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The Bicycle Illusion: Sidewalk Science Informs the Integration of Motion and Shape Perception

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The authors describe a new visual illusion first discovered in a natural setting. A cyclist riding beside a pair of sagging chains that connect fence posts appears to move up and down with the chains. In this illusion, a static shape (the chains) affects the perception of a moving shape (the bicycle), and this influence involves assimilation (averaging) rather than opposition (differentiation). These features distinguish the illusion from illusions of motion capture and induced motion. The authors take this bicycle illusion into the laboratory and report 4 findings: Naïve viewers experience the illusion when discriminating horizontal from sinusoidal motion of a disc in the context of stationary curved lines; the illusion shifts from motion assimilation to motion opposition as the visual size of the display is increased; the assimilation and opposition illusions are dissociated by variations in luminance contrast of the stationary lines and the moving disc; and the illusion does not occur when simply comparing two stationary objects at different locations along the curved lines. The bicycle illusion provides a unique opportunity for studying the interactions between shape and motion perception.

Keywords: motion and shape perception, motion assimilation, visual illusion

It is satisfying when a serendipitous observation leads to new scientific understanding. Here, we report on a recently discovered and naturally occurring illusion that promises new insights on how motion and shape processing interact. The observation occurred while the scene depicted in Figure 1A was being viewed by one of us (Michael E. J. Masson) from a park bench. Pedestrians and cyclists were passing on both sides of the waterway. It was the peculiar behavior of the cyclists on the far side of the waterway that caught Michael E. J. Masson's notice; they could be seen passing behind a white fence consisting of two strands of chain strung between posts. Curiously, the cyclists seemed to bob upward as they reached a post and dip downward as they passed the sagging portion of the chains. A possible physical explanation for the bobbing was that the pathway rose and fell with each section of fence, but the path was perfectly smooth (see Figure 1B).

We concluded that the up-and-down motion was clearly an illusion of some kind, but that it did not correspond to any familiar illusion. We therefore set out to construct a simulation so that we could study it more closely. Our initial efforts to recreate the illusion with computer displays included a schematic cyclist moving horizontally alongside two stationary sagging lines, as shown in Figure 2A. This animation failed to produce the illusion seen in the natural setting. Instead of the cyclist moving in concert with the sagging fence rails, the animation yielded an illusion in which the apparent vertical component of the cyclist's motion was in opposition to the sagging lines, as shown in Figure 2C. We recognized that the cyclist moving in opposition to the contour of the rails was a possible variant of the well-known illusion of *induced motion* that occurs when the position of a rectangular frame is oscillated around a stationary dot at the center of the frame (Duncker, 1929; Gogel, 1979). At least the direction of the illusion was the same, in that the illusory component of motion in the cyclist served to contrast or exaggerate his or her position relative to the position of the stationary rails.

We also recognized, however, that the moving and stationary stimuli were playing different roles in this illusion. Whereas in classical induced motion, a moving frame imparts an illusory percept of motion to a stationary dot, in our initial animations (see Figure 2), the shape of the stationary sagging lines was imparting an illusory percept of vertical motion to a cyclist who was already moving horizontally. This meant the moving cyclist appeared to shift upward as he or she passed by the lowest part of the sagging rails and to move downward as he or she approached the apex of the rails. We will hereafter refer to this as an illusion of motion *opposition*.

Serendipity played another role in our first successful rendering of the original illusion on a computer screen. While a version of the animation was running in a continuous loop, we noted that the illusion of opposition occurred when we were close to the screen but that it reversed into an illusion of *assimilation* (see Figure 2B) when we viewed it from a distance. This observation made it clear

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Figure 1. View of the location of the original observation of the bicycle illusion (A) and a close-up of the smooth, paved trail on which cyclists were riding (B).

that the direction of the illusion depended critically on the size of the display on the eye (i.e., on the retinal visual angle), with the illusion of assimilation occurring only when the elements in the display were quite small. This was consistent with the viewing conditions under which the illusion was initially observed because Michael E. J. Masson had been watching the cyclists on the pathway from a considerable distance.

We next created a range of demonstrations using a simple disc rather than a rendering of a cyclist as the moving object (see Figure 3) to explore the boundaries and influences of various factors on these two illusions. These are illustrated by three demonstrations on our website: www.psych.ubc.ca/∼ennslab/research/research_index.html.

