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Stimulus factors affecting illusory rebound motion

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Abstract

Stimulus attributes that influence a recently reported illusion called "illusory rebound motion" (IRM; [Hsieh, P.-J., Caplovitz, G. P., & Tse, P. U. (2005). Illusory rebound motion and the motion continuity heuristic. *Vision Research*, *45*, 2972–2985.]) are described. When a bar alternates between two different colors, IRM can be observed to traverse the bar as if the color were shooting back and forth like the opening and closing of a zipper, even though each color appears in fact all at once. Here, we tested IRM over dynamic squares or disks defined by random dot or checkerboard textures to show that (1) IRM can be perceived in the absence of first-order motion-energy (or when the direction of net first-order motion-energy is ambiguous); (2) the direction of IRM is multistable and can change spontaneously or be changed volitionally; and (3) the perceived frequency of IRM is affected by several factors such as the contours of the stimulus, stimulus texture, and motion-energy.

Keywords: Transformational apparent motion; Texture; Form

1. Introduction

The phenomenon of apparently smooth and continuous shape change has been termed "Transformational Apparent Motion" (TAM; Tse & Cavanagh, 1995). A precedent to TAM was first described by Kanizsa (1951, 1979), and termed "polarized gamma motion." This phenomenon was rediscovered in a more compelling form by Hikosaka, Miyauchi, and Shimojo (1993a, 1993b), which they called "illusory line motion" (ILM). They showed that when a horizontal bar is presented shortly after an initial stimulus, the bar appears to shoot away from the initial stimulus. A related illusion called "illusory rebound motion" (IRM) has recently been discovered (Hsieh, Caplovitz, & Tse, 2005). When a bar of a different color replaces a bar over which ILM has just occurred, observers report that the color appears to shoot in the opposite direction relative to the previous direction of ILM, in the absence of any cuing. Additionally, if bars of different colors are presented one after another at a constant stimulus onset asynchrony (SOA) following ILM, IRM can be perceived to occur over every color with alternating direction, as if a 'zipper' were opening and closing. It has also been shown that when viewing bars flashing between black and white on a gray background, this "zipper-like" IRM (or zipper motion) can actually happen spontaneously without being preceded by ILM. Moreover, the bistable percept will alternate between IRM and simply flashing (Hsieh, Caplovitz, & Tse, 2006). The stimulus is truly bistable because any time motion is seen, it appears as IRM, and any time IRM is not seen, flashing is seen instead of motion.

In this article, rather than bars, we report the results of experiments that used squares or circles defined by dynamic random dot or checkerboard textures. Results reveal that (1) IRM can be perceived in the absence of motion-energy (no net motion-energy); (2) the direction of IRM is multistable and can change spontaneously or be changed volitionally; and (3) the perceived frequency of IRM is influenced by multiple stimulus factors, including contour relationships, texture, and motion-energy.

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2. Experiment 1: The minimum and maximum refresh rates necessary to perceive IRM

The goal of Experiment 1 was to determine the minimum and maximum refresh rates that permit the perception of IRM. We tested this by letting subjects adjust the refresh rates of a square defined by random dots.

2.1. Method

2.1.1. Observers

Ten subjects (eight naïve Dartmouth students and two authors) with normal or corrected-to-normal vision carried out the experiment. Before the experiment, all subjects were shown the stimuli and all reported being able to perceive a horizontal zipper-like IRM.

2.1.2. Stimulus displays

The fixation point was a small red (luminance: 21.41 cd/m^2; CIE, $x = 0.628$, $y = 0.341$) square that subtended 0.05° of visual angle on a background filled with random dots. The random dots were composed of small squares (288×216 squares) abutting each other across the monitor ($20° \times 15°$ visual degree). On average, there were 14.4×14.4 small squares with random brightness between white and black over $1° \times 1°$ visual degree (the visual angle subtended by a single square element was $0.069° \times 0.069°$ visual degrees). The refresh rate of the random dots within a square window ($6° \times 6°$ visual degree), centered at the fixation spot, was under the control of the subjects. The visual stimulator was a 2 GHz Dell workstation running Windows 2000. The stimuli were presented on a 23-in. SONY CRT monitor with 1600×1200 pixels resolution and 85 Hz frame rate. Observers viewed the stimuli from a distance of 57 cm with their chin in a chin rest.

2.1.3. Procedure

The stimulus configuration used in Experiment 1 is shown in Fig. 1A. The experiment was conducted in two blocks, each containing 10 trials. In the first block, the square window of random dots was initially refreshed either every 50 ms (4 frames ≈ 47.06 ms; frame refresh rate = 85 Hz) or every 500 ms (42 frames ≈ 494.12 ms), alternatively across trials. Subjects were required to adjust the refresh rate to find the maximum rate (minimum stimulus duration) under which they could still perceive the horizontal zipper-like IRM. In the second block, the initial refresh rate was either every 500 ms (42 frames ≈ 494.12 ms) or every 2400 ms (204 frames ≈ 2399.04 ms), alternatively across trials. Subjects were required to adjust the refresh rate to find the minimum rate (maximum stimulus duration) under which they could still perceive the horizontal zipper-like IRM.

