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Spatiotemporal Rivalry: A Perceptual Conflict Involving Illusory Moving and Static Forms

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Abstract

In human vision, mechanisms specialized for encoding static form can signal the presence of blurred forms trailing behind moving objects. People are typically unaware of these motion-blur signals because other mechanisms signal sharply defined moving forms. When active, these mechanisms can suppress awareness of motion blur. Thus, although discrepant form signals can be produced, human vision usually settles on a single coherent perceptual outcome. Here we report a dramatic exception. We found that, in some circumstances, static motion-blur form signals and moving-form signals can engage in a dynamic competition for perceptual dominance. We refer to the phenomenon as spatiotemporal rivalry (STR). Our data confirm that moving- and static-form mechanisms can generate independent signals, each of which can intermittently dominate perception. STR could therefore be exploited to investigate how these mechanisms contribute to determining the content of visual awareness.

Keywords

visual consciousness, multistable perception, visual binding, temporal vision

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Mechanisms in human vision are often described as spatiotemporal, as they are sensitive to stimulus changes spread across space and time. There are, however, distinct patterns of sensitivity that can cause mechanisms to generate discrepant signals following exposure to coherent input. For instance, a rapidly moving object can prompt moving-form mechanisms to signal the presence of an apparently sharply defined moving object (Burr, 1980; Chen, Bedell, & Ogmen, 1995). At the same time, static-form mechanisms can signal the presence of a blurred form elongated along the trajectory of motion (Burr & Ross, 2002; Geisler, 1999; Geisler, Albrecht, Crane, & Stern, 2001). Blurred-form signals are generated because static-form mechanisms integrate information relatively slowly. Thus, like a camera with a slow shutter speed, they can signal motion blur trailing behind a rapidly moving object (Burr & Ross, 2002; Geisler, 1999; Geisler et al., 2001).

Motion-blur signals can seem mysterious, as they are usually suppressed from awareness (Burr, 1980; Chen et al., 1995). It has been proposed that this happens because, when active, moving-form mechanisms suppress awareness of motion-blur signals (Burr, 1980). To explore this interplay, we designed stimuli intended to prompt static- and moving-form mechanisms to generate discrepant signals.

Our initial stimulus was a rapidly rotating windmill pattern with thin arcs of a different color at the midpoints of the windmill arms (as depicted in Fig. 1a). We reasoned that the rapid directional movement would generate high rates of stimulus repetition that would exceed the temporal resolution of static-form mechanisms. Evidence suggests that the critical rate of repetition is approximately 10 Hz. This estimate comes from a study suggesting that moving dots elicit greater responses in neurons with receptive fields elongated along the trajectory of motion, as opposed to orthogonal to the direction of motion, whenever dot speeds exceed approximately 1 dot width per 100 ms (Geisler, 1999). Thus, when stimulus speed is sufficient to generate repetitions of approximately 10 Hz, some mechanisms in human vision will encode that movement as cojoined blur (Burr & Ross, 2002; Geisler, 1999; Geisler et al., 2001).

Equally importantly, we reasoned that mechanisms that encode rapid movement as blur would be sensitive to finer

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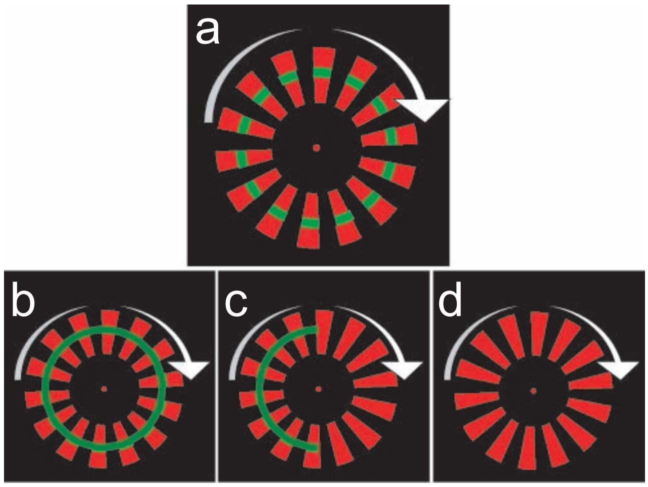

Fig. 1. Depiction of the stimulus used in Experiment 1 (a) and of the illusory forms experienced during spatiotemporal rivalry (b–d).

spatial scales than mechanisms that encode rapid movement as movement. This assumption is based on observations that the sensitivity of human vision shifts toward progressively coarser spatial resolutions as movement speeds increase (Burr & Ross, 1982), and that direction-tuned mechanisms tend to have larger receptive fields than do static-tuned mechanisms (Gegenfurtner, Kiper, & Levitt, 1997). To our surprise, we found that viewing our rapidly rotating windmill pattern (Fig. 1a) instigated a dynamic competition for perceptual dominance involving two illusory forms.

