國立臺灣大學理學院心理學研究所

碩士論文

Graduate Institute of Psychology
College of Science
National Taiwan University

Master Thesis

走走停停錯覺：
注意力與運動訊息對運動知覺之影響

Stop-and-go illusions:
The effects of attention and motion signals on motion perception

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中華民國 98 年 6 月

June, 2009

摘要

Anstis （2001） 發現在「腳步錯覺」(footsteps illusion）中，移動中物體的對比（contrast）會影響對物體的速度知覺。物體的移動在對比低的情況下速度會減慢，並且在完全沒有任何對比差異時完全停下來。過去以對比和運動偵測相關的低階機轉解釋錯覺的產生，並且將完全停下來的原因訴諸低對比下運動訊號的缺乏。然而另一個相似的「走走停停」錯覺—扇子錯覺（fan illusion）卻受注意力操弄的影響（Yeh、Chiu、及 Hsiao，2007)。我們透過實驗一與二連結兩種錯覺，發現不論是否有運動訊息，扇子與腳步錯覺都受對比的影響，不過受影響的方式卻與過去的解釋（Howe et al.，2006）不符。由於物體遮蔽時的追蹤需要注意力資源(attentive tracking)，實驗三證實注意力為基的視覺追蹤確實影響「走走停停」的錯覺現象。因此，我們透過本研究連結兩項解釋上完全不同的錯覺現象，提出兩者背後具有共同的運作機轉，並認為對物體的運動知覺是由運動訊號與物體追蹤機轉決定，前者受物體對比影響，而後者仰賴注意力維持。

關鍵詞：對比、運動知覺、腳步錯覺、扇子錯覺、注意力、遮蔽、知覺速度。

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Abstract

In the footsteps illusion (Anstis, 2001), motion speeds up at high contrasts and slows down at low contrasts, coming to a complete halt at equiluminance. Such speed change has been attributed to low-level contrast-dependent mechanisms, with motion signals completely absent at equiluminance. However, a seemingly similar illusion that also shows the "stopping" illusion, the fan illusion, has been shown to be affected by attention (Yeh, Chiu, & Hsiao, 2007). To link the footsteps illusions with the fan illusion, we demonstrated that in the presence and absence of motion signals, both the footsteps and fan illusions are similarly affected by contrast (Experiment 1and 2), but in ways that are inconsistent with previous explanations (Howe, Thompson, Anstis, Sagreiya, & Livingstone, 2006). In Experiment 3, we further showed that manipulation of attentive tracking influenced illusion strength. We conclude that both contrast-dependent motion perception and attentive tracking determine perceived speed in the two illusions.

Keywords: contrast, motion, tracking, footsteps illusion, fan illusion, attention, occlusion, perceived speed.

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Introduction

Anstis (2001) discovered a "footsteps illusion," in which a bar moving steadily across a field of black-and-white background stripes is perceived to momentarily speed up at high contrast, slow down at low contrast, and stop at equiluminance, with the effect being strongest in an observer's peripheral vision. Thus, aligned black and white bars appear to stop and go in alternation on the background stripes, creating an illusion of walking footsteps (see Figure 1a or browse http://epa.psy.ntu.edu.tw/EPA/demo/Chiu-Yeh-09 for all demonstrations and figures in this study).

Explanations of the footsteps illusion involve low-level, pre-attentive mechanisms because it has been well established that perceived speed appears to slow down at low contrasts (Thompson, 1982; Stone & Thompson, 1992; Blakemore & Snowden, 1999, 2000). The contrast-ratio theory explains the perceived speed differences of the bar in the footsteps illusion by changes in contrast at its leading and trailing edges (Anstis, 2001). Following Thompson's (1982) model, Anstis (2004) proposes multiple contrast-sensitive speed-tuned units as a possible neuro-mechanism. Furthermore, Howe, Thompson, Anstis, Sagreiya, and Livingstone (2006) showed that perceived speed of the bar is also determined by the contrast-modulated motion signals of the top and bottom edges of the bar and the edges of the background stripes.

Because these theories assume that motion signals determine motion perception, when the bars appear to halt during equiluminance, it is suggested that this is due to the lack of motion signals required for motion perception (Anstis, 2001).

In real life, motion signals often transiently disappear out of sight during blinks, eye-saccades, object occlusions, or changes in the lighting of one's environment. Nevertheless, they do not consequently "go out of existence." Occluded objects can be amodally integrated (Flombaum, Scholl, & Santos, 2009; Yantis, 1995) and perceived as persisting through time. For example, the distance of occluded dots moving at a constant rate can be accurately extrapolated (Ehrenstein, 2003) and pre-occlusion trajectory paths are incorporated into both one's predictions of an occluded-object's location and one's eye-tracking paths (Mrotek & Soechting, 2007). In addition, neurophysiological (Olson, Gatenby, Leung, Skudlarski, & Gore, 2004; Shuwairi, Curtis, & Johnson, 2007) and behavioral (Hespos, Gredeback, von Hofsten, & Spelke, in press) evidences support that both infants and adults can "keep briefly occluded objects in mind," which has been shown to be a mental computation that is both ontologically and phylogenetically primitive (Cheries, Mitroff, Wynn, & Scholl, 2009). When the conditions for amodal integration are disrupted, objects viewed prior to and after an occlusion are interpreted as two distinct objects instead of one (Flombaum et al., 2009).

The perception of occlusion events requires representations of depth between the occluding and occluded objects (Yantis, 1995) and also the representation of object spatiotemporal continuity during occlusion. Displays in multiple object tracking (MOT) paradigms (Pylyshyn & Storm, 1988), similar to those in the footsteps illusion, are 2-D in nature. Therefore, an observer must first represent the depth relations between the occluding and occluded objects for objects to be tracked behind occluders. It has been shown that both binocular disparity and presence of T-junctions can improve MOT (Viswanathan & Mingolla, 1998).

Even if depth information is present, local spatiotemporal information is still required for the disappearing and appearing object to be interpreted as moving *smoothly* during occlusion. When objects gradually decrease and subsequently increase in size along a fixed contour, they provide the deletion and accretion cues necessary to indicate the occurrence of an occlusion event. Deletion cues allow the perceptual system to infer the presence of objects behind a surface instead of representing them as going out of existence (Scholl & Feigenson, 2004) and accretion cues enable object onsets to be interpreted as the disocclusion of pre-existing objects instead of an abrupt appearance of something new (Holcombe, 2003). The presence of deletion or accretion cues has been shown to be necessary for tracking (Bower, 1974) while the lack of such cues has been shown to impair MOT (Scholl & Pylyshyn, 1999).

In the footsteps illusion, when the moving bar and the stationary stripes are equiluminant, the surfaces are not segregated. Therefore, instead of perceiving the connection and subsequent disconnection of a moving surface to a stationary surface as a moving object disappearing and subsequently reappearing behind a stationary object, an observer might interpret it as two surfaces that merge into one. Furthermore, merged surfaces make it difficult for an observer to discern the fixed contours that are required for deletion and accretion cues (Scholl & Pylyshyn, 1999). Because the bar spans the width of two stripes, it provides an observer with the perception that it is either moving or stopping rather than gradually decreasing and increasing in size due to its moving behind the occluder. This might make it more difficult for an observer to track the movement. Taking the above concerns into account, an alternative explanation of the complete halt during equiluminance in the footsteps illusion is that the impairment of tracking is due to the lack of surface segregation and deletion/accretion cues.

Attentional resources are also required for the maintenance of an object's representations behind occluders. During MOT, occluded objects appear to acquire more attentional resources than visible targets and distracters, because the probes on the surfaces of any occluders that occlude either the targets or the distracters are detected quicker (Flombaum, Scholl, & Pylyshyn, 2008). Hespos et al. (in press) discovered that predictive reaching of invisible objects is more difficult when the invisible objects are occluded rather than hidden by darkness. They suggest that while objects in darkness merely lack visibility, occluded objects compete with their occluders for attention, which results in a deterioration of performance. These findings suggest that an observer's attentional resources might be a primary requirement for maintaining object persistence during occlusion.