2.2. Results and discussion

The minimum stimulus duration (1/refresh rate) required to perceive IRM was 313.00 ± 58.99 ms, and the maximum stimulus duration required to perceive IRM was 1863.50 ± 100.59 ms. These data are consistent with our previous finding (Hsieh et al., 2005) that the perception of first-order IRM asymptotes to 80% starting at about 300 ms (stimulus onset asynchrony, SOA), and can be perceived at this high percentage level at a 500 ms SOA and beyond.

3. Experiment 2: Controlling for eye movements

In the previous experiment, subjects reported that they could perceive IRM not only horizontally, but also vertically or diagonally. More interestingly, subjects also reported that they could volitionally switch between different percepts of IRM such that the perceived axis of IRM could be changed at will. This suggests a role for top-down feedback in the generation of the IRM percept. However, an alternative hypothesis is that the switching between different percepts is not influenced by top-down factors, but is instead triggered by bottom-up stimulus changes or is caused by saccades or microsaccades. Subjects might volitionally or non-volitionally move their eyes, which would lead to a perceptual switch, and they might then attribute the perceptual shift to an act of will after the fact. To test whether eye movements are correlated with the perceived directions of IRM, eye movements were monitored in Experiment 2 while subjects spontaneously switched between different directional percepts of IRM over a constant stimulus configuration.

3.1. Method

3.1.1. Observers

Six subjects with normal or corrected-to-normal vision carried out the experiment. All of them had participated in Experiment 1. The stimuli were the same as those of Experiment 1 except that the random dots within a square window ($6° \times 6°$ visual degree), centered at the fixation spot, were refreshed at a constant rate of 2 Hz. Before the experiment started, they were informed of four kinds of possible percepts of IRM: horizontal IRM, vertical IRM, upper-right diagonal (upper-right to lower-left) IRM, and upper-left diagonal (upper-left to lower-right) IRM. These encompassed the directions of perceived motion that subjects typically perceived spontaneously.

3.1.2. Stimulus displays and procedures

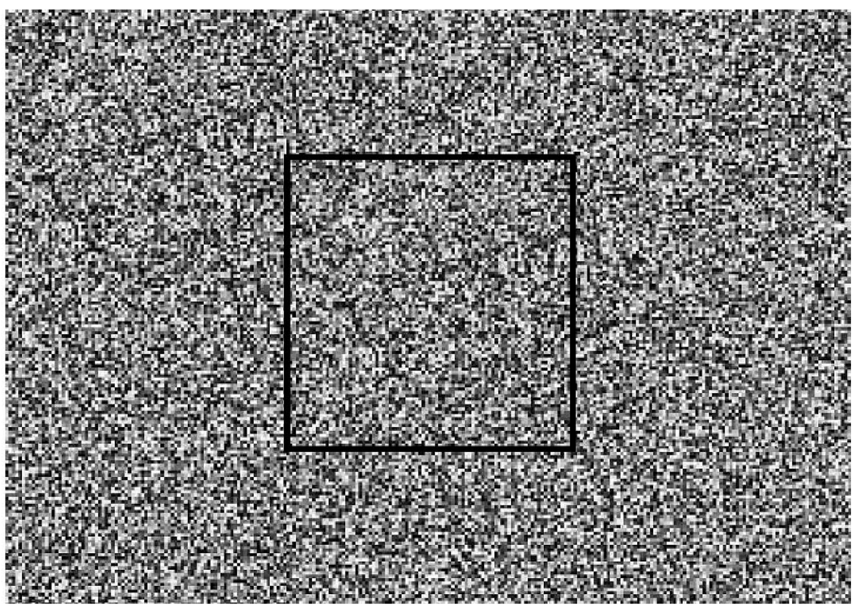
All the stimuli and procedures are similar to those of Experiment 1 except that the square window of random dots was constantly refreshed every 500 ms (42 frames ≈ 494.12 ms). Subjects were instructed to respond by judging which of the four axes (horizontal, vertical, and two diagonal axes) was most closely aligned to the perceived direction of IRM.

The experiment contained one trial that lasted for 450 s, during which time the subjects were required to answer which one of the four percepts they perceived by pressing one of the four buttons on a joystick. They were also asked not to press any button if they perceived just random dots statically refreshing (which was in fact what was occurring) or any other percept besides IRM along the four specified directions. Eye movements were monitored by using a head-mounted eyetracker (Eyelink2, SR research, Ontario, Canada; Tse, Sheinberg, & Logothetis, 2002), with a sampling rate of 250 Hz and a high spatial resolution (noise < 0.01°).

3.2. Results and discussion

Behavioral data are shown in Fig. 1B where the percentage of times during which subjects perceived different directions of IRM are plotted. During debriefing, subjects reported that during those times when they were not pressing any button, they almost always perceived flickering random dots in the absence of any global motion. This percept is marked as "no motion" in Fig. 1B. Also, none of our subjects ever mentioned that they had a problem judging the direction of perceived IRM. It seems that perceived IRM directions are strongly aligned with these four axes; ambiguous directions in-between these four axes were rarely observed. Some subjects (two authors who are experienced observers) reported occasionally perceiving other types of motion, such as rotation in either a clockwise or counterclockwise direction, or expansion and contraction between the fixation spot and the four corners of the square window.