1. *Viewing size, not speed, governs the illusion*. The display shows four discs moving horizontally at different speeds past pairs of sinusoidal rails. For the two larger sets of rails (shown at the top) and for the two smaller sets of rails (shown at the bottom), one disc is moving at about three times the speed of the other. This difference means that during a fixed period of time, the slower disc in the smaller display is traveling past the same number of waves as the faster disc in the larger display. Yet, the illusion of opposition is seen in both larger displays, and the illusion of assimilation is seen in both smaller displays. Thus, under these large variations in speed, viewing size is the critical factor. Readers should also view this display from various distances to experience the reversal in the illusion that occurs with viewing size. When one is sufficiently far from the screen, even the large display will reveal the assimilation illusion.

2. *A blurred moving object enhances the illusion*. This demonstration examines the effects of the relative acuity of the two elements in the illusion. Three sizes of rails and discs are shown on each page to accommodate a large range of screens and viewing distances. The goal is to compare an illusion of assimilation with an illusion of opposition on each page. Viewers may need to adjust

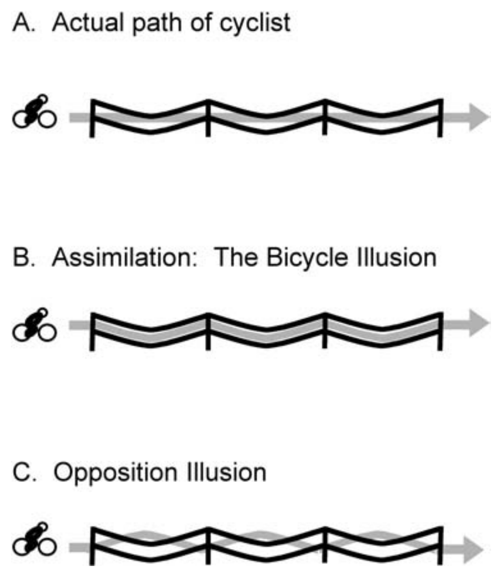

Figure 2. Schematic of actual and visually experienced paths followed by a cyclist riding behind curved rails.

their distance from the screen so that this is accomplished. The first page shows the disc and rails at equal levels of contrast with the background. When this page is viewed from a distance at which the smallest display yields a strong illusion of assimilation, note that the illusion in the medium-sized display is somewhat ambiguous and that the larger display reveals an illusion of opposition. In the next page, the discs are drawn with blurred edges. When viewed from the same distance, the middle display will now also tend to show an illusion of assimilation. And if you look slightly above (or below) the largest display, even it may show an illusion of assimilation. Thus, a moving object with less distinct edges yields a stronger illusion. Finally, the discs on the third page are drawn with greater contrast than the rails. Viewed at the same distance as the previous two, even the small display now shows only a weak illusion. These observations indicate that the illusion depends on the relative distinctness (contrast) of the edges of the discs versus the rails, with discs of a lower contrast resulting in the strongest illusion and rails of a higher contrast resulting in the weakest illusion.

We also noted that parafoveal viewing (with fixation above or below the rails) has two effects, depending on the contrast of the moving disc relative to that of the curved rails. When the contrast of the moving disc is equal to (Demo 2, p. 1) or less than (Demo 2, p. 2) that of the curved rails, viewing the illusion parafoveally increases the illusion. However, when the contrast of the moving disc is greater than that of the curved rails (Demo 2, page 3), parafoveal viewing decreases the illusion. We interpret this as indicating that parafoveal viewing is akin to viewing a display with reduced contrast (the edges become less distinct). If parafoveal viewing selectively reduces the edge of the moving disc (because disc contrast is already weaker), then the illusion is enhanced. If parafoveal viewing selectively reduces the edge of the rails (because the contrast of the rails is already reduced), then the illusion is reduced.

3. *Bicycle Illusion Demo (VSS 2006)*. The insights gained from these and other observations were presented at the annual Demonstration Night at the Vision Sciences Meetings (Dodd, Masson, & Enns, 2006) and can be viewed as the third demonstration on our website. They also formed the basis for the systematic experiments we report here.

Three working hypotheses guided our experiments. First, the bicycle illusion is an illusion of assimilation (also sometimes called averaging or integration), not an illusion of opposition (also sometimes called contrast or differentiation). Experiments 2 and 3 were conducted in an effort to confirm the hypothesis that the assimilation and opposition illusions are dissociable.