In fact, attention has been shown to be involved in a similar illusion called the "fan illusion," first reported by Petter in 1956 (Kanizsa, 1979). When a fan that rotates at a constant speed is superimposed over a stationary fan, the rotating fan appears to "pause-and-go" for a split second as the two fans overlap and separate (Figure 1b). The fan illusion is stronger at slower speeds (longer occlusion duration), with the addition of more leaves (higher perceptual load), and during the presence of visual and auditory distracters (Yeh, Chiu, & Hsiao, 2007).

These attention effects in the fan illusion suggest that attentive tracking might be involved in the illusion. Consistent with the findings of Yeh et al. (2007), tracking involves a limited attentional resource pool in which the upper speed limit for successful MOT linearly decreases with the number of targets (Alvarez & Franconeri, 2007). Furthermore, tracking performance deteriorates with longer occluding durations as effortful attention deteriorates with time (Oksama & Hyona, 2004).

There are many similarities between the footsteps illusion and the fan illusion at both the phenomenal and stimuli levels. Phenomenally, the moving bars and fan leaves appear to stop whenever their moving edges overlap with the stationary stripes or a motionless fan. On the stimuli level, both illusions lack surface segregation between the equiluminant moving and the stationary stimuli. It is entirely possible that the two illusions share common mechanisms.

If the fan illusion shares common mechanisms with the footsteps illusion, then during the presence of motion signals, contrast manipulation should affect the strength of the fan illusion just like that in the footsteps illusion. Furthermore, if impairment of attentive tracking causes both illusions, motion perception should be smoother after the addition of surface segregation and deletion or accretion cues that facilitate tracking; on the contrary, motion perception begins to decrease after the escalation of attention interference by means of longer occlusion durations and the addition of visual distracters.

Experiment 1: Effect of contrast

In the footsteps illusion, as the moving bar "stops" whenever its two moving edges overlap with the stationary stripes, the footsteps illusion is a kind of '"static capture" in which the stationary stripes dominate motion of the bar. Anstis (2001) found that the perceived speed of the moving bar is determined by changes in contrast at its leading and trailing edges, with a mid-grey bar (luminance half of black and white) producing the weakest illusions.

On the other hand, Howe et al. (2006) devised a "motion-capture" variation of the footsteps illusion in which a stationary bar appears to move in the direction of moving stripes. When the front and back edges of the black stationary bar overlap black moving stripes, the motion signals from the stripes dominate and "capture" the motion of the bar. According to Howe et al. (2006), this variation also has consistent effects with changes in contrast. If the fan illusion and footsteps illusion share common mechanisms, then a motion capture variation analogous to the motion capture versions of the footsteps illusion could be created by rotating the originally stationary fan and stopping the originally rotating fan.

In the footsteps illusion, the leading and trailing edges of the moving bar simultaneously transverse stripes of the same color. We thus devised an analogous fan display in which one of the original 4-leaf fans was substituted by *radial stripes*, namely, a 16-leaf fan. Thus, the rotating leaves of the moving 4-leaf fan in this experiment spun two black stripes (Figure 2b), similar to the way the bars straddled two stripes in the footsteps illusion (Figure 2a) (named “straddled” hereafter).

We predicted that by manipulating the luminance of a fan/bar, illusion strength would vary with contrast in both the fan and footsteps illusions. Low-contrast fans/bars would produce stronger illusions than mid-contrast fans/bars in both static capture (Experiment 1A) and motion capture (Experiment 1B) variations.

Stimuli

All displays were projected onto white projector screens. The stimuli were constructed by Macromedia Flash 8 and ran as .swf flash files on Windows XP IBM-compatible computers.

In Experiment 1A, for the footsteps illusion, the moving bar (12% screen width x 8% screen height) moved at a constant speed of 13% screen width/sec. from left to right across background stripes. The background stripes consisted of four and a half cycles with each stripe extended 6% screen width x 36% screen height, spaced 6% screen width between, aligned to the upper right corner of the screen. Participants were asked to fixate at a red cross (8% screen width x 10% screen height) aligned to the lower left corner of the screen.

In the fan illusion, the display consisted of two overlapping fans (radius 57% screen width) centered on the screen. In the static capture variation, a 4-leaf fan rotated at a constant speed (0.55 arc/sec, rotating clockwise) above radial stripes (i.e., the 16-leaf fan). The width of each leaf was 20 arc degrees for the 4-leaf fan (spaced 90 arc degrees) while those of the 16-leaf fan were 10 arc degrees (spaced 12.5 arc degrees).

In Experiment 1B, the configurations of the two fans in the motion capture variation of the fan illusion are the same as those in Experiment 1A, but reversed in motion, with the 16-leaf fan rotating beneath the 4-leaf fan.

Contrast was manipulated by changing the grey-scale shade of the bar/ 4-leaf fan from Middle Contrast (light grey, RGB 192) to Low Contrast (dark grey, RGB 64). In a dimly-lit lab chamber, the light grey bar's luminance (49.57 cd/m^2) was near the mid-point of the black (0.21 cd/m^2) and white (92.38 cd/m^2) stripes. Therefore, the leading or trailing edges of the light grey bar had similar contrast values on both black (Weber contrast = -0.996; L_{black}-L_{grey}/L_{grey}, Anstis (2001)) and white (Weber contrast = 0.863) stripes. On the other hand, the dark grey bar's luminance (5.50 cd/m^2) was closer to those of the black bar. Therefore, the leading or trailing edges of the dark grey bar had lower contrast values on black (Weber contrast = -0.961) than on white (Weber contrast = 15.796) stripes.

Participants

A class with 39 high school students from the Affiliated Senior High School of National Taiwan Normal University (ages 15-16) participated in Experiment 1A and Experiment 1B on separate days in return for small gifts.

Procedure

Before the experiment, we confirmed that all participants could perceive the standard static and motion capture illusions from the demonstrations. A footsteps display (Figure 2a) and two black straddled fan displays (one static capture variation, the other motion capture variation) (Figure 2b) were defined as having the strongest illusion strengths.

The displays were presented to the whole class, with each student viewing the stimuli from different directions and distances. Illusions in Experiment 1A and 2B were together randomly blocked by illusion type with each individual condition randomly mixed within the blocks. Participants were asked to rate the illusion strength of each display on a 7-point Liker's scale ("7" defined by the demonstrations as having the strongest illusion effects) by circling the chosen number on a paper form. The experimenter manually advanced to the next display after confirming that all participants have answered.

Results and discussions

In Experiment 1A, four participants did not complete the rating form and were thus excluded from further analysis. The static capture variation was consistently stronger for the Low Contrast moving bar/fan of the footsteps illusion ($F(1,34) = 112.12$, $MSE = 2.19$, $p < .0001$) (Figure 3a) and the fan illusion ($F(1,34) = 27.83$, $MSE = 2.10$, $p < .0001$) (Figure 3b), compared to the weaker illusions (smoother motion perception) at Middle Contrast for both illusions.

In Experiment 1B, six participants did not complete the rating forms and were excluded from the results. Consistent with Experiment 1A, the Low Contrast stationary 4-leaf fan's motion was more "captured" by the moving stripes than those of the Middle Contrast fans ($F(1,32) = 28.15$, $MSE = 60.14$, $p < .0000$) (Figure 3c).

This result showed that contrast affects motion perception the same way in the fan illusion as in the footsteps illusion. As the stimuli were perceived by the students from varying viewing conditions, the luminance of the grey bars differed for each participant. Thus the results represented averaged luminance values.