Eye-tracking data show that only 18.50 ± (SE) 2.59% of the onsets of all the IRM percepts were immediately (within 1000 ms) preceded by a microsaccade, suggesting that microsaccades are not necessary for inducing IRM. In other words, IRM was not induced by microsaccades about 80% of the time, which is consistent with subjects' reports

A


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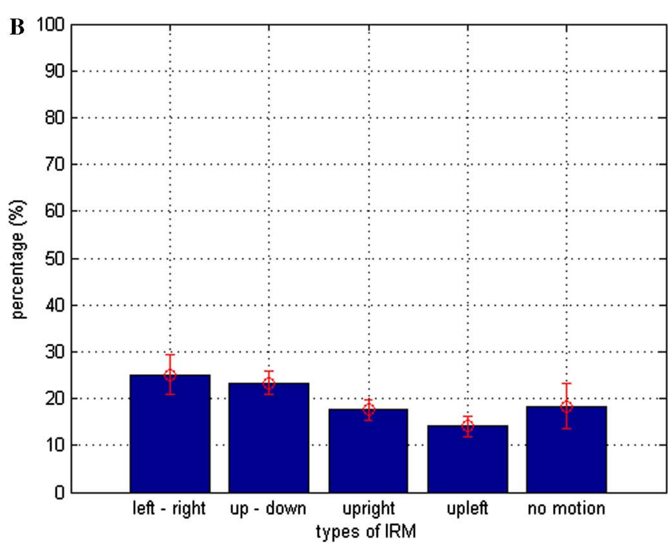

Fig. 1. Stimuli and percepts. (A) IRM over random dots. If the random dots within a square window refresh at a constant SOA on a background filled with fixed random dots, IRM can be perceived. (B) Percentage of time spent perceiving different directions of IRM. Directions were horizontal, vertical, or diagonal to the left or right. Error bars indicate standard error of the mean percentage of 10 subjects.

that the perceived directions of IRM could switch spontaneously. The directions of microsaccades during the four reported directions of IRM are plotted in Fig. 2A. The end position of each microsaccade was plotted as a dot on the *x*-*y* plane on which the zero point represents the fixation point that the subjects were fixating before making a microsaccade. Statistical analysis, described below, reveals that there is no difference between microsaccades that occur during these different perceptual states, implying that the directions and amplitudes of microsaccades are not correlated with IRM.

Since the direction and amplitude of each microsaccade could be decomposed into horizontal and vertical components, we first calculated the mean of the horizontal component (absolute value) of all microsaccades in each group, and then compared the four means from the four groups. Similar calculations were done for the vertical component. If the directions of microsaccades during IRM were correlated with the perceived direction of IRM, then, for example, we would expect those microsaccades that occurred during horizontal IRM to have a bigger mean of horizontal component than the other groups. Similarly, those microsaccades that occurred during vertical IRM should have a bigger mean vertical component than the other groups. The result shows that these means are not significantly different in either the horizontal component (ANOVA, $F(3,872) = 1.63$, $P = 0.18$) or the vertical component (ANOVA, $F(3,872) = 0.73$, $P = 0.53$), implying that the directions of microsaccades are not correlated with the perceived directions of IRM.

Although microsaccades are not necessary for inducing IRM and the directions of microsaccades during IRM are not correlated with the perceived direction of IRM, those microsaccades that occur immediately prior to the onset of IRM ($1.46 \pm 1.06\%$ of total microsaccades) might be sufficient to bias the perceived direction of upcoming IRM. For example, the microsaccades that occurred immediately prior to the reporting of a horizontal IRM percept might be more horizontal, and those that occurred immediately prior to the reporting of a vertical IRM percept might be more vertical (Fig. 2B). However, this trend does not reach significance when comparing among the horizontal components (ANOVA, $F(3,42) = 1.11$, $P = 0.36$) or vertical components (ANOVA, $F(3,42) = 0.44$, $P = 0.73$) of such microsaccades for the four groups. Thus, the directions of microsaccades that do occur immediately prior to the onset of IRM are not correlated with the perceived direction of upcoming IRM. We therefore cannot conclude that microsaccades are not sufficient to dictate a particular direction of perceived IRM.

It is also possible that the size of microsaccades might play some role in influencing the perceived direction of IRM. For example, those microsaccades that occurred immediately prior to an IRM percept might have bigger amplitudes and therefore might be able to generate relatively large image shifts in the retinal image that may in turn induce IRM. Our data imply that this is not the case. The mean amplitude of these microsaccades (mean = $29.79 \pm$ S.E. 5.09 visual millidegrees) is not significantly bigger than the mean of those that happened during IRM (mean = $27.34 \pm$ S.E. 0.79 visual millidegrees).Therefore it is unlikely that these microsaccades can induce IRM because they have bigger amplitudes.