Second, the signals being assimilated (averaged) in the bicycle illusion are derived from two sources often considered to be processed in distinct cortical systems: the processing of stationary shape in the so-called parvocellular or ventral visual stream versus the processing of motion in the magnocellular or dorsal visual stream (Livingstone & Hubel, 1987; Ungerleider & Haxby, 1994; Van Essen & DeYoe, 1995). The implied direction of influence in the bicycle illusion—stationary shape influences perceived motion—distinguishes it from the *motion capture* illusion, in which a moving shape influences the perceived motion of another moving shape, and sometimes even a stationary shape (Braddick, 1993; Ido, Ohtani, & Ejima, 2000; Murakami & Shimojo, 1993; Nawrot & Sekuler, 1990).

Third, some spatial properties of the stationary rails are used erroneously by the visual system to determine the spatial position of the disc in motion. Our proposal is that the spatial position of the moving disc is represented with greater uncertainty than the spatial position of the stationary rails. There are a number of possible reasons for this reduction in certainty, including that the disc has very little contour in comparison with the rails, that contours of an object in motion are represented less faithfully than are those of a stationary object, and that, at the limits of acuity (viewing small elements), these differences in representation between the disc and the rails are likely even greater than in larger displays. In any case, the higher certainty contours of the rails are being used to deter-

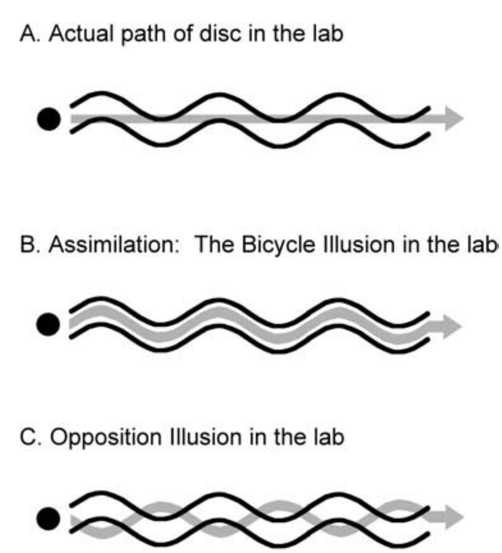

Figure 3. Schematic of actual and visually experienced paths followed by a disc moving behind a pair of curved rails in the displays used in the reported experiments.

mine the spatial position of the lower certainty contours of the moving disc. This account is qualitatively different from the one we propose for the opposition illusion that occurs in large displays, in which the rails are being used as a contrasting reference frame for the moving discs. Here, we think the illusion is simply another instance of the well-known motion induction phenomenon (Duncker, 1929).

In the remainder of this article, we report four psychophysical experiments intended to test these hypotheses. We conclude by discussing how the bicycle illusion offers a unique way of studying the integration of shape and motion perception.

Experiment 1: Measuring the Bicycle Illusion in the Laboratory

Observers were given the task of discriminating two discs that moved horizontally across the visual field at the same time and speed but that differed in how much they appeared to oscillate vertically (we refer to this vertical motion as *wiggle*). Discrimination occurred under three conditions: no rails (two solitary moving discs), straight rails (one solitary disc and one disc moving against a background of two horizontal lines separated by the diameter of the discs), and curved rails (one solitary disc and one disc moving against a background of two sinusoidal lines separated by the diameter of the discs). We varied the wiggle of each disc independently on each trial, giving observers the opportunity to compare the perceived wiggle of discs moving in different contexts while minimizing all memory demands. We used the no-rails condition as a standard for assessing wiggle sensitivity in the absence of any local spatial reference. The straight-rails condition served to test whether the presence of a pair of straight lines would also influence the perception of wiggle.

Method

Subjects. All subjects tested in all four of the experiments were undergraduate students from the University of British Columbia who received course credit for participation. All had normal or corrected-to-normal vision and were naïve about the purpose of the experiment. In Experiment 1, 10 subjects were randomly assigned to each of three conditions.

Apparatus, procedure, and design. The experiment was conducted on a Pentium 4 PC with a 36-cm VGA monitor (60 Hz) in a well-lit room. Subjects were seated 184 cm from the front of the computer monitor with a keyboard placed on their laps. Responses were made using the “z” and “/” keys on the keyboard (representing the top disc and the bottom disc, respectively).