Experiment 2: Effects of Surface Segregation and Deletion/Accretion Cues

In this experiment, surface segregation and deletion/accretion cues were added to examine whether the "stopping" static capture illusion at equiluminance was, in addition to the lack of motion signals, also caused by the lack of such conditions for amodal integration,. As perception of occlusion events rely both on the representation of depth and spatiotemporal continuity, we predicted that segregating occluding and occluded object surfaces and adding deletion/accretion cues would aid attentive tracking and enable smoother motion perception in the absence of motion signals.

In the footsteps and fan illusions, there are no motion signals when the leading or trailing edges overlap with equilumimant stationary stripes. To keep this lack of motion signals constant even after changing the segregating the surfaces of the moving bar/fan and stationary stripes, the depth orders of the stripes and bar/fan were reversed in this experiment. In the footsteps illusion, the black bar now moved beneath the black stripes (Figure 2c) whereas in the fan illusion, the moving fan rotated under the stationary fan (Figure 2d). This way, the surfaces of the occluding stripes and the moving bar/fan could be differentiated while the motion signals of the bar/fan were kept invisible via occlusion.

We then examined the effects of contrast-induced surface segregation and deletion/accretion cues on the two illusions. In the original fan illusion (Figure 1b), the rotating fan-leaves are smaller than the larger stationary fan-leaves and could thus gradually disappear, go out of sight, and then slowly re-emerge from behind the stationary leaves. However, in the footsteps illusion (Figure 1a), the straddled moving bars would never gradually disappear or reappear (Figure 4a). Therefore, only when the moving fan/bar is smaller than the stripe widths would there be deletion/accretion cues for the perception of gradual disappearance and re-appearance (Figure 4b) in both illusions (hereafter called “un-straddled” versions).

For fair comparison, we compared the effects of contrast-induced surface segregation between straddled (Figure 2c, 2d) and un-straddled (Figure 2g, 2h) versions of the footsteps and fan illusions. We predicted that as the un-straddled moving bar/fan disappear and reappear in ways indicating a single persisting object (Figure 4b), both contrast-induced surface segregation and deletion/accretion cues would contribute to perception of an occlusion event. However, the moving bar/fan in the straddled versions do not have deletion and accretion cues even with contrast-induced segregated surfaces (Figure 4a), and thus illusion strength would still be strong regardless of surface segregation.

In addition to rating, the un-straddled fan illusion was also tested with a 2-forced choice (2-AFC) staircase procedure. Because ratings are possibly subject to shifts in judgment criteria, we adopted the 2-AFC staircase procedure developed by Yeh et al. (2007) to ensure the reliability of the rating results. The procedure was used to measure how the "stopping" fan illusion strength changes under different conditions. Yeh et al. (2007) discovered that stronger illusions require faster rotating speeds for the fans to be perceived as rotating smoothly. Therefore, the speed under which the presence of the "stopping" illusion is perceived in half of the trials (point of subjective equivalence, PSE) can be measured and compared: the higher the PSE, the stronger the illusion.

Stimuli

After reversing the depth orders of the moving fan/bar and stationary stripes, Experiment 2A compared the straddled and un-straddled versions of the reversed footsteps illusion (Figure 2c, 2g) while Experiment 2B compared those of the reversed fan illusion (Figure 2d, 2h).

The straddled configurations of both the footsteps and fan illusions were the same as Experiment 1, except reversed in depth. In the footsteps illusion, to control possible attention capture of sudden motion onsets in the footsteps settings of Experiment 1, the stripes in Experiment 2 now spanned the whole width of the screen and participants were asked to fixate the same red cross aligned to the bottom center of the screen.

In the un-straddled displays of the footsteps illusion, the moving bars were shrunk to 1/10 (0.6% screen width) of the original width. In the fan illusion, two 4-leaf fans, with the rotating fan-leaves (10 arc degrees width) half the size of the stationary ones (20 arc degrees width), were used for the un-straddled displays.

The 2-AFC staircase experiments were conducted in a dimly-lit laboratory chamber. Stimuli were controlled by a personal computer and presented on a color cathode-ray tube (CRT) monitor (ViewSonic G90f+ color monitor, 18” viewable diagonal, 70 Hz). The staircase procedures were programmed using C++ and OpenGL. Participants sat at a 57 cm viewing distance from the screen, with a chin rest stabilizing their heads. The height of the chin rest was adjusted to a comfortable position for each participant.

The same grey-scale shades in Experiment 1 were used. In the rating procedure, the moving bars/fans were always black, and the occluding stripes were Middle Contrast, Low Contrast or Equiluminant (black) for the footsteps illusion and Middle and Low Contrast for the fan illusion, providing different degrees of contrast-induced surface segregation. In the staircase procedure, the luminance of the stationary occluders in the staircase procedures were white (thus “Invisible”) (92.38 cd/m^2), Middle Contrast (49.57 cd/m^2), Low Contrast (5.50 cd/m^2), and Equiluminant (0.21 cd/m^2), and all moving fans/bars were Black (0.21 cd/m^2).

Participants

In Experiment 2A, the participants were the same as Experiment 1. In Experiment 2B, another class of 35 high school students from the same school participated in the rating procedure. Twenty-four college students and non-student observers (estimated ages 18-55) participated in the 2-AFC staircase procedures in return for a small fee or course credit.

Procedure

The rating procedures were the same as in Experiment 1. For the 2-AFC staircase procedure, the initial speed of the staircase procedure was set at 139.86 deg/sec and changes made with 41.96 deg/sec steps. After four reversing points, the speed was set at the average of the last two reversing points and 13.99 deg/sec steps. Upon obtaining six reversing points, the PSE was averaged from the last four reversing points. Four data points were obtained and averaged for each condition. All conditions within each experiment were blocked and Latin-Square counterbalanced.

After demonstrating a black "smooth" fan (a single-leaf rotating fan, with the single leaf 3/4 arc degree width of a stationary leaf) and a black "stopping" fan

(Figure 1b, the standard fan illusion, with the rotating leaves 1/2 arc degree width of stationary leaves) with the same rotation speed, participants were instructed to choose either "smooth" (by pressing the "z" key) or "stopping" (by pressing the "/" key) while fixating the center of each fan display. They were instructed to answer only after the fan rotated more than 90 degrees. After obtaining each data point, they were asked to take a self-paced rest and requested to take a 2-minute rest before the next condition began.

Results and discussions

In Experiment 2A, two participants did not complete the footsteps illusion forms and were thus excluded from further analysis. The un-straddled versions were significantly weaker than the straddled versions ($F(1,36) = 88.83$, $MSE = 355.68$, $p < .0000$), consistent with Howe et al.'s (2006) results that smaller bars had weaker illusions than larger bars. Overall, there were no main effects of stationary : moving bar contrast ($F(1,36) = 2.82$, $MSE = 4.60$, $p = .0663$), but as predicted, contrast interacted with the straddled/un-straddled configurations ($F(2, 72) = 3.97$, $MSE = 6.68$, $p < .05$). Only the un-straddled configurations had stronger "stopping" illusions with decrease of contrast ($F(2, 144) = 6.57$, $MSE = 10.89$, $p < .005$) while the straddled illusions remained the same regardless of contrast ($F(2,144) = 0.23$, $MSE = 0.39$, $p = 0.792$). For the un-straddled versions, the increase of illusion strength linearly correlated with decrease in contrast ($F(1, 144) = 11.16$, $MSE = 18.50$, $p < .051$) (Figure 5a).

In Experiment 2B, although the rating data showed no differences between illusion strengths of the straddled and un-straddled versions in the fan illusion ($F(1,34) = 0.05$, $MSE = 0.11$, $p = .8262$), there was interaction between contrast and straddled/un-straddled configurations ($F(1,34) = 7.28$, $MSE = 7.31$, $p < .05$). The main effect of contrast ($F(1,34) = 9.11$, $MSE = 15.11$, $p < .005$) originated from the significant decrease of illusion strength in the un-straddled versions with change in contrast ($F(1,66) = 16.31$, $MSE = 21.73$, $p = .0001$), while there was no difference between the straddled versions ($F(1,66) = 1.68$, $MSE = 2.80$, $p = .2018$) (Figure 5b, left axel).