Spatiotemporal Rivalry

Here, we present a new form of multistable perception involving an intermittent illusion of a static ring seen at locations corresponding with thin colored arcs (as depicted in Fig. 1b). We suggest that this illusion occurs because the arcs are encoded as motion blur by static-form mechanisms. These blurred forms become perceptually fused because of rapid movement and the repetitive nature of our stimulus. This illusion competes with an intermittent impression of an illusory single-colored rotating windmill, with no apparent trace of the color associated with the thin arcs (as depicted in Fig. 1d). We suggest that this single-colored windmill is perceived because moving-form mechanisms integrate color information across relatively broad spatial regions, which encompass the locations of the thin colored arcs in our stimulus. We refer to this dynamic competition as spatiotemporal rivalry (STR), as we believe it is a new form of multistable perception driven by distinct spatiotemporal mechanisms signaling discrepant illusory forms (see http://www2.psy.uq.edu.au/~darnold/STR.htm for interactive demonstrations).

General Method

The stimuli in the experiments reported in this article consisted of windmill patterns rotating against a black background (as depicted in Fig. 1a). Rotation direction was randomized from trial to trial. The outer diameter of the windmill subtended 10° visual angle, and the central circular black region subtended 5°.

Stimuli were generated with a ViSaGe from Cambridge Research Systems (Rochester, United Kingdom) and displayed on a gamma-corrected 19-in. Sony Trinitron G420 monitor, at a resolution of 1024 × 768 pixels and a refresh rate of 120 Hz. Stimuli were viewed from 57 cm with the head placed in a chin rest. Responses were signaled via button presses. All participants had normal or corrected-to-normal visual acuity and color vision.

Preliminary Observations

We viewed rapidly rotating windmill patterns (0.36 revolutions/s), each with arms of a predominant color except for thin arcs of a second color at the midpoint (as in Fig. 1a). The stimuli included all possible combinations of the following colors (defined according to the Commission Internationale de l'Éclairage, or CIE, 1931 chromaticity chart: blue (x = 0.15, y = 0.07, Y = 17.14), red (x = 0.62, y = 0.35, Y = 17.14), green (x = 0.27, y = 0.62, Y = 17.14), and yellow (x = 0.40, y = 0.51, Y = 17.14). STR was experienced for all combinations. Consequentially, STR cannot be ascribed to an interaction between a specific color pairing.

We were also able to rule out simple explanations for the intermittent illusions. For instance, when observers tracked one of the rotating arcs with their eyes, the illusory static ring could not be seen. Physically tracking an object effectively stabilizes the tracked image on the retina, but does not change the physical properties of the display. Thus, the impression of a static ring cannot be due to the physical properties of the display. Instead, it must be related to a selective perceptual persistence (Efron, 1970) of the thin colored arcs as they move across the retina. This selective persistence must be sufficient for the physically offset arcs to become perceptually fused as a result of the repetitive nature of the stimulus.

Finally, when we slowed the stimulus (0.09 revolutions/s), neither intermittent illusion was seen. We can therefore rule out the possibility that the intermittent impression of a single-colored rotating windmill is driven by a selective fading of one of the two stimulus colors (Troxler, 1804) that is unrelated to rapid stimulus movement.

Experiment 1: Criteria for STR

In Experiment 1, we tested two predictions. We predicted that STR will occur only when stimulus movement induces rapid rates of repetition (~10 Hz), which static-form mechanisms will encode as motion blur (Geisler, 1999). Similarly, we predicted that STR will occur only when the stimulus contains thin color-defined regions (as depicted in Fig. 1a), which will simultaneously be encoded at a coarse spatial resolution by mechanisms that encode rapid movement as movement and at a finer spatial resolution by mechanisms that encode rapid movement as blur (Burr & Ross, 1982).

Method

In Experiment 1, the windmill arms were colored red (x = 0.62, y = 0.35, Y = 25.63) and green (x = 0.27, y = 0.62). Green luminance was set to a value subjectively equal to red luminance, determined individually via a minimum-motion technique prior to the experiment (see Anstis & Cavanagh, 1983).