Each trial began with a display of two small circular discs (yellow; 0 deg, 2 min, 34 s in diameter; 157.5 cd/m^2) on the left side of the screen, separated vertically by 1 deg, 45 min on a black background (6.5 cd/m^2). After 1 s, the discs simultaneously moved left to right across the screen, at a speed of 20 arcmin/s of time, before disappearing. During the next 4 s, subjects could indicate with a key press response whether the top or the bottom disc was wiggling more (i.e., had a larger vertical amplitude). Four sinusoidal wiggle amplitudes were randomly intermixed, traversing vertical distances of 0; 31 s; 1 min, 2 s; or 1 min, 33 s. We simply refer to these distances as wiggle amplitudes of 0, 1, 2, or 3, corresponding to the number of pixels of vertical shift in the displayed image that was involved in producing wiggle.

The task was difficult to do without fixating each of the discs directly, so subjects were instructed to look at each disc carefully before making a decision as to which was wiggling more. Subjects were asked to respond on every trial and to guess if they were unsure. If no response was made within 4 s following the offset of the display, the trial was classified as a no-response trial, and the next trial began. Otherwise the next trial began 500 ms following each response. Each subject was tested on 320 trials.

In the no-rails condition, only the two discs appeared on screen. The rails, when visible, were presented randomly in the path of the upper or lower disc and subtended 1 deg, 25 min of horizontal visual angle. In the straight-rails condition, one of the two discs moved behind a set of horizontal white rails (each rail was 30 s thick and separated vertically by 1 min, 33 s; 157.5 cd/m^2). The curved rails consisted of a sequence of eight sinusoidal waves (10 min per cycle) with an amplitude of 1 min, 2 s per wave (identical to a wiggle amplitude of 2), each rail subtending 1 deg, 21 min of horizontal visual angle (and separated vertically by 1 min, 33 s; 157.5 cd/m^2).

In the natural setting in which the bicycle illusion was first observed, the distance between fence posts was 24 min, 0 s, with the rails vertically separated by 9 min, 0 s. A typical bicycle was 34 min, 48 s in length, its wheels were 13 min, 48 s in diameter, and the distance between the wheels was 6 min, 36 s. Because the bicycle illusion depends critically on the size of the display, we began our experiments with display elements that were even smaller than their real-world counterparts. In subsequent experiments, the bicycle illusion is measured with slightly larger displays that approximate more closely the dimensions of the natural setting.

Results and Discussion

All statistical tests were based on a Type I error rate of .05. Preliminary analyses indicated that motion perception did not differ as a function of whether the rails appeared in the path of the upper or lower disc and so we averaged the data over this factor. Subjects failed to respond on 1.6% of all trials, and these trials were excluded from further consideration.

The percentage of trials on which subjects perceived more motion in the disc on the rails relative to the solitary disc is shown in Table 1. To examine the influence of the rails on motion perception most directly, we examined trials for which the wiggle amplitude was identical for both the on-rail and solitary discs. These data are shown in Figure 4, and they reveal three important findings. First, subjects in the no-rails condition perceived equal wiggle in the two discs at all four levels of objective wiggle (the upper or lower solitary disc was randomly chosen as the reference disc on each trial in this condition). Second, there was a strong influence of the curved rails on wiggle discrimination, as reports of more wiggle on rails was over 85% when there was no wiggle at all and over 80% when there was actually one unit of wiggle in both discs. When the wiggle in the discs exceeded the stationary curved rails (at a wiggle amplitude of 3), subjects reported that the disc on the rails wiggled less than the solitary disc. Third, there was a similar strong influence of the straight rails, but in the opposite direction. When equal wiggle amplitudes of 0 and 1 were present, subjects reported that the disc on the rails was wiggling less than the solitary disc, but by the time the wiggle amplitude

Table 1
Percentage of Trials in Experiment 1 on Which Subjects Perceived More Motion in the On-Rails Disc Relative to the Solitary Disc as a Function of Wiggle in Each Disc and Rail Type

Rail type and solitary-disc wiggle	On-rail disc wiggle			
	0	1	2	3
No rails[a]				
0	49.3	82.2	92.9	97.5
1	17.6	50.5	93.8	97.9
2	3.2	4.6	50.9	84.0
3	2.2	1.0	14.0	46.9
Straight rails				
0	21.7	67.6	97.4	99.4
1	7.2	32.9	93.4	98.0
2	2.7	3.6	50.5	87.4
3	4.1	1.6	21.8	65.1
Curved rails				
0	85.7	98.0	98.5	99.0
1	50.0	80.5	94.5	97.5
2	7.0	19.1	42.5	73.3
3	0.5	0.5	11.6	32.7

[a] On each trial in the no-rails condition, the upper or lower disc was randomly selected to be the reference disc.

increased to 3, the straight rails were serving to exaggerate the perception of wiggle in the moving disc.