Another interesting finding is that the rate of microsaccades decreases before the onset of IRM, and then increases (returns) to its normal baseline rate after IRM onset (Fig. 3A). Because our eyetracking data show that the directions of microsaccades and the directions of IRM are not correlated while IRM is perceived, this general increase of the baseline rate of microsaccades seems to happen regardless of the perceived direction of IRM. One possible explanation is that the decrease and then increase of microsaccade rate might be the result of subjects paying either more or less attention immediately before or immediately after the change in perceptual shifts in attention may alter the baseline microsaccade rate. Several authors have reported changes in the baseline rate of microsaccades after the onset of a peripheral cue that captures attention in humans (Engbert & Kliegl, 2003; Hafed & Clark, 2002; Rolfs, Engbert, & Kliegl, 2004; Tse et al., 2002, Tse, Sheinberg, & Logothetis, 2004) and monkeys (Horwitz & Albright, 2003). It is possible that when IRM is not perceived, subjects paid more or less attention to the stimuli and therefore made fewer microsaccades. This alternative explanation might also be able to account for the fact that the rate of eyeblinks increases slightly after a perceptual onset of IRM (Fig. 3B).

4. Experiment 3: Stimulus factors that affect the frequency of perceived IRM

Three possible factors that may affect the frequency of perceived IRM were tested: The shape of the global contour, the random-dot pattern, and motion-energy between randomly occurring peaks/troughs of luminance energy that happen to exist in the stimulus. One explanation of why people tend to see left-right, up-down, and diagonal IRM is that our visual system tends to interpret motion as moving along/between existing contours or salient features. For example, it is possible that left-right, up-down, and diagonal IRM are most probable because the contours of the square window are horizontal and vertical and because the four corners are salient features that lie on the two diagonals. If IRM involves a matching process between successive images, it would seem natural to match such features. A second explanation is that motion is interpreted to move along the orientation of the pattern of random dots inside the square window. A third explanation is that the direction of IRM is driven by motion-energy between randomly occurring peaks/troughs of luminance energy that happen to exist in the stimulus. Textures defined by random dots will inevitably form blobs of black/white/gray when a group of adjacent random dots happens to have similar luminance values. The first-order motion system would