In Experiment 1a, we determined minimal rotation speeds for creating an illusory static ring (as in Fig. 1b) using rotating windmill patterns with radial frequencies of 7, 14, and 28 (which refer to the number of windmill arms). Each stimulus presentation persisted for 1 s. The participant then reported if he or she had seen a static ring. Green arcs at the midpoints of otherwise red windmill arms (as shown in Fig. 1a) subtended 0.10°. During a run of trials, a range of rotation speeds was sampled (six times for each speed) in a random order, for a total of 126 trials. The different revolution speeds caused the windmill arms to repeatedly cross local stimulus points at different frequencies. We refer to these as local repetition rates. Each participant completed two runs of trials. This experiment was completed by 2 of the authors and an additional 2 participants who were naive as to the purpose of the experiment.

In Experiment 1b, we determined the proportions of presentation time during which illusory forms were experienced. The authors and an additional 4 observers, naive as to the purpose of the experiment, participated. The stimulus rotated at 0.36 revolutions/s for 30 s. Four different green-arc widths were tested, in a random order. During a run of trials, each arc width was presented four times. During stimulus presentations, participants held down one of three buttons to indicate when they saw an illusory static green ring (as depicted in Fig. 1b), a rotating red windmill with no apparent trace of green (see Fig. 1d), or a partially completed green ring in some stimulus sections with no apparent trace of green in others (see Fig. 1c). They were instructed to continue to press each button for as long as they saw the corresponding pattern.

Results

From each run of trials in Experiment 1a, we determined the proportion of trials on which participants perceived the illusory static ring as a function of local repetition rate for windmills with radial frequencies of 7, 14, and 28. Weibull functions were fitted to individual distributions, and 50% points were taken as estimates of the necessary rate of local repetition for STR to occur. For radial frequencies of 7, 14, and 28, these rates corresponded to 8.2 (± 0.7), 7.6 (± 0.4), and 7.1 (± 0.4) Hz (see Fig. 2a), or 1.3, 0.5, and 0.3 revolutions/s, respectively (see Fig. 2b). The invariance of the rate of local stimulus repetition necessary for STR (~7.7 Hz), coupled with the variance observed when this rate is expressed in terms of revolutions per second, suggests that the critical aspect of movement is the

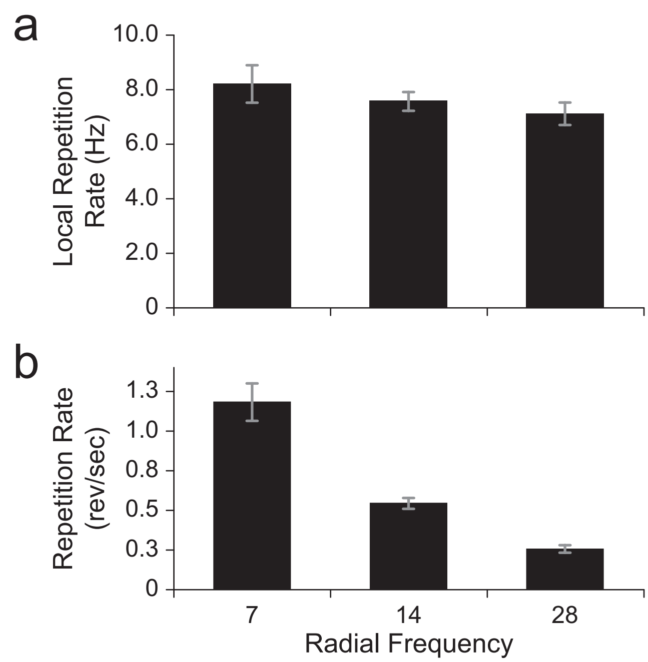

Fig. 2. Bar plots depicting estimates of the critical repetition rate necessary for spatiotemporal rivalry to occur (Experiment 1a). Estimates are given for windmill patterns with radial frequencies of 7, 14, and 28 and are expressed in terms of local repetition rate (a) and revolutions per second (b). Error bars depict ±1 *SE*, calculated from four individual estimates.

induced rate of local repetition, and not the physical speed at which the windmill arms rotate.

Figure 3 presents the results of Experiment 1b. STR was inversely related to the widths of the green arcs in the display (single-colored windmill: r = –.453, p = .009; completed green ring: r = –.585, p < .001). When the green arcs were sufficiently wide, perception of the stimulus was veridical with the physical input. Thus, STR was robust only when the stimulus contained thin colored arcs. This finding is consistent with our suggestion that a conflict is generated by moving- and static-form mechanisms encoding the stimulus at different spatial resolutions (Burr & Ross, 1982).