Results for the fan illusion were further backed up with decrease in PSE ($F(3, 23) = 7.69$, $MSE = 715.8$, $p < .0005$) with the White occluder (“invisible” occluders) condition significantly weaker than Equiluminant ($p < .05$), while Middle Contrast was weaker than both Low Contrast ($p < .05$) and Equiluminant ($p < .01$) fans (Figure 5b, right axel). It seemed odd at first that invisible occluders would have stronger illusion strength than Middle Contrast ones, since Scholl and Pylyshyn (1999) have shown that tracking performance with invisible occluder contours is equivalent to those with visible ones. However, there is the possibility that as the shape of the invisible occluders cannot be seen, the 4 leaves of the fan might be perceived as individually disappearing along each of their own occluders at the beginning of occlusion. When the 4 leaves re-emerge from the occluders, the strong Gestaltian cross configuration would again group them as a single fan. Some participants reported that the display seemed like two different 4-leaf fans jumping in alternation. This ambiguity explains the higher variation (SE = 13.61) compared to other conditions.

Overall, Experiment 2 showed that surface segregation improved only the un-straddled versions where deletion/accretion cues were present for both footsteps and fan illusions. This is in contradiction with the low-level explanations of the footsteps illusion. If motion perception is just determined by presence of motion signals, then as long as there is occlusion of the moving edges, neither surface segregation nor the presence of occlusion cues would affect illusion strength. Furthermore, according to Howe et al. (2006), the contributions of stationary signals from the background edges are consistent in both straddled and un-straddled versions while the signals from all other edges are kept constant, thus there should be no difference between the two versions. Therefore, the difference indicates that additional factors caused the change in illusion strength. We thus propose that contrast changes help segregate the occluding and occluded surfaces, with attentive tracking activated only for those fan/bars that have deletion/accretion cues.

Experiment 3: Effect of Distracter Interference

If surface segregation and deletion/accretion cues can cause smoother motion perception in the static capture footsteps and fan illusions by enabling attentive tracking, interference of tracking could then increase the “stopping” motion perception. In Experiment 3A, we tested if attentive tracking was involved in both the fan and footsteps illusions by increasing the overlap durations of the moving fan/bar and stationary stripes in un-straddled fans and footsteps, predicting stronger “stopping” illusions for longer durations. In Experiment 3B, a distracter was added to both a Middle Contrast and a black fan display (the Middle Contrast and Equiluminant fan display in Experiment 2B, see Figure 5b). If, as proposed in Experiment 2, the smoother motion of the Middle Contrast fan was due to attentive tracking, then adding distracters should regain illusion strength. On the other hand, if illusion strengths were purely determined by contrast-dependent mechanisms, then interference should have no effects.

Stimuli

In Experiment 3A, stimuli were displayed on a light-emitting diode (LED) monitors (1024 X 768, 15” viewable diagonal, 60Hz / 1024 X 768, 12” viewable diagonal, 50 Hz). In Experiment 3B, the same lab chamber and apparatus in Experiment 2B was used.

In Experiment 3A, the widths of the stationary stripes were manipulated to 1, 1.3, 2 or 4 times the size of the moving bar/fan. Therefore, in the footsteps illusion, the moving bar was 6% screen width while the stripe widths were 6%, 8%, 12% or 24% screen widths. In the fan illusion, the moving fan was 15 arc degrees width while the stripe widths were 15, 20, 30, 60 arc degrees. The space between the stationary stripes was kept constant at 30 arc degrees for the fan illusion and 6% screen width for the footsteps illusion.

In Experiment 3B, interference was introduced by adding a 50 ms visual distracter (a red dot) at the center of Middle Contrast and Equiluminant fans whenever the midpoint of each rotating leaf aligned to a stationary leaf. Control stimuli were the same fan displays without visual distracter interference.

Participants

Eight college students participated in Experiment 3A, and twenty-four college students participated in Experiment 3B in return for course credits or a small amount of fee.

Procedure

In Experiment 3A, the same rating procedure as in Experiment 1 was used. In Experiment 3B, the four conditions (two contrast conditions (Middle and

Equiluminant) x two interference conditions (with or without visual distracter)) were Latin-square counterbalanced across participants, and the same 2-AFC staircase procedures as in Experiment 2B was used.

Results and discussions

In Experiment 3A, longer overlap durations resulted in stronger illusion strengths (F(3,7)=25.90, MSE = 0.45, p < .0001; F(3,7) = 17.56, MSE = 0.60, p < .0001, for fan and footsteps illusions, respectively) with significant linear trends between duration and illusion strength for both illusions (F(1,7) = 76.91, MSE = 34.85, p < .0001; F(1,7) = 50.80, MSE = 30.33, p < .0001, for fan and footsteps illusions, respectively). In the fan illusion, when the moving fan passed a fan-leaf of the same width, the illusion was significantly weaker than 1.33 the size (p < .05) and even weaker than those twice or four times its size (ps < .01). Fans passing behind occluders 1.33 its size were also significantly weaker than the two larger sizes (ps < .01). In the footsteps illusion, when stationary stripes were twice and four times the size of the moving objects, the illusion was significantly stronger than when they were equal (ps < .01) or 1.33 in size (p < .05, p < .01, respectively, for the two sizes) (Figure 6).

In Experiment 3B, as in Experiment 2B, illusion strength was weaker for the Middle Contrast than Equiluminant fans (the main effect of contrast: F(1,23) = 14.77, MSE = 27432.58, p < .001). However, the addition of interference increased illusion strength for both Middle Contrast and Equiluminant fans (the main effect of distracter: $F(1,23) = 13.77$, $MSE = 5596.07$, $p < .005$) (Figure 7). As there was no interaction between contrast and interference ($F(1,23) = 0.36$, $MSE = 882.04$; $p = .57$), this indicates that the illusion strength decreased by the presence of contrast-defined surface segregation in the Middle Contrast conditions could be linearly increased with distracter interference.

General Discussion

In Experiment 1 and 2, we demonstrated that contrast affected both the footsteps and fan illusions in the same way regardless if motion signals at the leading or trailing edges were present (Experiment 1A) or absent (Experiment 2). Furthermore, a motion capture variation of the fan illusion analogous to that of the footsteps illusion (Howe et al., 2006) also varied with contrast as predicted (Experiment 1B). These results are consistent with Anstis's (2001) and Howe et al's (2006) explanations of the footsteps illusion.

However, according to Howe et al.'s (2006) model, straddled and un-straddled versions of the static motion footsteps illusion should be affected by the change in contrast of background stripes in the same way. Contrary to this prediction, in the absence of motion signals from the leading and trailing edges of the moving bar, only the un-straddled versions of the footsteps and fan illusion had decreased illusion strength at higher stripe contrasts while the straddled versions remained the same (Experiment 2). This result indicates that something more is involved in determining illusion strength other than the contrasts of the edges.

A critical difference between the two versions is the presence of deletion/accretion cues in the un-straddled versions revealed by contrast-induced surface segregation of the occluding stripes and occluded bars/fans. The manner objects disappear and subsequently reappear indicate both the presence of an occluder and the spatiotemporal continuity of the moving objects. Spatiotemporal continuity has often been regarded as a necessary or even sufficient condition for object persistence (Scholl, 2007). During occlusion, mid-level representations of objects (the object files, Treisman, 1992) are maintained by spatiotemporal continuity (Cheries et al., 2009; also see Flombaum, et al., 2009, for a review) and representation of spatiotemporal continuity is sufficient for representing identical objects even after complete feature change during occlusion (the tunnel effect, Michotte, 1991). The primate brain might have been hard-wired to realistically represent the way objects move according to physical laws, even when they are occluded (Scholl, 2007).