These observations were confirmed with an analysis of variance (ANOVA). A significant main effect of rail type, $F(2, 27) = 4.32$, $MSE = 748.26$, and a significant interaction between rail type and wiggle amplitude, $F(6, 81) = 23.29$, $MSE = 225.22$, indicated that rail type had a strong influence on motion perception and that this influence changed over various wiggle amplitudes. This was examined in more detail with simple effects. There was a significant effect of rail type when wiggle amplitude was either 0, $F(2, 27) = 67.22$, $MSE = 153.56$, or 1, $F(2, 27) = 15.94$, $MSE = 363.77$, with on-rail discs in the curved-rail condition perceived as wiggling more than on-rail discs in the no-rails condition ($p < .05$), which were in turn perceived as wiggling more than on-rail discs in the straight-rails condition ($p < .05$). There was also an effect of rail type when wiggle level was 3, $F(2, 27) = 6.16$, $MSE = 427.16$, though in this case the ordering of the conditions was reversed.

We also noted that the curved stationary rails influenced motion perception even when the solitary disc was actually wiggling more than the on-rail disc. When the on-rail disc had a wiggle amplitude of 0 (only horizontal motion) and the solitary disc had a wiggle amplitude of 1, more wiggle was seen in the on-rail disc 50.0% of the time in the curved-rails condition relative to 17.6% of the time in the no-rails condition and only 7.2% of the time in the straight-rails condition (see Table 1). Moreover, when the on-rail disc moved with a wiggle level of 1 while the solitary disc moved with a wiggle level of 2, subjects perceived more motion in the on-rail disc 19.1% of the time in the curved-rails condition relative to 4.6% of the time in the no-rails condition and only 3.6% of the time in the straight-rails condition. These observations were supported by an ANOVA that examined these two wiggle conditions (0–1 and 1–2), which revealed significant main effects of wiggle, $F(1, 27) = 25.78$, $MSE = 146.44$, and rail type, $F(2, 27) = 18.96$, $MSE = 252.53$, along with a significant interaction, $F(2, 27) = 6.57$, $MSE = 146.44$.

These results confirm that small amounts of wiggle in a moving disc are assimilated to the rails, leading to greater perceived wiggle when the rails are curved and reduced apparent wiggle when the rails are straight. Once the amplitude of actual wiggle begins to exceed that of the amplitude of the curved rails (at a wiggle amplitude of 3), however, the rails exert an influence of a different sort. For curved rails, a large-amplitude wiggle is attenuated (which is still an assimilation of motion to the shape of the stationary rails), but for the straight rails, a large-amplitude wiggle is exaggerated, as though the straight rails are providing a stable reference point that helps to accentuate the motion of the disc in that context.

On the whole, these psychophysical data conform well to our informal observations of the bicycle illusion in a natural setting. There is an aspect of the illusion, however, that is not captured in the data from Experiment 1. A bicycle seen moving along the chain-link fence not only seems to be bobbing up and down, but it seems to do so in phase with the sagging chains. Strictly speaking, Experiment 1 shows only the extent to which the amplitude of the perceived wiggle is influenced by the context of rails. In Experiment 2, we measured whether the perceived wiggle was in or out of phase with the curved rails.

Experiment 2: Two Illusions or One?