Discussion

We have shown that the appearance of an illusory static surface during STR depends on a rapid rate of local stimulus repetition. This rate (~7.7 Hz) approximates the critical frequency for the production of motion-blur signals (~10 Hz; see Geisler, 1999). Our data are therefore consistent with the proposal that this illusion occurs when physically offset colored arcs become perceptually fused because of motion blur and the repetitive nature of our stimulus.

We have suggested that STR is a dynamic competition between two illusory form signals. The intermittent disappearance of one of the illusory forms, a static ring, is driven by the integration of broad moving-form signals across the locations of thin colored arcs; this integration brings about the other

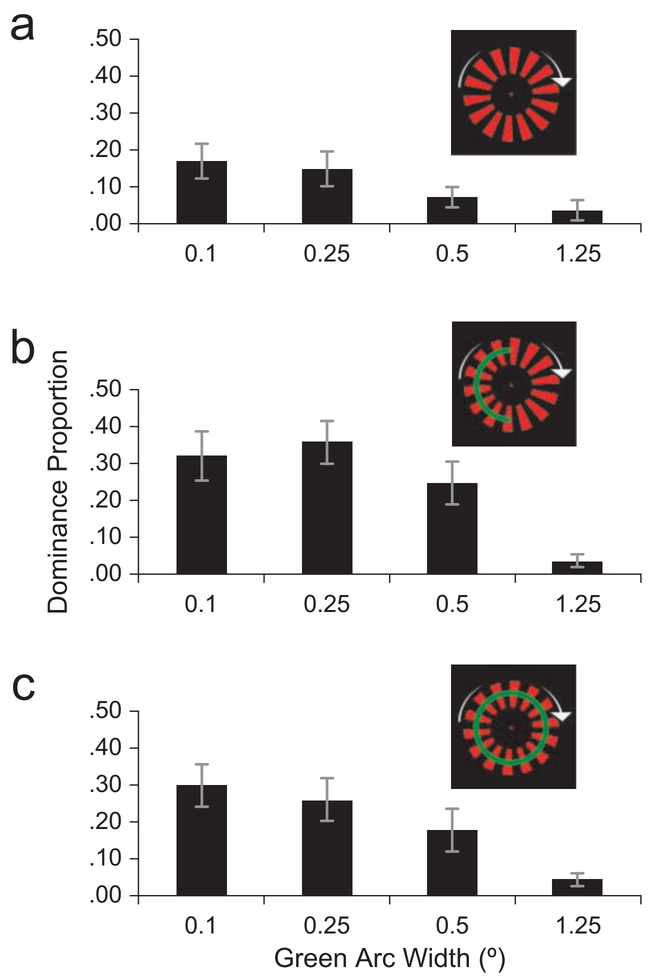

Fig. 3. Bar plots depicting the proportion of presentation time during which participants reported seeing (a) an illusory single-colored rotating windmill, (b) a partially completed illusory static green ring in some stimulus sections with no apparent trace of green in other sections, or (c) an illusory static green ring surrounded by a rotating red windmill pattern (Experiment 1b). These dominance proportions are plotted as a function of the width of the green arc (in degrees of visual angle). Error bars represent ±1 *SE*, calculated across 8 participants.

illusory form—a single-colored rotating windmill. It should therefore be possible to disrupt STR via manipulations that prevent the integration of broad moving-form signals that cross the locations of the thin colored arcs. One way to do so would be to reverse the rotation direction for the inner, relative to the outer, sections of the red windmill arms (the scrambled condition; see Fig. 4). When these two red sections rotate in opposite directions, they are inconsistent with the existence of a broad coherent moving form that extends across the locations of the green arcs. Another way to disrupt the integration of the moving-form signals would be to shift the green arcs, converting the stimulus into a checkerboard pattern (the checkerboard condition; see Fig. 4).

It should also be possible to disrupt STR via manipulations that enhance the sensitivity of moving-form mechanisms to the presence of the green arcs. As these mechanisms are sensitive to both color and, more important, motion direction (Nishida, Watanabe, Kuriki, & Tokimoto, 2007), this could be achieved by reversing the direction of rotation for the green arcs relative to the rest of the display (the reversed-ring condition; see Fig. 4).

Experiment 2: Three Manipulations That Disrupt STR

In Experiment 2, we tested our predictions for these three new conditions. The methodological details were the same as in Experiment 1b, with the following exceptions. During a run of trials, each of three stimulus configurations (scrambled, checkerboard, and reversed ring; see Fig. 4) was presented four times (for 30 s), in a random order. In the scrambled condition, the green arcs rotated in the same direction as the inner sections of the red windmill arms. The widths of the central green arcs subtended 0.25° in all conditions.