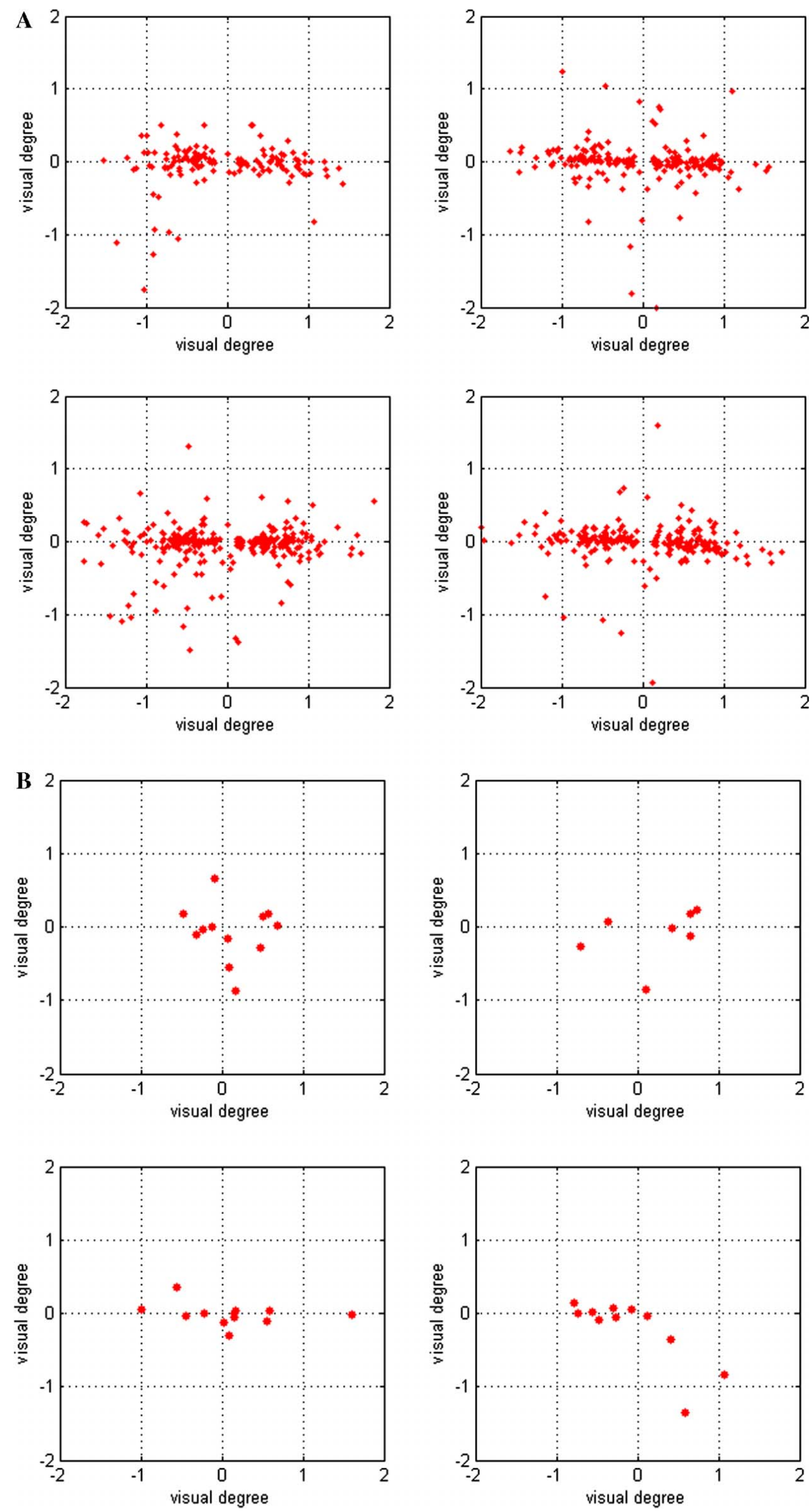

Fig. 2. The directions and amplitudes of microsaccades during four different states of perceived direction of IRM. (A) The directions and amplitudes (vertical and horizontal components in degrees of visual angle) of all microsaccades during four different IRM directions are plotted together for all subjects. The end position of each microsaccade was plotted as a dot on the x-y plane on which the zero point represents the fixation point that the subjects were fixating before making a microsaccade. For example, the lower-right subfigure shows the directions and amplitudes of all the microsaccades when IRM was perceived to be moving up and down, and the lower-left subfigure shows the directions and amplitudes of all the microsaccades when IRM was perceived to be moving left and right. Each dot indicates the horizontal amplitude (x-axis) and vertical amplitudes (y-axis) of each microsaccade. There is no significant difference between directions or amplitudes of microsaccade during the four different IRM states. (B) The directions and amplitudes of those microsaccades that occur immediately before perceptual onset of IRM appear to be slightly correlated with the upcoming perceived direction of IRM, but this effect does not reach significance. (See text for statistics detail) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

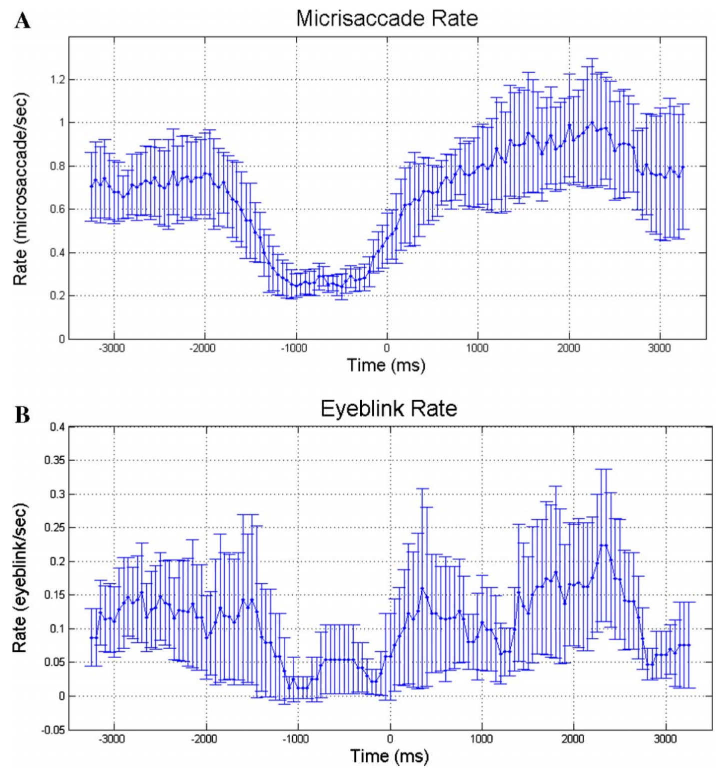

Fig. 3. Rate of microsaccades and eyeblinks. (A) The rate of microsaccades decreases before perceptual transitions, and rises after perceptual transitions. (B) Similar results were observed for the rate of eyeblinks. (B) The rate of eyeblinks increases steadily after perceptual switches. This is also true for the rate of microsaccades. The y-axis unit represents the number of microsaccade per sec (microsaccades/sec). Each data point is plotted by calculating the number of total microsaccades within a 500 ms window around the data point, and then divided by 0.5 s. Therefore, approximately 0.2 (microsaccades/sec) for one second preceding the interval in which IRM is perceived would mean that there was an average of 0.2 microsaccades every 1 s. Note that the measured microsaccade rate in our experiment (about 0.7 microsaccades/sec). Error bars indicate standard error of the mean rate of six subjects.

detect changes in the distribution of luminance as motion-energy. If motion-energy happens to lie predominantly in one direction upon a random dot refresh just by chance, this could bias IRM to be perceived in the corresponding direction.