Human and nonhuman primates prioritize spatiotemporal continuity when tracking objects (Flombaum et. al., 2009). We propose that (1) the cause of the static capture illusion was the lack of conditions for tracking and (2) attentive tracking aids in smoother motion perception. This was supported by Experiment 2 and 3. In Experiment 2, the presence of depth (surface segregation) and deletion/accretion cues (in the un-straddled fans) resulted in smoother motion perception. In Experiment 3A, longer overlapping durations taxing attentional resources further increased the static capture of equiluminant fans and footsteps displays. In Experiment 3B, interfering distracters caused the smoother mid-contrast fan in Experiment 2 to “stop.”

There may be more factors influencing attentive tracking, such as the importance of object history to the object updating process (Moore, Mordkoff, & Enns, 2007). In the straddled versions, the moving fans/bars are never completely in view, but in the un-straddled versions, they are entirely exposed before disappearing completely. Therefore, the smoother motion perception in the latter might also be caused by better attentive tracking with longer viewing histories.

Attentive tracking can explain the difference in illusion strength in the straddled and un-straddled footsteps illusions, while Howe et al.'s (2006) explanation would lead to somewhat odd implications. Howe et al. (2006) explain the stronger illusion for the straddled version with larger contrast-weighted stationary signals from the top and bottom edges of the moving bar. However, when the moving bar and stationary stripes were equiluminant, even though there were no motion signals when all leading and trailing edges overlap with the stripes, the illusion strength was still different for the two versions (Experiment 2). We explain the stronger illusion of the straddled version by impairment of attentive tracking, but according to Howe et al. (2006), this is because the stationary signals of the top and bottom edges of the straddled bar have made the already stationary display become even more stationary!

Furthermore, motion capture has been shown to be dependent on whether the stationary and moving objects are represented on the same surface (Cavanagh, 1992;

Culham & Cavanagh, 1994; Ramachandran & Anstis, 1986). Therefore, the effect of contrast manipulation in Experiment 1B could also be caused by the segregation of surfaces that decreases motion capture. As other motion capture stimuli have been shown to be modulated by attentive tracking (Cavanagh, 1992; Culham & Cavanagh, 1994), the motion capture variation of the footsteps and fan illusions might also share common mechanisms related to attentive tracking.

Previous studies in the footsteps illusion have overlooked attention as a factor influencing perceived motion. Anstis (2001, 2004) mentioned that the footsteps illusion is stronger in the observer's peripheral vision. Sunaga, Sato, Arikado, and Jomoto (2008) demonstrated that in the footsteps illusion, low frequency samplings of a static contrast-induced mis-alignment illusion contributed largely to the alternating mis-alignments of the black and white moving bars. As high-spatial-frequency information is less sensitive in peripheral vision, they concluded that this was the main cause of the illusion. However, Intriligator and Cavanagh (2001) found that the resolution of attention scales with larger eccentricity and is coarser in the upper visual field and along the radial lines from fixation. Therefore, attention and eccentricity may be confounded in these findings. As this study shows that attentional modulation can affect and may be the cause of the footsteps and fan illusions, the role of attention can be a future line of investigation for footsteps and other contrast-dependent motion illusions.

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(a)

(b)

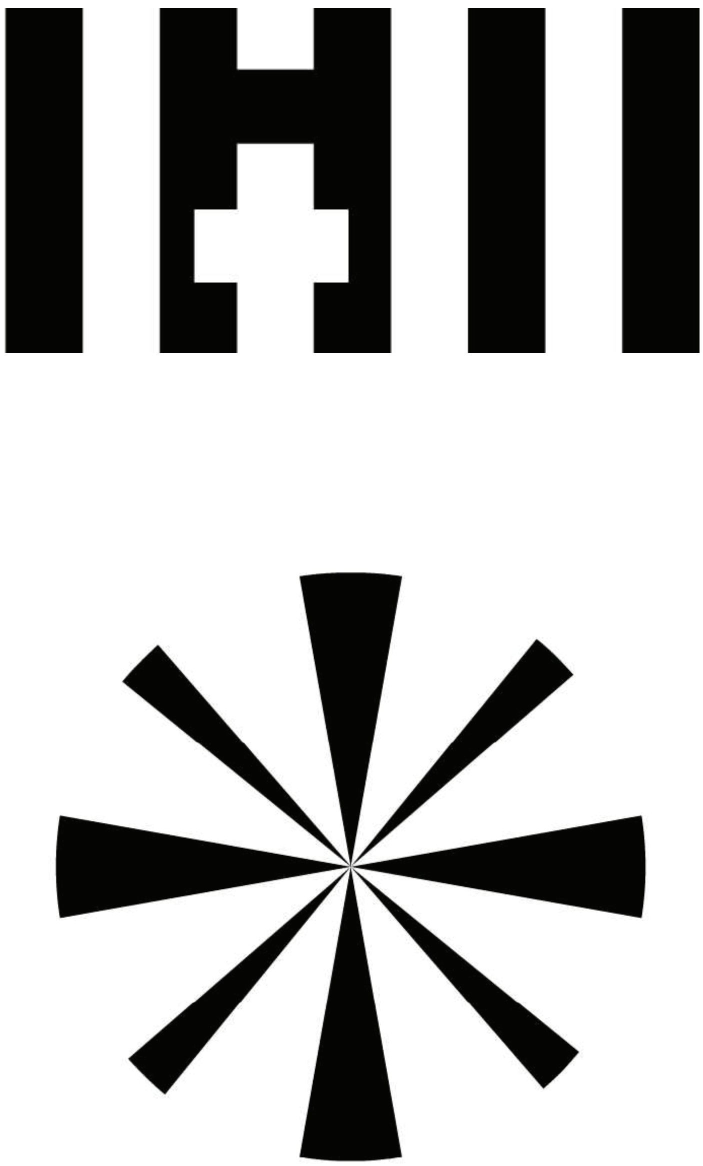

Figure 1. The standard footsteps illusion consists of black and white bars that appear to stop-and-go when moving across black-and-white stripes (a). In the standard fan illusion, a smaller rotating fan also appears to stop-and-go when superimposed with a stationary fan (b).

