Explaining the footsteps, belly dancer, Wenceslas, and kickback illusions

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The footsteps illusion (FI) demonstrates that an object's background can have a profound effect on the object's perceived speed. This illusion consists of a yellow bar and a blue bar that move over a black-and-white, striped background. Although the bars move at a constant rate, they appear to repeatedly accelerate and decelerate in antiphase with each other. Previously, this illusion has been explained in terms of the variations in contrast at the leading and trailing edges of the bars that occur as the bars traverse the striped background. Here, we show that this explanation is inadequate and instead propose that for each bar, the bar's leading edge, trailing edge, lateral edges, and the surrounding background edges all contribute to the bar's perceived speed and that the degree to which each edge contributes to the motion percept is determined by that edge's contrast. We show that this theory can explain all the data on the FI as well as the belly dancer and Wenceslas illusions. We conclude by presenting a new illusion, the kickback illusion, which, although geometrically similar to the FI, is mediated by a different mechanism, namely, reverse phi motion.

Keywords: motion, speed, contrast, motion capture, position capture, aperture problem

Introduction

In its original form, the stimulus of the footsteps illusion (FI) comprises a yellow bar and a blue bar that traverse a black-and-white, striped background (Figure 1a). Although the bars both move at the same constant speed, they appear to alternately accelerate and decelerate (Anstis, 2001, 2003a, 2003b, 2003c), as depicted in Figure 1b. Both the yellow and blue bars have a length equal to one period of the background grating; thus, for each bar, its leading edge is always over the same color stripe as its trailing edge. The yellow bar appears to move slowly while its leading and trailing edges pass over the white stripes and more quickly while these edges pass over the black stripes; conversely, the blue bar appears to move slowly while its leading and trailing edges pass over the black stripes and more quickly while these edges pass over the white stripes. Under the right conditions, the effect can be very large, especially in peripheral vision, with most subjects perceiving each bar to periodically come to a complete halt.

At first glance, the illusion appears to have an obvious explanation: The variations in perceived speed of the yellow and blue bars could be caused by the variations in contrast at the leading and trailing edges of these bars that occur as the bars traverse the black-and-white, striped background (Anstis, 2004). Consider the limiting case of the FI where the yellow bar is lightened so that it is virtually white and the blue bar is darkened so that it is virtually black. When the leading and trailing edges of the yellow bar are over the white stripes, the contrast between these edges and the white stripes would be too small to be detected. Consequently, no motion signals would be generated; hence, the yellow bar would appear to stop. Conversely, when the yellow bar's leading and trailing edges are over the black stripes, they can be readily detected; thus, in this circumstance, the yellow bar would appear to move. The net effect would be that the yellow bar would appear to stop when it reaches a white stripe but would appear to move again when it reaches a black stripe. Similar reasoning would apply to blue bar; hence, it would appear to stop when it reaches a black stripe and would appear to move when it reaches a white stripe. For convenience, we will refer to this explanation of the FI as the leading and trailing edge hypothesis.

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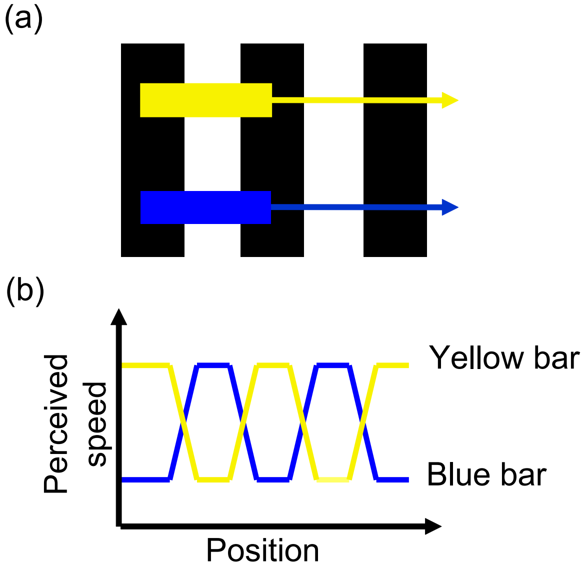

Figure 1. (a) The FI. A yellow bar and a blue bar move over a striped background. (b) The two bars appear to repeatedly accelerate and decelerate in antiphase, although they, in fact, move at the same constant rate.

If the leading and trailing edge hypothesis were true, then the FI would demonstrate only that the contrast at an object's leading and trailing edges affects the object's perceived speed. As it is already well known that contrast can affect perceived speed (Campbell & Maffei, 1981; Gegenfurtner & Hawken, 1996; Stone & Thompson, 1992; Thompson, 1976, 1982), there would be little point in studying the FI any further. However, in this article, we will show that this hypothesis cannot explain the FI; thus, this illusion must be caused by different mechanisms. Deducing what these mechanisms are is the purpose of this article.

Methods

Stimuli were generated using Matlab® and the Cogent Graphics psychophysical toolbox. They were presented on a 41.5 × 30 cm NEC MultiSync 6FGP CRT monitor (72 Hz refresh rate, noninterlaced). The room was blacked out, and the only illumination came from the computer monitor. This monitor was calibrated with a Spectra® PRITCHARD® Photometer. A combined head and chin rest ensured that the viewing distance was maintained at 77 cm. The monitor was placed on its side so that it was taller than it was wide. At the viewing distance used in the experiment, the monitor subtended 22.0° × 30.2°.