The psychophysical task now required observers to discriminate whether a single horizontally moving disc was wiggling in phase or out of phase with the curved rails. We again varied the actual wiggle from an amplitude of 3 to an amplitude of −3. An amplitude of 2 meant that the disc was moving in perfect alignment with the curved rails. The full range of wiggle ranged from a disc moving with identical wavelength and phase to the curved rails but at an even greater amplitude (3), an equal amplitude (2), or a

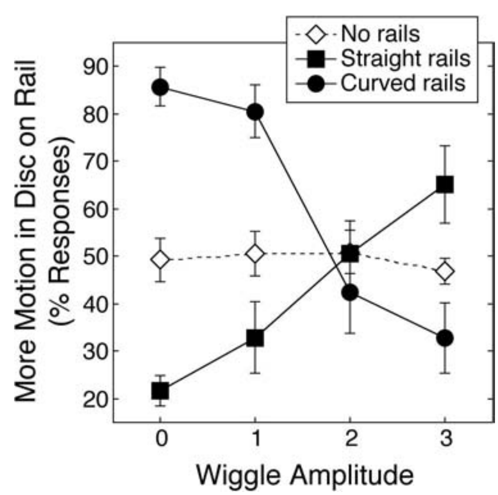

Figure 4. Percentage of trials on which more vertical motion was perceived in the on-rail disc when both the on-rail and solitary discs were moving with an identical wiggle amplitude in Experiment 1. In the no-rails condition, designation of the on-rail disc was arbitrary and varied randomly from trial to trial. Error bars indicate one standard error of the mean.

weaker amplitude (1) to that of a disc moving only horizontally (0 amplitude), and then to a disc moving out of phase with the curved rails at amplitudes of −1, −2, or −3.

A second factor was the size of the display. As described in the introduction, we had observed that the bicycle illusion was strongest when the bicycle was seen from a distance. Experiment 2, therefore, measured observers' ability to discriminate wiggle phase when they were viewing the display from a distant or a near vantage point.

Method

Subjects. Twenty subjects were tested, with 10 randomly assigned to each of the two display size conditions.

Apparatus, procedure, and design. The experiment was conducted using equipment similar to that used in Experiment 1. There were two experimental conditions: a small-display condition, in which subjects were seated 184 cm from the front of the computer monitor, and a large-display condition, in which subjects were seated 92 cm from the front of the monitor. In both conditions, subjects responded by way of a keyboard placed on their laps, and responses were made using the "z" and "/" keys on the keyboard (representing "in phase" and "out of phase," respectively).

At the beginning of each trial, a small circular disc (yellow; 4 min, 34 s in diameter in the small-display condition or 9 min, 8 s in diameter in the large-display condition; 157.5 cd/m^2) appeared along with a set of white "rails" of equal contrast (two continuous sinusoidal waveforms that repeated eight times). In the small-display condition, the rails had amplitudes of 2 min, 36 s per wave (identical to a wiggle level of 2), with each rail subtending a horizontal visual angle of 3 deg, 41 min and separated vertically by 3 min, 15 s. In the large-display condition, the rails had an amplitude of 5 min, 12 s per wave, with each rail subtending a horizontal angle of 7 deg, 22 min and separated vertically by 30 min.

The disc moved left to right in the path of the rails, and subjects were asked to indicate whether they perceived the disc as moving in phase or out of phase with the rails. The disc could either move in a straight line (at a wiggle amplitude of 0) or with a sinusoidal waveform that was out of phase (at a wiggle amplitude of −1, −2, or −3) or in phase (at a wiggle amplitude of 1, 2, or 3). For the small-display condition, these corresponded to wiggle amplitudes of 1 min, 18 s; 2 min, 36 s; or 3 min, 54 s, and in the large-display condition, they were 2 min, 36 s; 5 min, 12 s; or 7 min, 48 s.

Wiggle amplitude was selected randomly on each trial. At a speed of 28 arcmin per degree (small) and 54 arcmin per degree (large), it took 8 s for the disc to move from the left to the right across the screen before disappearing from view. Subjects were permitted to make a key press only after the display had disappeared. The next trial began 500 ms following each response.

Subjects were instructed to look directly at the disc before making a decision as to whether it was wiggling in phase or out of phase. Response instructions were the same as in Experiment 1. There were 280 trials.

Results and Discussion

The percentage of trials on which subjects perceived the disc as moving in phase with the rails as a function of wiggle amplitude and display size is shown in Figure 5. Wiggle amplitude ranged from −3 to 3, with 0 representing the disc moving in a straight horizontal line, positive numbers indicating when the disc was moving in phase with the rails, and negative numbers indicating when the disc was moving out of phase from the rails. Only 1.3% of all trials resulted in no response.