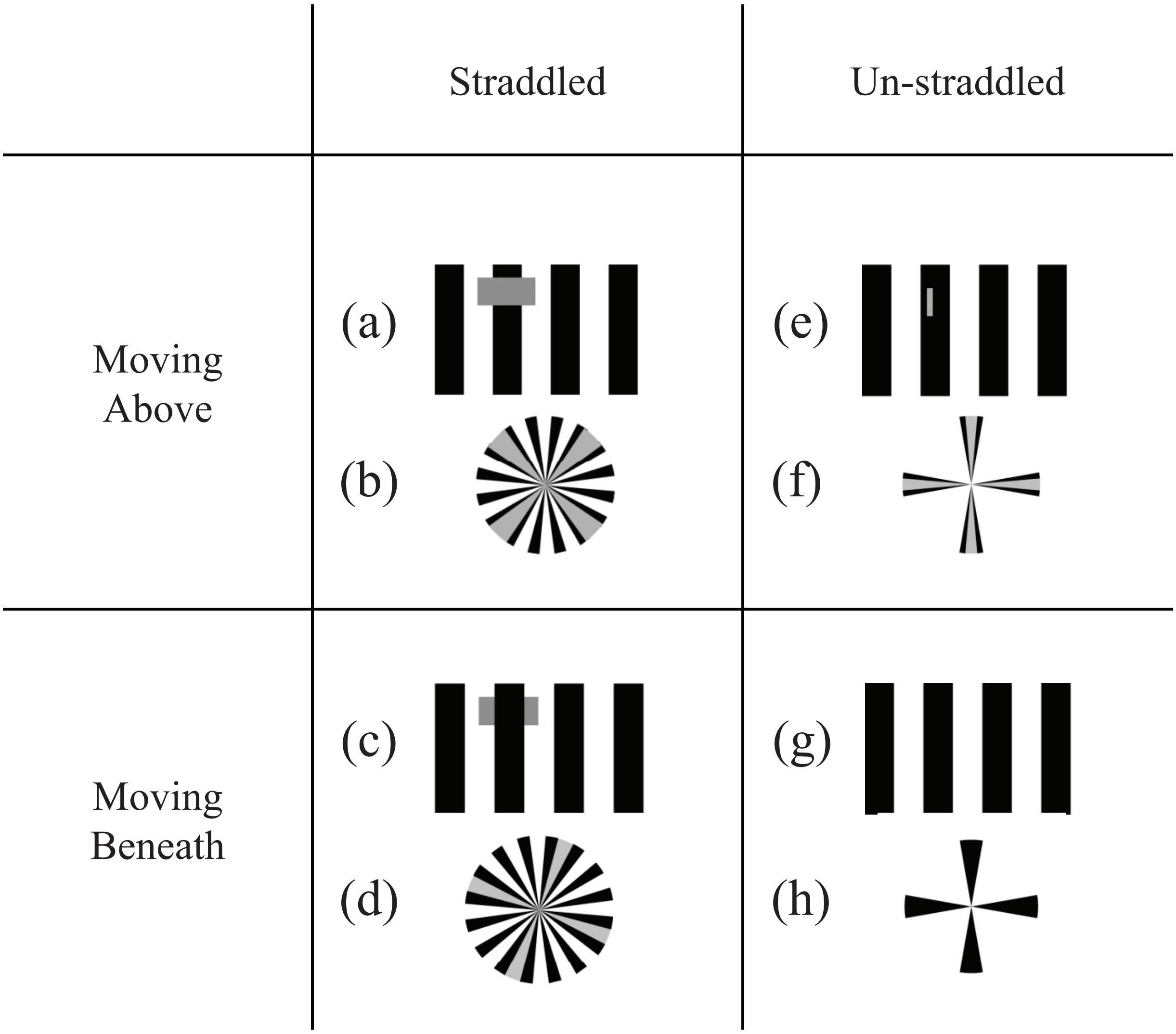

Figure 2. The moving fans/bars overlay multiple stripes in the straddled versions (a)-(d) but are smaller in width than a single stripe in the un-straddled versions (e)-(h). Moving edges are visible when the fans/bars move above the stripes (a), (b), (e), (f) and occluded when beneath the stripes (c), (d), (g), (h).

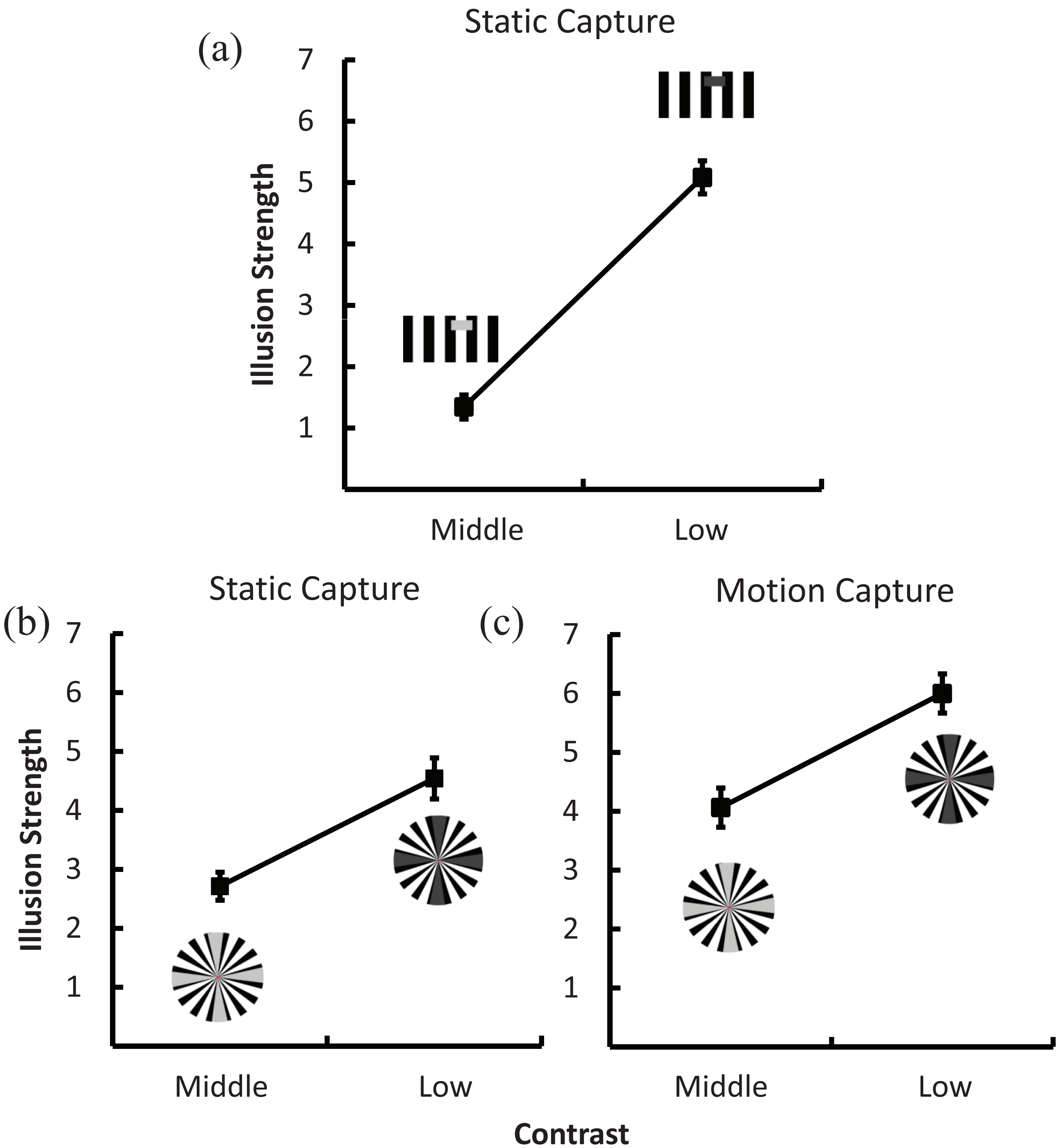

Figure 3. The results of Experiment 1. When the leading and trailing edges of the "static capture" illusion bar (a), fan (b) and "motion capture" illusion fan (c) were lower in contrast compared to the black stripes, the illusion strength was stronger than when their luminance were at the mid-point of black and white. All error bars in this study show two standard errors.