For the standard FI, the stimulus comprised a background grating of vertical black (0.6 cd/m^2) and white (79.1 cd/m^2) stripes. Twenty-nine periods of the grating were shown. At the center of the display was a red (23.6 cd/m^2) fixation cross. A yellow (61.7 cd/m^2) bar repeatedly traversed from left to right at 1.4°/s. Unlike the original FI, there was no blue bar to ensure that subjects paid attention to the yellow bar. The yellow bar subtended 0.7° × 0.4°, with its length being equal to the period of the grating. The closest the bar came to the center of the fixation cross was 3.3°. Fifteen observers were used. Ages ranged from 18 to 65 years, and all had normal or corrected-to-normal visual acuity.

Because all the explanations in this article are in terms of the luminance contrast of the yellow bar, the color of the bar is irrelevant. Consequently, we could have replaced the yellow bar with a light gray bar. Indeed, it has previously been shown that the FI continues to occur if this substitution is performed (Anstis, 2001). We decided to use a yellow bar, instead of a light gray bar, because only with a colored bar can one have the situation in which the bar is visible but approximately equiluminant with the background, thus maximizing the visibility of the bar while minimizing its motion signals. This distinction between the detectibility of the bar and its apparent motion is doubtless due to the differences in color sensitivity in the magnocellular and parvocellular pathways of the primate visual system (Livingstone & Hubel, 1987).

At the start of the experiment, each observer was shown the standard FI stimulus. In keeping with Anstis (2004), the observers were told that this was the reference stimulus, and the periodic change in the apparent speed of the yellow bar in this stimulus corresponded to a rating of 10 on a scale where a rating of 0 indicates completely smooth motion.

In each trial, this reference stimulus was shown first, and then a test stimulus was presented. By pressing a key, observers could alternate at will between the two stimuli, and they were allowed to view each stimulus for as long as they wished. Observers were asked to rate the strength of the illusion, that is, the periodic alternation in the perceived speed of the yellow bar in each test stimulus. Each test stimulus was rated once by each observer. The test stimuli were presented in a random order.

Results

Iconic representations of the reference stimulus and the seven test stimuli are shown in Figure 2. These stimuli are arranged according to the strength of the illusion they induced. An approximation of the reference stimulus (Figure 2a) is shown in Stimulus 2a demo. The reader should vary the viewing distance or vary the image size of this demonstration until a large FI is perceived while also remembering to maintain fixation on the red fixation cross. Stimulus 2b (Stimulus 2b demo; Figure 2b) was identical to Stimulus 2a except that the height of the yellow bar was increased so that it spanned the entire display. This produced an illusion just as strong as the reference stimulus (illusion strength = 10.0 ± 0.4). Stimulus 2c (Stimulus 2c demo; Figure 2c) was identical

