned off" all at once, leaving only the uniform white background, illusory motion is perceived to continue for several hundred milliseconds. Our data rule out several hypothesized mechanisms that may underlie this effect, and is consistent with the hypothesis that the effect arises from the rapid initial decay of the afterimage.

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