All three manipulations successfully disrupted STR, resulting in perceptual experiences that were veridical with the physical display (see Fig. 4 and cf. Figs. 3a and 3c).

One aspect of STR that requires further explanation concerns the location of the illusory static ring. If this ring is related to motion-blur signals, why did it appear in only one stimulus section, given that motion-blur signals are coupled with movement throughout the stimulus? We believe that the illusory ring appeared in only one stimulus section because there was only one region containing thin colored arcs prompting a localized conflict between mechanisms that encode rapid movement as movement at a coarse spatial resolution and mechanisms that encode rapid movement as blur at a finer spatial resolution (Burr & Ross, 1982). Accordingly, we predicted that we could induce a more widespread STR by including more thin colored regions, and we tested this prediction in Experiment 3.

Experiment 3: Widespread STR

Methodological details for Experiment 3 were similar to those for Experiment 1b, with the following exceptions. The authors and an additional 2 observers, naive as to the purpose of the experiment, participated. We predetermined individual thresholds for detecting red and green stripes against otherwise yellow windmill arms. These were determined by manipulating the color of the stripes along a vector running between red ($x = 0.62$, $y = 0.35$, $Y = 25.63$) and green ($x = 0.27$, $y = 0.62$), with the end-point green luminance set to a value subjectively equal to red luminance. During the experiment, windmill arms were striped red and green (see Fig. 5a), with each color set to 3 times the individual's threshold contrast. Stripe widths subtended 0.13°, 0.25°, 0.50°, or 1.00°. During each trial, participants reported when they could see only an illusory static surface resembling a striped doughnut (as in Fig. 5b) or an illusory single-colored rotating windmill (as in Fig. 5c).

As Figure 5d shows, we were able to induce STR that spread across the stimulus. Readers should note, however, that this stimulus caused less perceptual dominance of exclusive

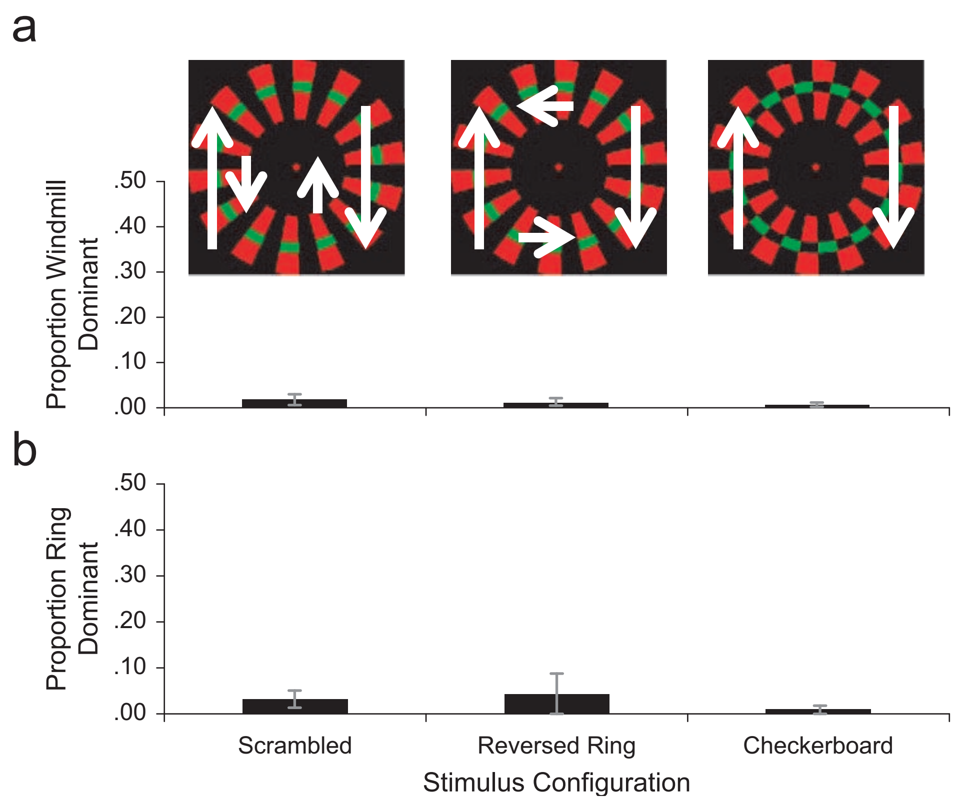

Fig. 4. Bar plots showing the proportion of presentation time during which participants in Experiment 2 reported seeing (a) an illusory single-colored windmill or (b) a stimulus with an illusory static opaque green ring. Data are shown for three stimulus configurations (see the text for descriptions). Error bars represent ±1 *SE*, calculated across the proportions reported by 8 participants.