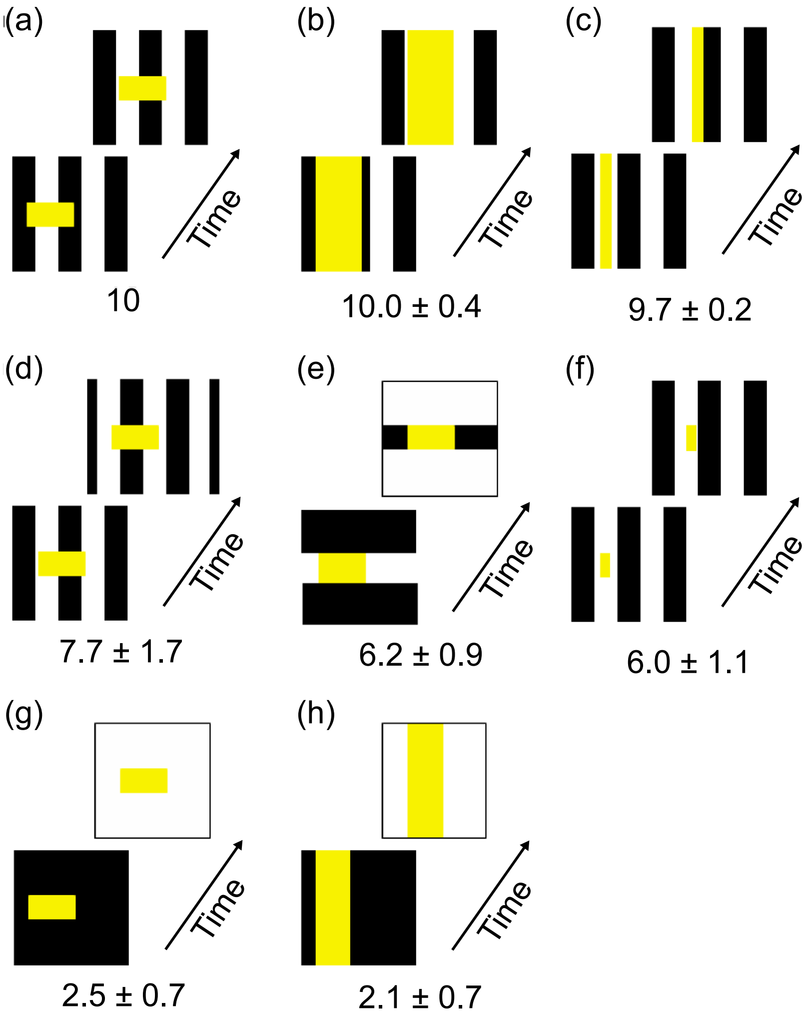

Figure 2. The stimuli used in the first series of experiments. (a) The reference stimulus. (b–h) The test stimuli. Each diagram represents a particular stimulus at two successive points in time. Under each icon is the strength of the illusion induced by the stimulus (*M* ± *SE*).

to Stimulus 2b except that the yellow bar was thinner by a factor of 10; this configuration also generated a strong (illusion strength = 9.7 ± 0.2) illusion. Stimulus 2d (Stimulus 2d demo; Figure 2d) was identical to Stimulus 2a except that the yellow bar was stationary, located 6.7° from the fixation cross, and the background traversed from right to left at the same speed as the yellow bar had traversed from left to right in Stimulus 2a. This resulted in a fairly strong (illusion strength = 7.7 ± 1.7) impression that the yellow bar moved periodically to the left when its leading and trailing edges were on white stripes but appeared to be stationary when they were on black stripes.

In Stimulus 2e (Stimulus 2e demo; Figure 2e), the yellow bar traversed from left to right at the same speed as in Stimulus 2a, and the background was uniform except for a horizontal stripe over which the yellow bar moved. The stripe and the rest of the background alternated between black and white in antiphase with each other so that when one was white, the other was black. The rate of this alternation was such that the variations in contrast at the leading and trailing edges of the yellow bar in this display were the same as those in Stimulus 2a. This resulted in a fairly strong illusion (illusion strength = 6.2 ± 0.9). Stimulus 2f (Stimulus 2f demo; Figure 2f) was identical to Stimulus 2a except that the horizontal length of the bar was reduced by a factor of 10: This manipulation reduced the illusion somewhat (illusion strength = 6.0 ± 1.1).

In Stimulus 2g (Stimulus 2g demo; Figure 2g), the yellow bar moved over the background at the same rate as in Stimulus 2a. The background was uniform and alternated between black and white at a frequency such that the variations in contrast at the leading and trailing edges of the yellow bar were identical to those in Stimulus 2a. This manipulation resulted in a very weak illusion (illusion strength = 2.5 ± 0.7). This reduction in illusion magnitude was also true for very tall bars on a homogeneous background (Stimulus 2h demo; Figure 2h); this display also produced a very weak illusion (illusion strength = 2.1 ± 0.7).

Discussion

The leading and trailing edge hypothesis is invalid

As discussed in the Introduction, Anstis (2004) suggested that the variations in the perceived speed of the yellow bar in the standard single-bar (Stimulus 2a demo; Figure 2a) were caused by the variations in contrast at the bar's leading and trailing edges that occurred as the bar traversed the black-and-white, striped background. We refer to this suggestion as the leading and trailing edge hypothesis. In Stimulus 2g, the uniform background alternated between black and white at such a rate that the variations in contrast at the leading and trailing edges of the yellow bar were the same as in Stimulus 2a. If the FI were due to these variations in contrast, then one would expect the illusion induced by the two stimuli to be equally strong. The illusion induced by Stimulus 2g was much weaker than that induced by Stimulus 2a, which caused us to reject the leading and trailing edge hypothesis (see also Thompson & Anstis, 2005).

The FI is not caused by lateral masking

While the leading and trailing edge hypothesis attempted to explain the FI in terms of the bar's actual contrast, one might think that the illusion is better explained in terms of the bar's *apparent* contrast. It other words, one might suggest that the yellow bar's perceived speed is affected by the variations in the apparent contrast at the bar's leading and trailing edges that occur as the bar traverses the black-and-white, striped background.

Unlike the leading and trailing edge hypothesis, this hypothesis would explain why Stimulus 2g induces a small FI but Stimulus 2a induces a large FI. The apparent contrast of an edge can be reduced by surrounding it with high-contrast edges, especially if the edges are viewed in the periphery (Zenger-Landolt & Koch, 2001). In Stimulus 2a, the yellow bar is surrounded by the high-contrast edges of the background, whereas in Stimulus 2g, the striped background has been removed. Consequently, the apparent contrast of the leading and trailing edges of the yellow bar is much less in Stimulus 2a than in Stimulus 2g, which could explain why most subjects perceived the yellow bar to periodically come to a complete halt when viewing Stimulus 2a, whereas the yellow bar appeared to slow down only slightly when viewing Stimulus 2g.

Despite its intuitive appeal, this hypothesis, which we will refer to as the lateral masking hypothesis, is flawed in that it cannot explain why Stimulus 2d induces a fairly strong FI. In Stimulus 2d, the yellow bar is stationary but the background moves. Because the yellow bar does not move, its leading and trailing edges do not generate any motion signals. Consequently, the lateral masking hypothesis incorrectly predicts that, regardless of whether the apparent contrast of the leading and trailing edges is high or low, these edges will never cause the yellow bar to appear to move; hence, no FI should be seen.