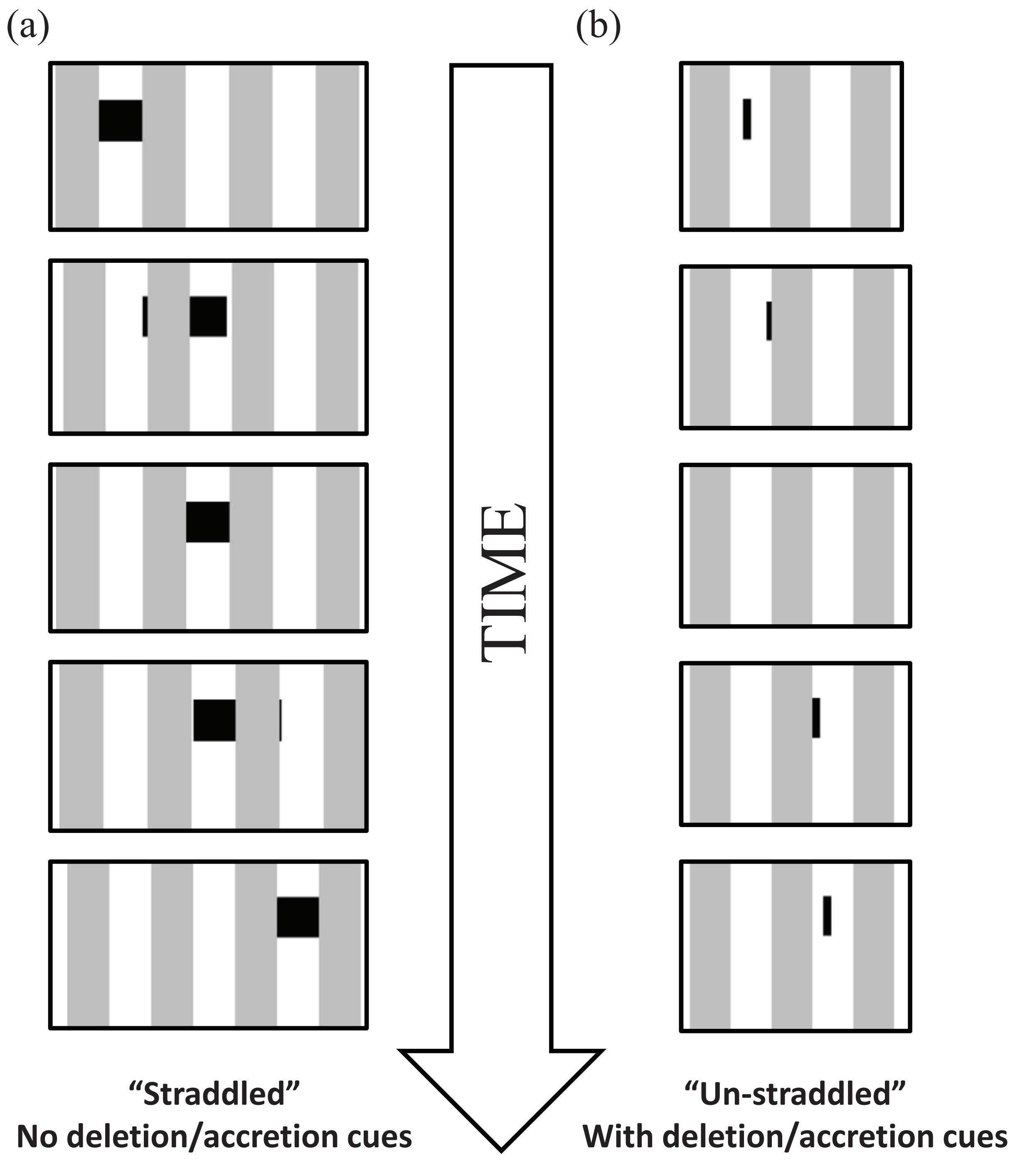

Figure 4. The stripes are shown in grey for demonstration purpose. When the moving edges are straddled upon two different stripes, the leading and trailing edges are always simultaneously visible or invisible (a). When they are smaller than the stripes, they gradually disappear behind (deletion cues) and reemerge from (accretion cues) the occluding stripes (b).

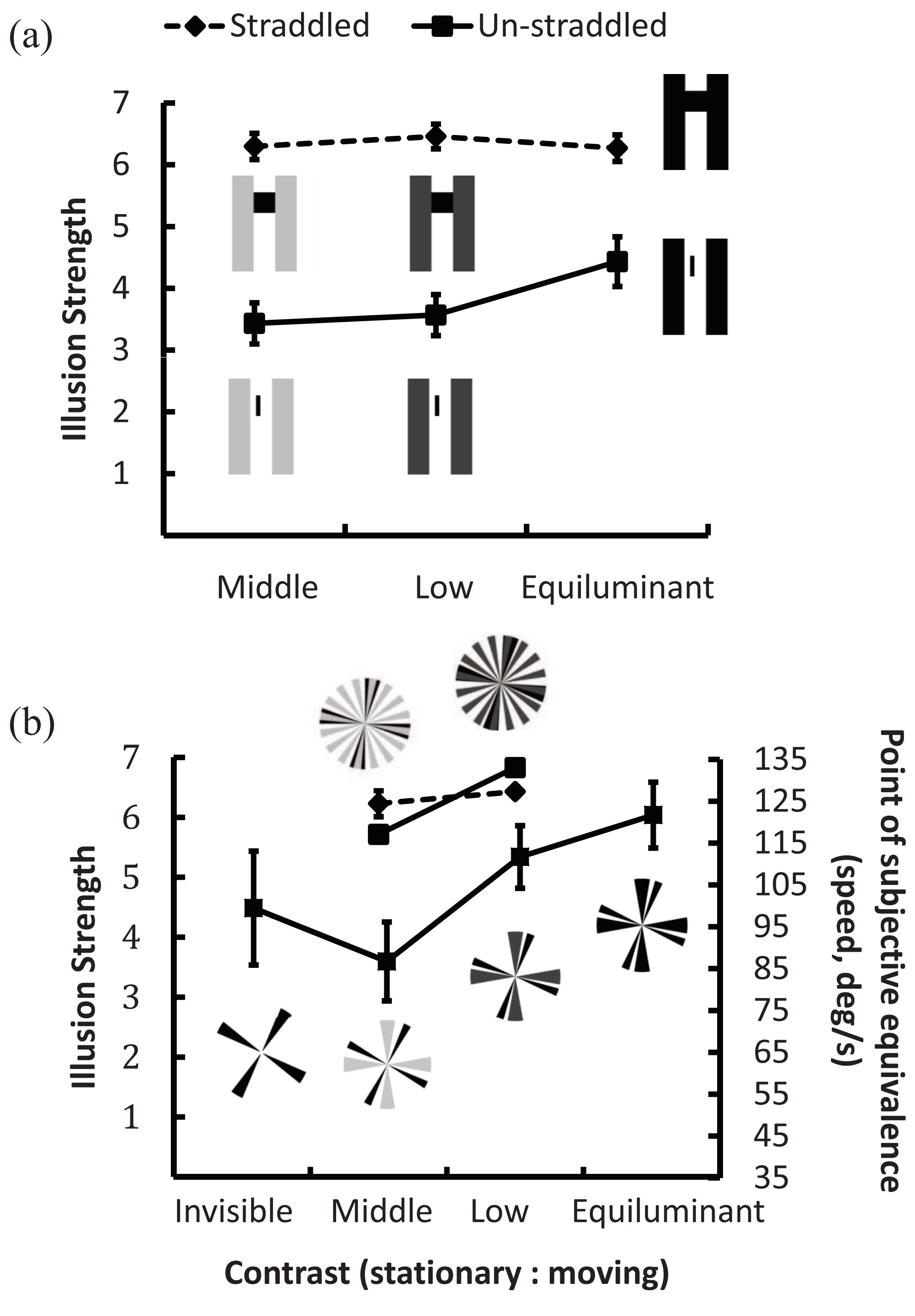

Figure 5. The results of Experiment 2. Dashed lines represent the straddled versions and solid lines represent the un-straddled versions. Contrast manipulation of the stationary stripes/fans only affected the illusion strength of un-straddled footsteps (a) and fan (b) displays. The fan illusion conditions (b, left) were replicated with a 2-AFC staircase procedure (b, right) and consistent results were obtained.