static and single-colored moving surfaces than did the stimulus in Experiment 1b (cf. Fig. 5d with Figs. 3a and 3c). In part, this was because participants often reported seeing both percepts concurrently, with the single-colored rotating surface seeming to float above a static, striped doughnut-like surface.

Note that Figure 5c depicts the color of the illusory single-colored rotating windmill as yellowish, and not a saturated red or green. This is deliberate. The color in the figure reflects the apparent color of this illusory form in Experiment 3. This finding suggests an additional question that we have not yet addressed: How is the apparent color of moving form determined during STR?

The apparent color of rotating forms during STR could be shaped by selective suppression, with one of the two stimulus colors suppressed from awareness while the other is perceptually spread across the stimulus. Alternatively, the effect could be induced by a spatial color-averaging process for moving form (Hsieh & Tse, 2009). To assess these possibilities, in Experiment 4 we manipulated the relative saturations of the two colors within our striped stimulus (see Fig. 5a).

Experiment 4: Accounting for Apparent Color During STR

Methodological details of Experiment 4 were as described for Experiment 3, with the following exceptions. The red and green stripes were both presented at 3 times threshold contrast (balanced condition), with red at 6 times and green at 3 times threshold (red condition), or with red at 3 times and green at 6 times threshold (green condition). On each trial, the participant waited until the stimulus seemed to consist of a single color and signaled this by pressing a button, at which point a static test stimulus appeared. The color of the static test pattern was initially set to a random point along a continuum between the participant's red and green color coordinates (determined in Experiment 1). The participant then manipulated the color of the static test stimulus, pressing one button to make it redder and another to make it greener, until he or she felt it matched the illusory single color of the preceding rotating windmill. We recorded the settings as a multiple of the relevant threshold (the minimal detectable distance from the midpoint of the participant's red-green continuum). If the color was matched to a point toward green (relative to the yellow midpoint), it was recorded as a positive value and expressed as a multiple of the green detection threshold. If the color was matched to a point toward red, it was recorded as a negative value and expressed as a multiple of the red threshold.

If participants had matched the test stimulus to the more saturated of the two stimulus colors, the matched values would have been +6 for the green condition and –6 for the red condition. Instead, matches were better predicted by color averaging (0 for the balanced condition, +3 for the green condition, and –3 for the red condition; see Fig. 5e). The small standard