The lateral edges of the yellow bar contribute to the illusion

Although Stimulus 2g demonstrates that the FI is not caused by the absolute variations in luminance contrast at the leading and trailing edges of the yellow bar, there remains the possibility that the FI is caused by the variations in luminance contrast at the leading and trailing edges of the yellow bar relative to the variations in luminance contrast at the lateral edges of the yellow bar. Because this ratio was constant in Stimulus 2g, such a hypothesis, which we will refer to as the ratio hypothesis, would correctly predict this stimulus to induce a very weak illusion.

Stimulus 2e tested the ratio hypothesis. In this stimulus, the luminance contrast at the leading and trailing edges varied in antiphase with the luminance contrast at the lateral edges. Consequently, the ratio hypothesis would predict that this stimulus should induce as strong an illusion as the standard FI. Although this stimulus induced a fairly strong illusion (illusion strength = 6.2 ± 0.9), it was not as strong as the standard FI, indicating that there is an additional mechanism that affects the FI.

A revised theory of the FI

Other than the leading, trailing, and lateral edges of the yellow bar, the only other set of edges in the standard FI display is that of the background stripes. Consequently, because the previous section showed that it is not possible to explain the FI solely in terms of the leading, trailing, and lateral edges of the yellow bar, we must conclude that the edges of the background play a role in the FI.

We also note that the visual pathway that responds to the motion/position of an object is much more sensitive to luminance contrast than to color contrast (Cavanagh & Favreau, 1985; Cavanagh, Tyler, & Favreau, 1984; Livingstone & Hubel, 1987). Consequently, for the purposes of our theory, color contrast can be ignored.

Finally, we note that Anstis (2001) demonstrated that in the FI, the leading and trailing edges of the yellow bar act independently. He did this by using the "inchworm" variant of the FI shown in Figure 3 (Stimulus 3 demo). In this variant, the yellow bar has a length equal to one and a half times the period of the background grating; thus, its leading edge is always above a different color stripe than its trailing edge. Anstis observed the two edges to move independently, accelerating and decelerating in antiphase with each other. Consequently, in our theory, we consider the motion of the leading and trailing edges separately.

Figure 3. The inchworm illusion. Because the length of the yellow bar is equal to one and a half times the period of the grating, the leading edge is always above a different color stripe than the trailing edge. As the yellow bar moves over the striped background, its leading and trailing edges accelerate and decelerate in antiphase, giving the impression of an inchworm. This illusion demonstrates that the leading and trailing edges act independently.

Below, we describe our theory in terms of the leading edge of the yellow bar. The same reasoning applies to the yellow bar's trailing edge; hence, throughout the remainder of the article, we will refer to only the yellow bar's leading edge, with the understanding that our reasoning applies equally to the bar's trailing edge.

The most parsimonious theory of the FI is that the apparent speed of the leading edge of the yellow bar is determined by the motion signals originating from the bar's leading edge, the bar's lateral edges, and the background edges in the vicinity of the leading edge, but the degree to which each edge contributes to the perceived motion of the leading edge is determined by the luminance contrast of the edge in question. This statement can be expressed mathematically as a weighted average:

$$S = \frac{w_1^* E_1 + w_2^* E_2 + w_3^* E_3}{w_1 + w_2 + w_3}, \qquad (1)$$

where S is the apparent speed of the leading edge, E_1 is the motion signal generated by the leading edge, E_2 is the motion signal generated by the bar's lateral edges, E_3 is the motion signal generated by the background edges in the vicinity of the leading edge, and W_i is the weight associated with edge E_i. Because the bar is moving parallel to its lateral edges, the lateral edges generate "no motion" signals, causing the leading edge to appear to slow down by an amount that is determined by their weight, W_2. We propose that varying the contrast of an edge has a small effect on the motion signal associated with the edge but has a much larger effect on the weight associated with the edge in Equation 1. We also assume that the weightings in Equation 1 are biased so that if the contrasts at all three sets of edges are the same, then the motion signal generated by the leading edge, that is, E_1, dominates the perceived motion of the leading edge. The other edges will have a significant effect on the perceived motion of the leading edge only when their contrast is larger than the contrast at the leading edge.

Previous studies

Our theory assumes that (1) the bar's lateral edges and (2) the edges in the background both influence the perceived speed of the leading edge. A study by Anstis (2003a) supports the first assumption. In this investigation, Anstis considered the perceived movement of a graded-contrast line that in reality moved vertically downward. When the contrast of the ends of the line was larger than the contrast of the sides of the line (Figure 4a), the motion signals from the ends dominated the perceived motion of the line, and hence, the bar's true downward motion was perceived. However, when the contrast of the ends was smaller than the contrast of the sides (Figure 4b), the motion signals of the sides dominated the percept. The situation was therefore analogous to the motion aperture problem (Marr, 1982; Wallach, 1935; Wuerger, Shapley, & Rubin, 1996), which occurs when a bar is viewed through an aperture so that its ends cannot be seen and, thus, cannot contribute to the perceived motion of the bar (Figure 4c). As in the aperture problem, the line in Figure 4b was perceived to move orthogonally to its orientation. Anstis therefore provided direct evidence that, consistent with our theory, the sides of a bar contribute to the bar's perceived motion and that the degree to which the sides influence the motion percept is determined by the luminance contrast of the sides relative to the luminance contrast of the ends. We note that this finding is consistent with a number of other studies (Castet, Lorenceau,