To determine the role of these three possible factors, we removed different factors in different conditions to see if the amount of time that IRM is perceived changes. In condition A, we removed the contour factors by using a round window (Fig. 4A′). In condition B, we removed the obvious directional alignment of the pattern of the random dots by using smaller random dots (Fig. 4B′). In condition C, luminance blobs formed by randomly occurring clumps of random dots of similar luminance value were removed by using checkerboards comprised of small black and white squares (Fig. 4C′), which eliminated the confound introduced by spurious motion-energy signals. In condition D, both salient features (straight edges and corners) along the contour and within the pattern of the random dots were removed by using a round window and smaller random dots (Fig. 4D′). In condition E, both salient features (edges and corners) along the contour and the luminance blobs formed by grouped random dots were removed by using a round window and checkerboards defined by interleaved small black and white squares (Fig. 4E′). Our hypothesis is that if matches take place between successive salient features, whether defined by the global pattern of the contour, orientation energy present in the pattern of random dots, or motion-energy also present in the succession of random dot displays, these matches can bias the perceived direction of IRM to be horizontal, vertical, or diagonal. Therefore, removing these factors should reduce the amount of time IRM is perceived in those (or any) directions.

4.1. Method

4.1.1. Observers

Ten subjects with normal or corrected-to-normal vision carried out the experiment. All of them had participated in Experiments 1 and 2.

4.1.2. Stimulus displays and procedures

The control condition in this experiment is exactly the same as Experiment 2 except that each trial lasted for 120 s instead of 450 s. All the stimuli and procedures in the testing conditions are similar to the control condition except for the following. In condition A, the square window was replaced by a round window (3° visual degrees in radius). In condition B, the previous pattern of the random dots was replaced by smaller random dots. On average, there were 62×62 small squares with random brightness between

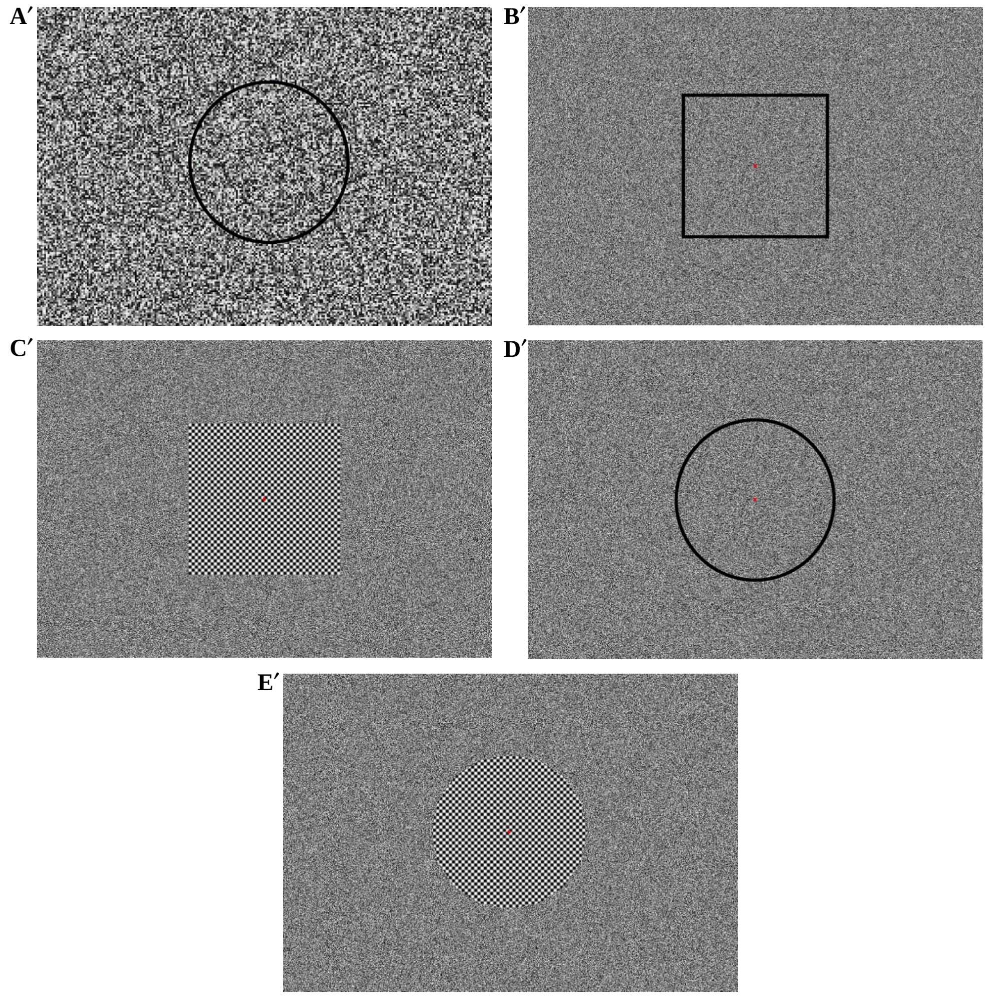

Fig. 4. Stimuli of Experiment 5. (A′) In condition A, the contour of the window was round. (B′) In condition B, the pattern of the random dots was removed by using smaller random dots. (C′) In condition C, blobs formed by grouped random dots were replaced by checkerboards. (D′) In condition D, both salient contour features and the pattern of the random dots was removed by using a round window and smaller random dots. (E′) In condition E, both salient contour features and the blobs formed by grouped random dots were removed by using a round window and checkerboards. Note that in conditions C, D, and E, the background (outside the square/round window) was also replaced by smaller random dots to match the texture size inside the square/round window. For interpretation of real texture sizes in figures, the reader is referred to Section 4.1.