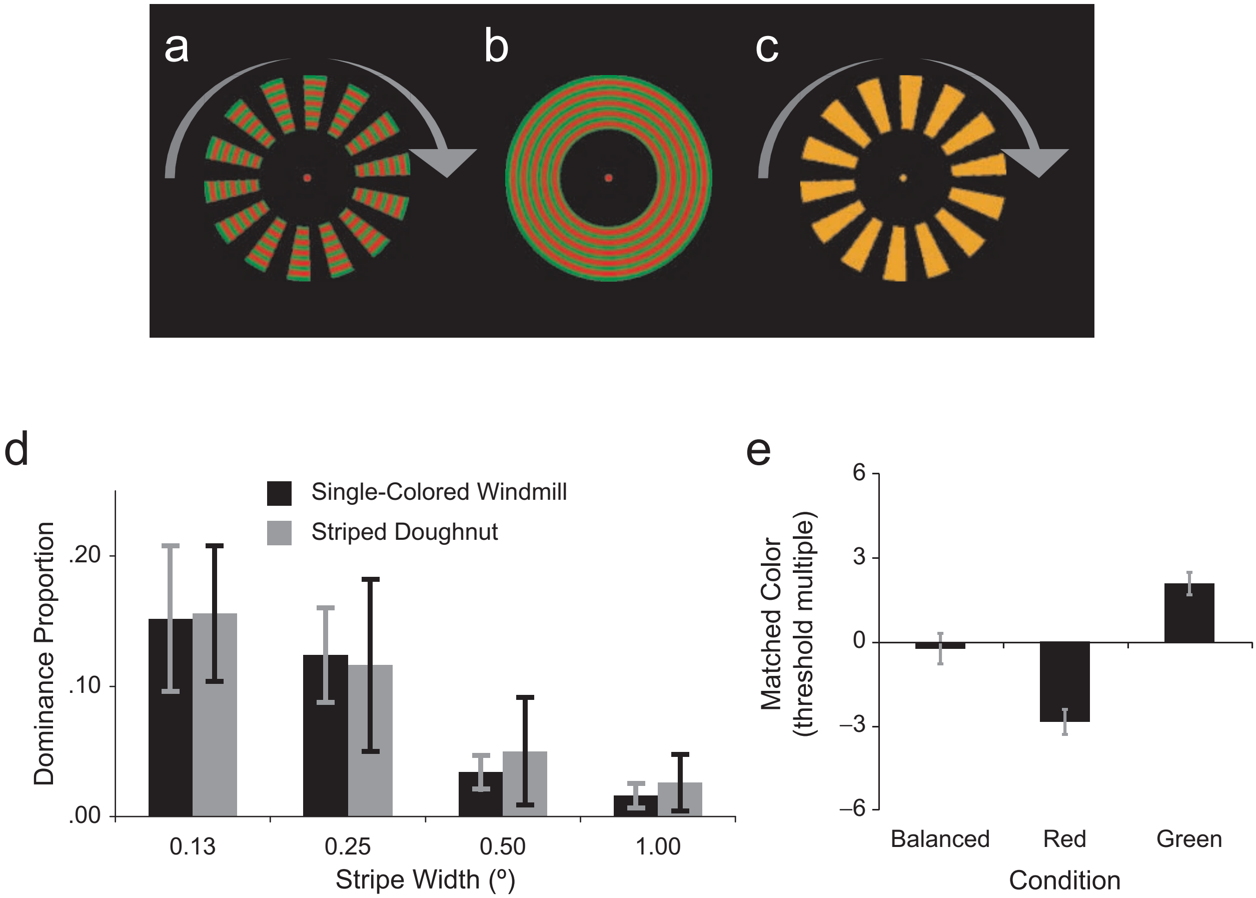

Fig. 5. Experimental stimulus, illusory forms experienced, and results in Experiments 3 and 4. In Experiment 3, participants viewed (a) a rotating windmill with arms striped red and green and reported when they saw (b) a static surface resembling a striped doughnut or (c) a single-colored rotating windmill. The bar plot in (d) depicts the proportions of presentation time during which participants reported seeing these two illusory forms, as a function of the width of the stripes on the experimental stimulus. Error bars represent ±1 *SE*, calculated across proportions reported by 6 participants. In Experiment 4, participants viewed a striped windmill stimulus and reported the color of the single-colored rotating windmill that they perceived. The bar plot in (e) depicts the mean static test colors matched to this illusory windmill, expressed as a multiple of the detection threshold (see the text for details). Error bars show the average standard error, across 10 matches for each observer.

errors associated with these matches show that participants were matching the test stimulus specifically to the averaged color, rather than alternately matching the test stimulus to each of the windmill's colors.

These data suggest that the color of moving forms during STR is shaped by a spatial color-averaging (or summation) process (also see Hsieh & Tse, 2009). This suggests that the impression of a red rotating windmill (without any apparent trace of green) in our initial display was probably a consequence of the scarcity of green in that stimulus.

General Discussion

We have reported a new form of multistable perception. STR is characterized by a dynamic competition for perceptual dominance involving two illusory forms. We have linked one of these forms, a motionless ring (or rings), to static-form mechanisms. To establish this link, we investigated the rate of local stimulus repetition required for the formation of an illusory static surface (see Fig. 2a). The established rate (~7.7 Hz) approximates the critical rate for the production of motion-blur signals (~10 Hz; see Geisler, 1999). We therefore attribute this illusion to perceptual fusion of the physically offset colored arcs (or stripes) as a result of motion blurs and the repetitive nature of our stimulus.

Although the critical rate of stimulus repetition for STR approximates the critical repetition rate for the production of motion blur (Geisler, 1999), STR may also be related to other phenomena. For instance, the critical repetition rate for STR exceeds the maximal rate at which moving elements can be tracked via attention (~5–7 Hz; see Verstraten, Cavanagh, & Labianca, 2000). This may not be coincidental. It seems that attentional tracking depends on visual mechanisms that cannot disambiguate inputs at high repetition rates. STR may be a visible consequence of this limit, with repetitive stimulus elements becoming perceptually fused when they cannot be disambiguated by the visual mechanisms used for attentional tracking (Burr & Ross, 2002; Geisler, 1999; Geisler et al., 2001).