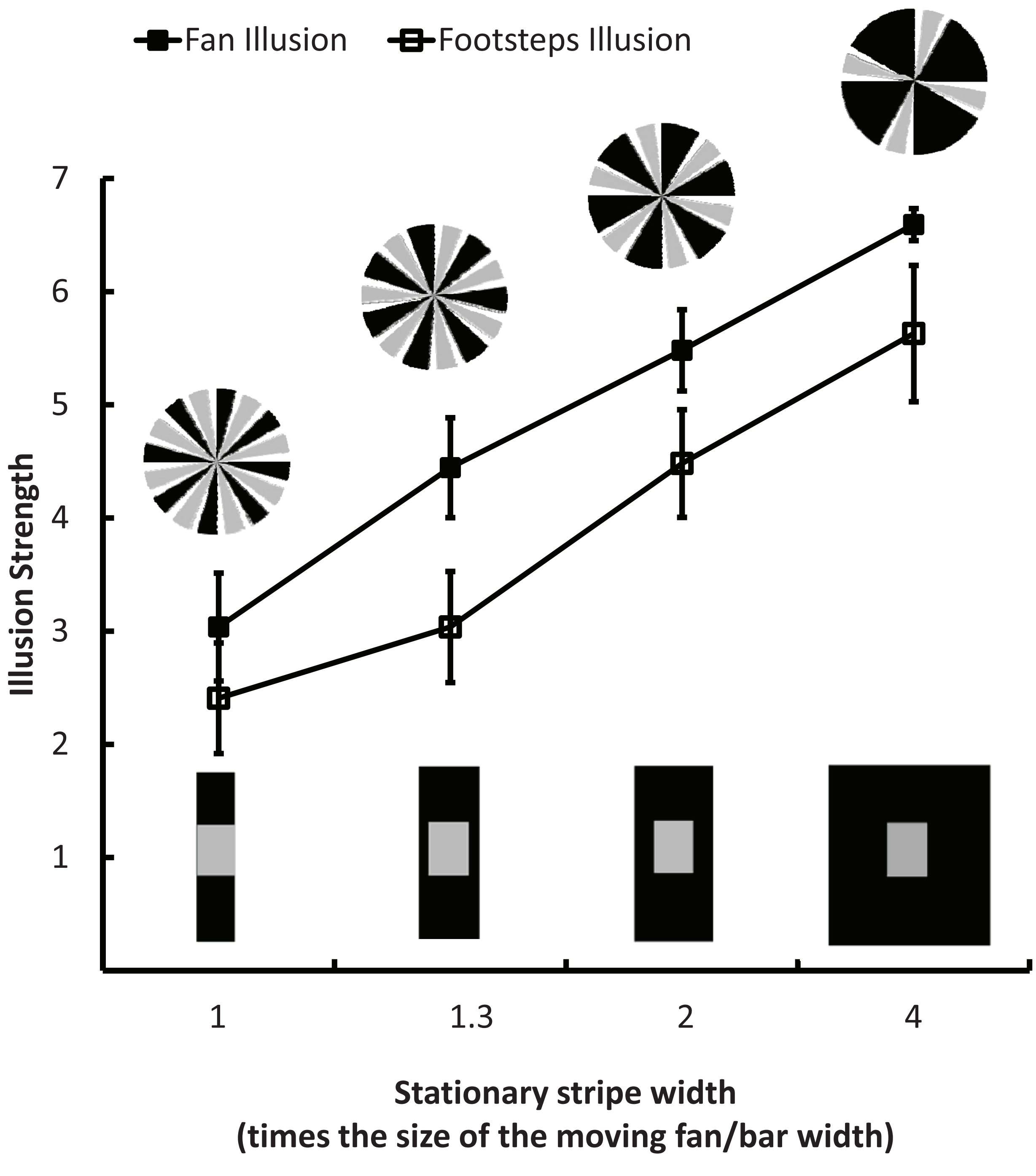

Figure 6. The results of Experiment 3A.The moving fan and bar are shown in grey here, but both are black in the experiment. The longer the width of the stationary stripes, the longer the moving stimuli stayed invisible. This caused an increase in illusion strength, possibly due to deterioration of attentive tracking.

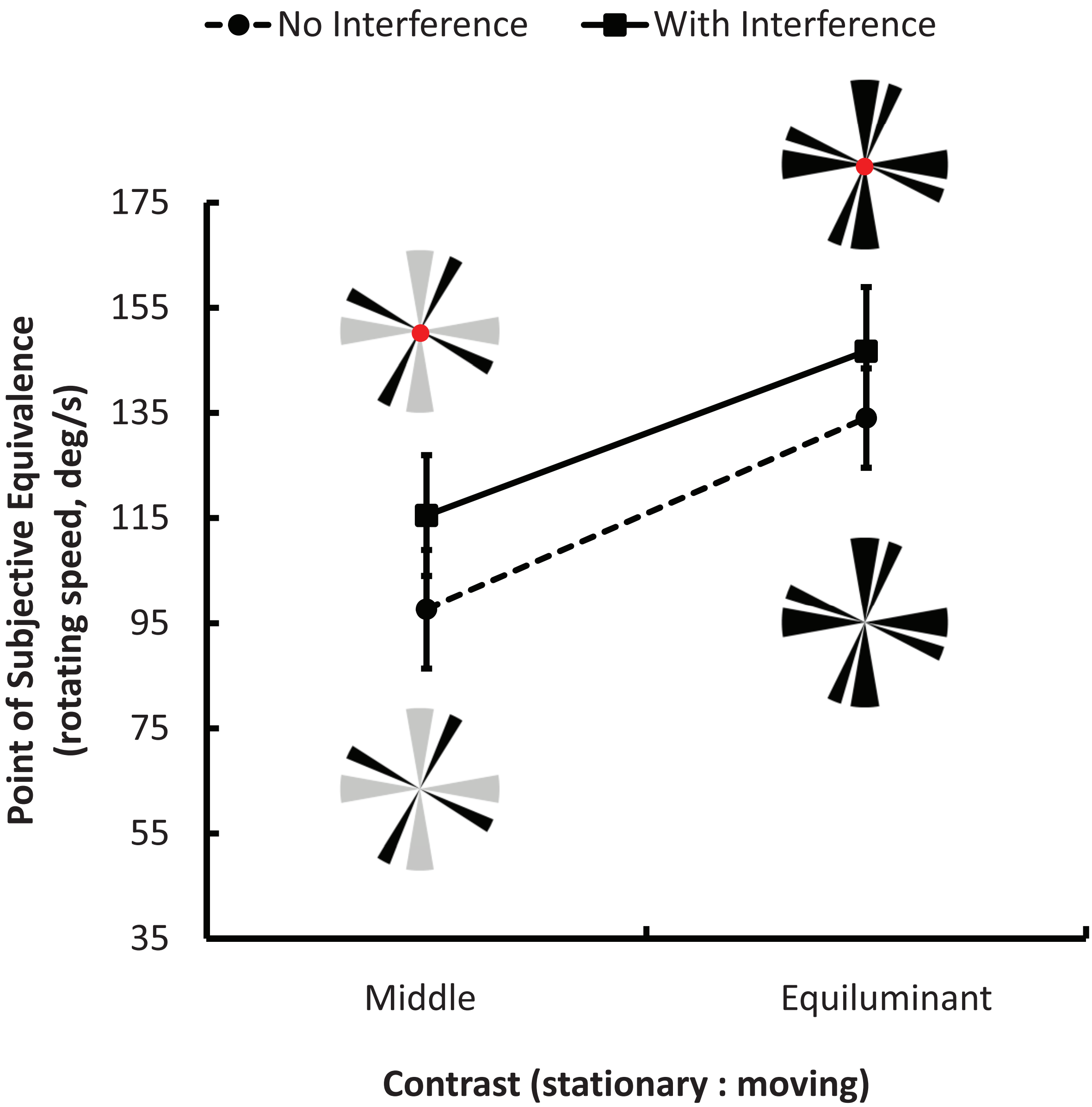

Figure 7. The results of Experiment 3B. Illusion strength was weaker with lower stationary fan contrasts, but stronger after addition of a visual distracter interference.