white and black over $1° \times 1°$ visual degree. In condition C, possible luminance blobs within the square window ($6° \times 6°$ visual degree) formed by grouped random dots were removed by displaying checkerboards (31×31 alternating black and white small squares/$1° \times 1°$ visual degree). Upon stimulus reset, black squares were replaced with white squares and vice versa. The first-order motion system should not respond to this stimulus in a direction-biased manner, because the luminance profile was identical before and after each refresh. In condition D, both contours and the pattern of random dots were removed by using a round window and smaller random dots. In condition E, both contours and the luminance blobs formed by grouped random dots were removed by using a round window and checkerboards composed of interleaved black and white squares on a black background. The order of different conditions was randomized, and all subjects participated one trial for each condition. Note that in conditions C, D, and E, the background (outside the square/round window) was also replaced by smaller random dots to match the texture size inside the square/round window. The comparisons between these conditions are shown in Table 1.

4.2. Results and discussion

The data in Fig. 5 show that, in every tested condition, the percentage of times during which subjects did not perceive IRM (marked as "no motion" on the x-axis) increased significantly with respect to the control condition (i.e., A > control, B > control, C > control, D > control, and E > control). Those conditions that are significantly different than the control condition are marked as '*' for a two-tailed paired t test ($P < 0.05$). In other words, in every condition, the percentage of time subjects perceived IRM drops significantly. These results suggest that all three stimulus factors (namely, the global contours of the stimulus, the orientation energy in its texture, and motion-energy) can and do contribute to the frequency of perceived direction of IRM.

Table 1
Comparisons between different experimental conditions in Experiment 3

	Window contour		Window texture			Background texture	
	Square contour	Round contour	Large random	Small random	Checker board	Large random	Small random
Control	x		x			x	
A		x	x			x	
B	x			x			x
C	x				x		x
D		x		x			x
E		x			x		x

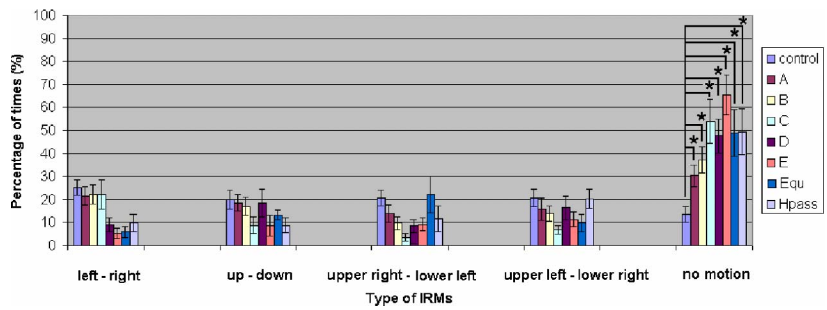

Fig. 5. Percentage of time different directions of IRM were perceived for different conditions. The percentage of time during which the subject did not perceive horizontal, vertical, or diagonal IRM increased significantly in every condition. Those conditions that are significantly different to each other are marked as '∗' for a two-tailed paired t test ($P < 0.05$). (See Section 4.1 for description of different conditions.)

5. Experiment 4: Controlling for first-order artifacts

One might argue that, based on Table 1, the only legitimate comparisons are (1) the comparison of A with the control, which would determine the effect of contour shape, and (2) the comparison of B with the control, which would determine the effect of texture size. Beyond that, comparisons entail multiple variables. Moreover, it is possible that the reason why IRM is still perceivable in conditions C (50%) and E (35%) is because that there are still first-order motion artifacts (i.e., luminance-defined motion-energy) in the checkerboard stimuli. For example, artifactual first-order information might be created due to local nonlinear integration of luminance across the black and white components of the checkerboard (Smith & Ledgeway, 1997). To rule out this possibility and make sure that IRM can be perceived in the absence of first-order information, two more conditions were tested in this experiment. In condition "Hpass," the stimuli were identical to those used in condition C except that the checkerboard was high-pass filtered, which has been shown to be a way that can successfully eliminate local first-order artifacts (Smith & Ledgeway, 1997). In condition "Equ," we replaced the checkerboard with a uniform color (alternating between equiluminant red and green) on a gray background. Since there was no texture (checkerboard) in the uniform red and green colors, there would therefore be no artifactual first-order information such as that might have been present in the checkerboard due to local integration of luminance across the black and white components. If there really existed first-order artifacts in the stimuli of condition C that were the cause of IRM, we would expect the frequency of perceived IRM to drop in the two conditions that used equiluminant stimuli. In contrast, if the IRM perceived in condition C had nothing to do with potential motion-energy artifacts, the frequency of perceived IRM should remain unchanged in these two conditions.

5.1. Method

5.1.1. Observers

Four subjects (two authors) carried out condition "Equ," and three subjects (one author) carried out condition "Hpass" in the experiment. All of them had participated in Experiments 1, 2, and 3.