The other intermittent illusion during STR is of an apparently single-colored rotating windmill (as depicted in Figs. 1d and 5c). Our data suggest that this illusion is due to the apparent color of moving forms being determined via integration across relatively broad spatial regions (see Experiment 4). In Experiment 1, this integration seems to have encompassed the green associated with the thin arcs and the red associated with the much larger surrounding stimulus regions, resulting in an overall impression of a red moving form (as depicted in Fig. 1d). In Experiments 3 and 4, integration seems to have encompassed equally thin red and green stripes (as depicted in Fig. 5a), resulting in an impression of a yellowish moving form (as depicted in Fig. 5c).

We provided further evidence of a link between STR and moving-form mechanisms in Experiment 2. In that experiment, we were able to disrupt STR via manipulations designed to prevent the formation of broad moving-form signals across the locations of thin colored arcs (the scrambled and checkerboard conditions). Reversing the direction of movement for the thin colored arcs relative to the rest of the display was equally effective (the reversed-ring condition). This last manipulation was designed to heighten the sensitivity of moving-form mechanisms to the presence of the thin colored arcs.

STR and other phenomena

STR is similar to other multistable phenomena in that it is characterized by intermittent switches between multiple perceptual states (Alais & Blake, 2005; Blake & Logothetis, 2002; Bonneh, Cooperman, & Sagi, 2001; Breese, 1899; Carter & Pettigrew, 2003; Levelt, 1967; Wheatstone, 1838). During STR, there are periods during which an impression of a single-colored rotating windmill dominates perception (see Figs. 3a and 5d) and periods during which an illusory static surface is seen (see Figs. 3c and 5d). There are also periods during which a partially completed static surface can be seen in some stimulus sections while no apparent trace of a second stimulus color is seen in others (see Fig. 3b). This last observation ties STR to localized operations, which are symptomatic of processing at relatively low levels of the human visual system.

Although reminiscent of other instances of multistable perception, STR is also novel. For instance, the phenomenon is characterized by a dynamic competition for perceptual dominance involving two illusory forms, rather than by intermittent disappearances or an apparent fading of physical input (Alais & Blake, 2005; Blake & Logothetis, 2002; Bonneh et al., 2001; Levelt, 1967; Troxler, 1804; Wheatstone, 1838). We have linked these intermittent illusions to mechanisms optimized for encoding moving and static forms. These well-established mechanisms (Apthorp & Alais, 2009; Burr & Ross, 2002; Edwards & Crane, 2007; Geisler, 1999; Geisler et al., 2001; Nishida, 2004; Nishida et al., 2007) could be targeted for physiological analyses during STR, which might reveal their role in determining the content of awareness.

Of the known multistable phenomena, STR is most like motion-induced blindness (Bonneh et al., 2001; Graf, Adams, & Lages, 2002; Grindley & Townsend, 1965; New & Scholl, 2008; Wallis & Arnold, 2008, 2009). Both are characterized by intermittent disappearances of perceptually static forms in the presence of movement. However, in STR, the impression of a static form is an illusion brought about by mechanisms that integrate information relatively slowly (Cao & Shevell, 2005; DeValois & DeValois, 1975) and produce motion-blur signals when exposed to rapid movement (Burr, 1980; Chen et al., 1995; Geisler, 1999). STR could therefore be described as a motion-induced motion blindness, as the stimulus sections that seem to disappear are physically moving.

We have recently suggested that motion-induced blindness (Bonneh et al., 2001) is driven by a functional process intended to suppress motion-blur signals from awareness (Wallis & Arnold, 2009). We take STR as support for this interpretation. It demonstrates that motion-blur and moving-form signals can engage in a dynamic competition for perceptual dominance. Although the static forms experienced during STR are illusory, we believe that the mechanism responsible for their intermittent suppression is the same as that which suppresses awareness of physically static objects during motion-induced blindness.

Conclusion

Vision depends on diverse spatiotemporal mechanisms that can generate discrepant form signals when exposed to a moving stimulus. Usually, however, the human visual system generates a single coherent perceptual outcome. STR is an example of a failure of this process, in which perception enters a multistable state, flipping between conflicting illusions of static and moving forms and occasional veridical perceptions of the stimulus. The stimulus used to elicit these effects is easily modifiable, and the mechanisms that drive the phenomenon could be targeted for physiological analyses. STR should therefore provide a useful tool for researchers who wish to examine how specific mechanisms contribute to determining the content of visual awareness.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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