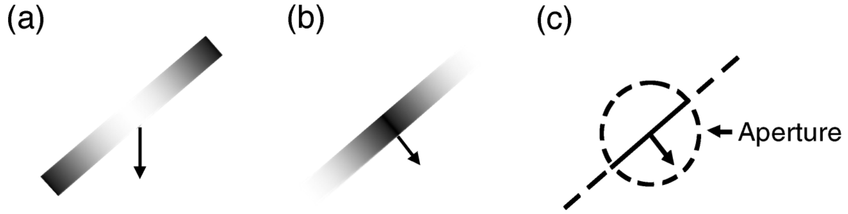

Figure 4. The apertureless aperture problem (Anstis, 2003a). An oblique bar moves downward. In Panel a, the ends of the bar are visible, and the true motion of the bar is seen. In Panel b, the ends of the bar are not visible; the situation is therefore analogous to the motion aperture problem shown in Panel c, and hence, the bar is perceived to move perpendicular to its orientation.

Shiffrar, & Bonnet, 1993; Chey, Grossberg, & Mingolla, 1997; Lorenceau, Shiffrar, Wells, & Castet, 1993).

There have also been studies that have shown that our other assumption, that the edges of background can influence the perceived motion of a target, is valid. Ramachandran (1987) used a stimulus that comprised a red square on a green background, where the square and the background had the same luminance. The square was surrounded by high-luminance-contrast dots. When the dots were moved, the square appeared to move in the same direction (see also Goda and Ejima, 1997, for a similar experiment). This showed that the motion of the high-luminance-contrast dots was misassigned to the low-luminance-contrast square. This phenomenon is typically referred to as "motion capture," which is defined as any situation where the motion of the background is wrongly attributed to a stationary target, thereby causing the target to appear to move. However, in the standard FI (Stimulus 2a demo; Figure 2a), the converse occurred, in that the stationary background caused the moving target to appear to slow down. Although the principle is the same as that of motion capture, the latter phenomenon is typically referred to as "position capture" (Murakami & Shimojo, 1993).

Explanation of data

In Figure 2a, when the leading edge of the yellow bar reaches a white stripe, the contrast at this edge is reduced. This reduces the weight associated with this edge; hence, the perceived motion of this edge is determined mainly by the motion signals of the lateral edges and the edges of the black-and-white, striped background. Because neither the lateral edges nor the background edges generate any motion signals, the leading edge appears to stop or at least to slow down as detailed by Equation 1. Conversely, when the leading edge is over a black stripe, the contrast at the edge is large; thus, the weight associated with this edge is large, with the consequence that the perceived motion of the edge is determined mainly by the motion signals associated with it. This would explain why the yellow bar appears to start moving again when it reaches a black stripe.

The stimulus of Figure 2b is identical to that of Figure 2a except that in the former, the leading and trailing edges extend beyond the observer's field of view; this reduces the visibility of the lateral edges, which in turn reduces their contribution to the perceived motion of the leading and trailing edges. However, the leading and trailing edges are now the same length as the edges of the striped background. Consequently, the background now has a stronger influence on the leading and trailing edges; that is, its weighting in Equation 1 has increased. Thus, in Stimulus 2b, the reduction in weighting of the lateral edges is compensated for by the increase in the weighting of the background; hence, the induced illusion is comparable to that induced by Stimulus 2a (illusion strength for Stimulus 2b = 10.0 ± 0.4).

The stimulus of Figure 2c is identical to that of Figure 2b except that in the former, the leading and trailing edges are closer together. This manipulation does not affect any of the above reasoning, which would explain why Stimulus 2c induces an equally strong illusion as that of Stimulus 2b (illusion strength = 9.7 ± 0.2).

The stimulus of Figure 2d is similar to that of Figure 2a except that in the former, the yellow bar is stationary and the background moves. This means that only the background generates any motion signals. When the leading edge of the yellow bar is over a white stripe, it is low contrast; thus, its motion is determined mainly by the motion of the background, and the edge appears to move in the same direction of the background. When the leading edge is over a black stripe, it is high contrast; hence, its "no motion" signal dominates, thereby causing the edge to appear to stop. Whereas the leading edge was in competition with both the lateral edges and the background in Figure 2a, the leading edge is in cooperation with the lateral edges and is in competition only with the background in Figure 2d, which would explain why a reduced illusion is perceived (illusion strength = 7.7 ± 1.7).

In the stimulus of Figure 2e, when the leading edge has a low contrast, the lateral edges have a high contrast, which allows the lateral edges to dominate the motion percept and cause the leading edge to appear to stop. Conversely, when the leading edge is high contrast, the lateral edges are low contrast; thus, the motion signals of the leading edge dominate the percept, causing this edge to appear to move. Because there are no background edges, the illusion is reduced in magnitude in comparison to the standard FI (illusion strength = 6.2 ± 0.9).