5.1.2. Stimulus displays and procedures

All stimuli and procedures were the same as those used in condition C of Experiment 3 except for the following. In condition "Equ," we replaced the checkerboard with a uniform color (alternating between red and green) on a gray background. In this condition, the luminance of the red, green, and gray was adjusted to become subjectively equal for each subject using the minimal flicker technique (Anstis & Cavanagh, 1983). In condition "Hpass," the checkerboard was high-pass filtered (filter radius = 0.5 pixel). The order in which conditions were tested was randomized.

5.2. Results and discussion

The results are shown in Fig. 5 (conditions "Hpass" and "Equ"). When compared to the control condition, the percentage of times that subjects did not perceive IRM in one of the four specified directions increased significantly in both conditions (two-tailed paired t test, $P < 0.05$). However, when compared to condition C of Experiment 3, there were no significant changes (two-tailed paired t test, $P > 0.83$). Therefore, these results imply that there was no artifactual first-order information in condition C. We conclude that (1) the perceived IRM in condition C of Experiment 3 is not due to motion-energy artifacts, and (2) IRM can be perceived in the absence of first-order information.

6. General discussion

In Experiment 1, we showed that subjects can perceive IRM over dynamic squares or disks defined by random dot or checkerboard textures. The results reveal that there are minimum and maximum stimulus durations necessary to create the percept of IRM in the absence of net motion-energy, which is consistent with our previous finding (Hsieh et al., 2005) that there is a minimum SOA necessary to create the percept of first-order IRM. Experiment 1 also provides evidence against the possibility that IRM is triggered by an attentional gradient. It has been hypothesized that attention might follow the trajectory of IRM and linger around the end of the IRM to create an attentional gradient, which could then trigger the next onset of IRM. We have previously provided experimental evidence against this hypothesis (Hsieh et al., 2005). This conclusion is further confirmed here by the fact that the maximum stimulus duration is as long as 1600 ms, which is much longer than the time that at least exogenously cued (or 'transient') attention would be expected to linger around a cued area (Carrasco & Yeshurun, 1998; Hsieh et al., 2005, Experiments 3 and 4; Posner, 1980; Yeshurun & Carrasco, 1999).

The data in Experiment 2 show that the perception of ambiguous flashing stimuli is multi-stable. One explanation of this phenomenon is that the visual system tries to explain ambiguous stimuli using some heuristic (Anstis & Ramachandran, 1987; Hsieh et al., 2005). For example, we (Hsieh et al., 2005) hypothesized that the percept of IRM traversing a flashing bar is governed by a new heuristic principle according to which motion is perceived to move away from the location where it last ceased, in the absence of stimulus information suggesting otherwise. This heuristic hypothesis suggests that the visual system tends to interpret objects as moving from where they last stopped moving, and in a direction most consistent with that previous motion. This heuristic also applies here. When a stimulus is symmetrical, such as a flashing square composed of random dots, there might be several interpretations that are equally good because the long axis existing on a bar that could be interpreted as a trajectory no longer exists in the case of a square. Therefore, IRM can be perceived in any one of several possible directions.

In Experiment 3, we examined several possible factors that affect the IRM percept. Our data suggest that the visual system tends to interpret a flashing stimulus as something that is moving in a direction biased by several stimulus factors, such the contours of the stimulus, the orientation energy present in its texture, and motion-energy that may arise in the stimulus.

Another interesting question worth studying in the future concerns whether IRM results from (bottom-up) motion detector activation, or top-down feedback or both. It seems that IRM can be affected by top-down control because observers reported that they could switch the axis of the rebound motion at will (Experiment 2). On the other hand, although subjects could volitionally switch the axis of perceived illusory motion, these percepts always rebounded from one end to the other. Subjects could never see successive "one-way" motions (i.e., no rebounding but always shooting in the same direction) even if they tried. Therefore, it seems that there are constraints on what volition can accomplish. Other constraints, presumably bottom-up, make IRM cognitively impenetrable to some degree.

Attention does not seem to be the main cause of (but could still affect) IRM, and the cause of IRM might be something entirely different and non-attentional in nature. In a recent experiment reported in the first paper on IRM (Hsieh et al., 2005, Experiments 3 and 4) we directly measured whether attention is drawn to the endpoint of motion by measuring reaction time. If attention lingers at the location where IRM is last seen to move, we would expect speeded reaction times at this location (Carrasco & Yeshurun, 1998; Posner, 1980; Yeshurun & Carrasco, 1999). We found that RTs were faster at this location, but only for a very brief time after the cessation of motion. In contrast, as Experiment 1 makes clear, IRM can be perceived 1600 ms after its previous IRM. We also found that there is no change in perceived contrast at the endpoint of IRM, as would be expected if IRM were an attentional effect, since attention is known to increase perceived contrast (Carrasco, Ling, & Read, 2004). These results suggest that IRM is not an attentional effect. It may be a representation that exists within the motion-processing system itself. Only future experimentation will be able to discern the nature of the representations and the neuronal mechanisms that cause IRM.

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