In the stimulus of Figure 2f, the yellow bar is almost always completely surrounded by either black or white; hence, the leading, trailing, and lateral edges almost always have the same contrast. Consequently, the influence of the lateral edges relative to the leading and trailing edges is constant, with the result that the lateral edges do not contribute to the illusion. The illusion is caused only by the competition between the leading edges and the background edges, which would explain why only a weak illusion is observed (illusion strength = 6.0 ± 1.1).

In the stimulus of Figure 2g, there are no background stripes to contribute to the illusion. Furthermore, the contrast at the lateral edges is always equal to the contrast at the leading edge. Consequently, the competition between these two sets of edges does not generate any illusion. The very weak illusion observed (illusion strength = 2.5 ± 0.7) is caused by the effect of contrast on perceived speed, as noted in previous studies (Campbell & Maffei, 1981; Gegenfurtner & Hawken, 1996; Stone & Thompson, 1992; Thompson, 1976, 1982). Similar reasoning applies to Figure 2h, which would explain why this display produces a similarly weak illusion (illusion strength = 2.1 ± 0.7).

In the clearing-in-a-forest version of the FI (Stimulus 5a demo; Figure 5a), the contrast at the leading and trailing

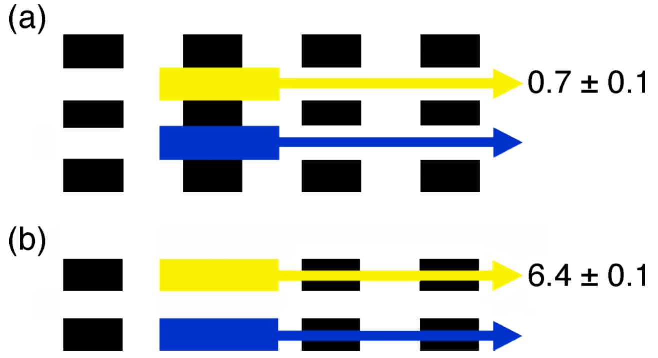

Figure 5. The other versions of the FI (Anstis, 2004). (a) The clearing-in-a-forest version and (b) the railroad track version.

edges does not vary. The average contrast of the lateral edges is also constant. Consequently, the weights associated with the leading edges, the lateral edges, and the background edges are constant, which is why the illusion is virtually abolished (illusion strength = 0.7 ± 0.1; Anstis, 2004).

In the "railroad track" version (Stimulus 5b demo; Figure 5b), the striped background has been reduced in size; thus, it has less of an influence on the perceived motion of the leading edges. This would explain why the illusion is somewhat reduced in comparison to the standard FI (6.4 ± 0.1; Anstis, 2004).

The belly dancer and Wenceslas illusions

Figure 6 shows a snapshot of the belly dancer illusion (Stimulus 6 demo) at one point in time. The illusion consists of a series of yellow bars that are aligned obliquely and move from left to right. Just as in the FI, when each yellow bar reaches a white stripe, it appears to slow down, and when it reaches a black stripe, it appears to speed up. Because the bars are staggered with respect to each other, the times at which the bars speed up and slow down are also staggered. The net effect is that the column of yellow bars appears to undulate as it traverses the striped background.

The static version of the belly dancer illusion is known as the Wenceslas illusion (Thompson & Anstis, 2005). The snapshot of the belly dancer illusion shown in Figure 6 is therefore an example of the Wenceslas illusion. What is especially interesting is that the undulations present in the belly dancer illusion occur even in the Wenceslas illusion. In other words, the undulation remains even when the bars do not move. This is readily explainable by our theory when it is realized that the same visual processing stream that handles motion perception is also responsible for position perception (Livingstone & Hubel, 1987). Just as our theory proposes that the background can affect the perceived speed of the yellow bar in the FI, our theory also proposes that the background can affect the perceived position of the yellow bars in the Wenceslas illusion. When the ends of the yellow bars in the Wenceslas illusion are over white stripes, their luminance contrast is low; hence, their position is influenced by the neighboring high-contrast edges of the background. Because these high-contrast edges are aligned vertically, the yellow bars also appear to be aligned vertically. Conversely, when the ends of the yellow bars are over black stripes, the luminance contrast of the ends are high; thus, the apparent positions of the ends are now less influenced by the high-contrast edges of the background. Consequently, in this case, the yellow bars are correctly perceived to be aligned obliquely. Because the yellow bars whose ends lie on black stripes appear to be aligned obliquely, whereas those yellow bars whose ends lie on white stripes appear to be aligned vertically, the net effect is that the column of yellow bars appears to undulate.

The finding that high-luminance-contrast edges can affect the perception of low-luminance-contrast, chromatically defined edges in the Wenceslas illusion is consistent with at least one previous study. Boynton (1982; cited in Goda & Ejima, 1997) showed that when a wavy, high-luminance-contrast contour was superimposed on a straight, low-luminance-contrast, chromatically defined edge, the chromatically defined edge appeared to be wavy.

The kickback illusion

In the course of our investigations, we generated another motion illusion that we call the kickback illusion. Figure 7a depicts the standard FI stimulus (Stimulus 7a demo). Figure 7b (Stimulus 7b demo) depicts

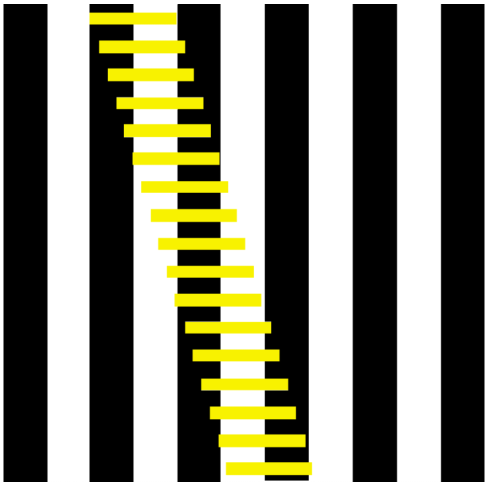

Figure 6. A snapshot of the belly dancer illusion. The yellow bars move from right to left across the striped background as in the standard FI.

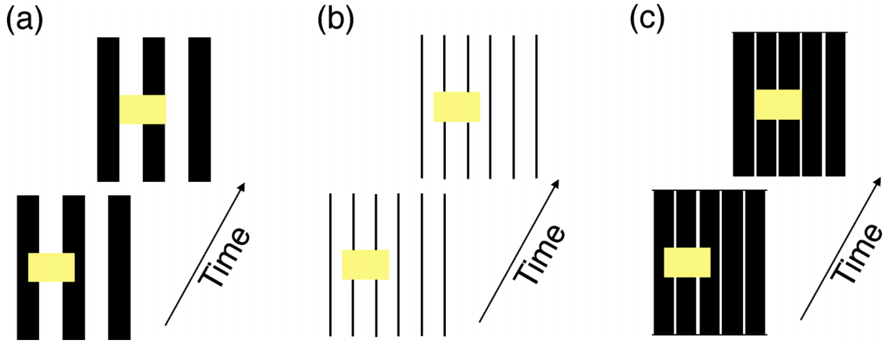

Figure 7. (a) The standard FI stimulus. (b) The kickback illusion stimulus. (c) A stimulus that does not generate a kickback effect.

the kickback stimulus in which a yellow bar moves across a white background on which a series of thin black lines have been placed. Figure 7c (Stimulus 7c demo) depicts a stimulus that was formed by inverting the luminance of the background of the Figure 7b stimulus.

When viewing Stimulus 7b, all subjects reported that when the yellow bar touched the black line, it appeared to jump backward. Most subjects reported the backward speed to be considerably greater than the forward speed. On average, the illusion of the irregular motion of the yellow bar was even stronger than in the standard FI, and was rated as 14.7 ± 1.8. For Stimulus 7c, in which the yellow bar moved across a black background with thin white stripes, the kickback effect was greatly reduced (illusion strength = 1.9 ± 0.8).

Because of their geometric similarity, one would expect the FI and the kickback illusion to be mediated by the same mechanisms. However, this is probably not the case. Figure 8a (Stimulus 8a demo) depicts a version of the kickback illusion where the moving bar is white and the background is yellow with black stripes. These color substitutions caused a dramatic change in the quality of the kickback illusion: The yellow bar appeared to kick forward when it touched a black stripe, which was the opposite of what happened in the yellow-bar, white-background version (Figure 7b). When we made the same color

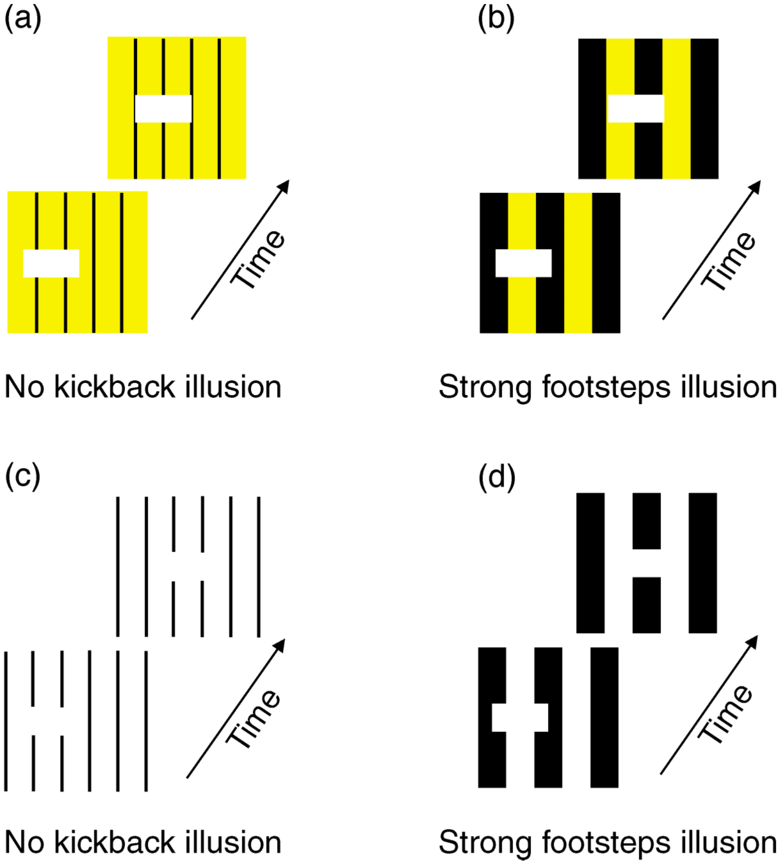

Figure 8. Variations of the kickback illusion and the FI.

substitutions in the conventional FI (Figure 8b; Stimulus 8b demo), a strong FI was still observed, with no qualitative difference between the yellow-bar, white-background and the white-bar, yellow-background versions. We also generated white-bar, white-background versions of both the kickback illusion (Figure 8c; Stimulus 8c demo) and the FI (Figure 8d; Stimulus 8d demo). For the white-bar, white-background version of the kickback illusion, no kickback effect was observed, but for the white-bar, white-background version of the FI, we saw a strong footsteps effect.

Because of the distinct differences in behavior between the kickback illusion and the FI under the above color substitutions, we have to propose a different explanation for the kickback illusion. Figure 9a shows a closeup of a yellow bar traversing a black line, as occurs in the kickback illusion. Just before the leading edge of the yellow bar reaches the black line, the edge has a dark–light contrast polarity. In the next time step, the leading edge touches the black line and the edge's luminance polarity reverses. In the following time step, the leading edge moves beyond the black line and its contrast polarity reverses again. Similarly, as shown in Figure 9b, the trailing edge also changes contrast polarity as it crosses the black line. In an apparent-motion stimulus, if an edge changes contrast as it is displaced, then it gives the appearance of moving in the opposite direction to the displacement, a phenomenon known as reverse phi (Anstis, 1970; Anstis & Rogers, 1975, 1986; Spillmann, Anstis, Kurtenbach, & Howard, 1997). We suggest that the "kick" part of the kickback illusion is an example of the reverse phi phenomenon.

At first glance, it would seem that analogous reasoning should apply to the stimulus depicted in Figure 7c. As the leading and trailing edges of the yellow bar traverse a white line, their contrast polarity inverts; thus, one would expect a kickback phenomenon. We suggest that this does not happen because the contrast between the leading and trailing edges and the background is always high, except for the brief instant when these edges traverse a white line; hence, strong forward motion signals are generated, which dominate the kickback signal. The result is a percept of almost completely smooth motion. Conversely, in the standard kickback illusion stimulus (Stimulus 7b demo; Figure 7b), the contrast between the leading and trailing edges of the yellow bar and the background is always low, except for the brief period when these edges traverse a black line; thus, the reverse phi signals generated as the edges traverse a black line have a relatively strong effect.

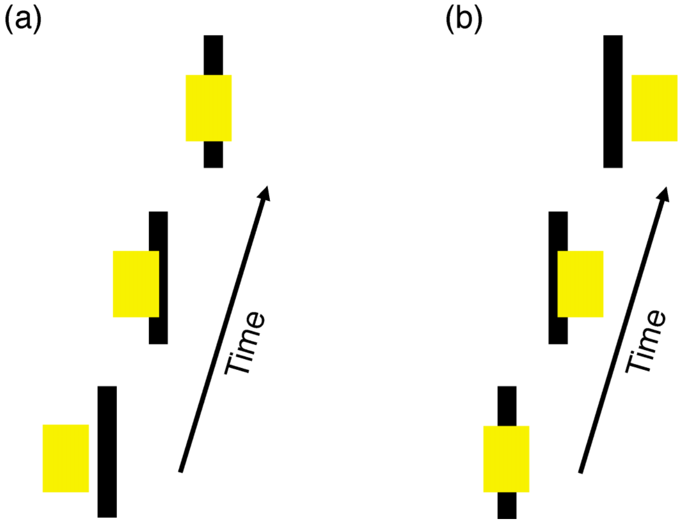

Figure 9. A blowup of the leading edge (a) and the trailing edge (b) of the yellow bar as they cross a black line in the kickback illusion.

We suggest that the stimulus of Figure 8a does not generate a kickback illusion because at no point does the contrast polarity of the leading edge of the white bar invert. Regardless of whether the leading edge touches a black line or not, the edge always has light–dark contrast polarity. Similarly, the trailing edge of the white bar always has dark–light contrast polarity; hence, neither edge generates any reverse phi motion signals. The dominant motion signals in this display are caused by the periodic occlusion of the black lines by the moving white bar. Every time this occurs, the bar appears to briefly jump forward.

The leading and trailing edges of the moving bar in Figure 8c have no contrast polarity; thus, reverse phi motion cannot occur. The only motion signals present in this stimulus are generated by the successive occlusion of the black lines.

Conclusion

The footsteps, belly dancer, Wenceslas, and kickback illusions are of interest because they demonstrate the dramatic effect the background can have on perception of both the speed and position of an object. The fact that the visual system cannot completely disassociate an object from its background in some conditions gives considerable insight into the mechanisms the visual system employs to determine an object's speed and position.

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