Inspection of Figure 5 reveals substantial differences in motion perception between large and small displays at a wiggle amplitude of 0. When the disc moved in a straight line in a small display, subjects perceived that disc as moving in phase with the rails 82% of the time. When the display was large, however, the disc was perceived as moving in phase with the rails only 26% of the time, meaning that as the visual angle increased, the illusion changed from an illusion of assimilation to an illusion of opposition. This difference was confirmed by an independent samples t test, $t(18) = 5.55$, $SED = 9.99$.

Analysis of all the data by an ANOVA revealed a main effect of wiggle amplitude, $F(6, 108) = 546.90$, $MSE = 80.40$, indicating that subjects were far more likely to perceive in-phase motion when the disc was moving in phase with the rails relative to when the disc was moving out of phase with the rails. The main effect of display type was also significant, $F(1, 18) = 30.23$, $MSE = 156.71$, indicating that subjects were more likely to perceive in-phase motion in the small than in the large display. Moreover, there was a significant interaction between wiggle amplitude and display type, $F(6, 108) = 26.98$, $MSE = 80.40$, reflecting the fact that the psychophysical functions diverged in the middle range of wiggle values.

Simple effects ANOVAs of the out-of-phase wiggle conditions (−1, −2, or −3) revealed main effects of wiggle amplitude, $F(2, 36) = 15.71$, $MSE = 27.19$, and display size, $F(1, 18) = 19.05$, $MSE = 76.93$, along with a significant interaction, $F(2, 36) =$

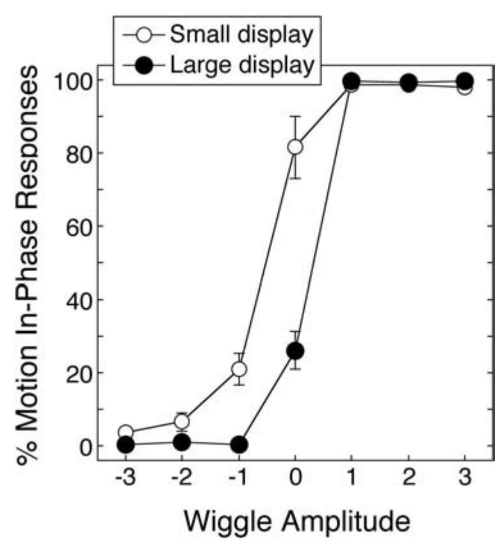

Figure 5. Percentage of trials on which the disc was perceived as moving in phase with the rails as a function of display size and wiggle amplitude of the disc in Experiment 2. Amplitude 0 indicates the disc was moving in a straight line, positive numbers indicate the disc was moving in phase with the rails, and negative numbers indicate the disc was moving out of phase with the rails. Error bars indicate one standard error of the mean; some bars are smaller than the symbols.

16.78, *MSE* = 27.19. Independent samples *t* tests confirmed that the difference in motion perception between the large and small displays was significant for all wiggle amplitudes in this range. This means that the curved rails in the small-display condition influenced motion perception in the direction of perceiving motion as in phase with the rails, even when the disc was actually moving out of phase with the rails.

More generally, these results show that the direction of the wiggle in the moving disc depends on the viewing size of the display. For small displays, the moving disc is seen wiggling in phase with the curved-rail context. For displays that were identical in every way except that they were larger, the moving disc appeared to wiggle out of phase with the curved rails.

Experiment 3: Dissociating Assimilation in Small Displays From Opposition in Large Displays

One way to establish that the assimilation illusion for small displays is truly different in kind from what is seen in large displays is to demonstrate that they are influenced differentially by the relative contrasts of the inducing (stationary curved rails) and test (moving disc) elements. Recall that our working hypothesis claims a perceptual confusion in the small displays between the shape of the stationary rails and the vertical component of motion in the disc. We therefore expected the confusion between disc and rail to be greater if the contours of the moving disc were less visible (making it more difficult to discern its signal from the rails or from the background), and we expected the confusion to be reduced if the relative visibility of the moving disc were increased (making it easier to detect its signal).

The same variation in relative contrast in the large displays, however, should have little or no effect, because our hypothesis for that illusion is that the relative distance between the clearly individuated large disc and the large curved rails is being falsely attributed to the vertical component of motion in the disc, causing its up-and-down motion to be exaggerated. Therefore, factors that are designed to change the relative visibility of the elements should have an influence on mechanisms of assimilation (averaging) but not on mechanisms of opposition (exaggeration). We repeated the procedure of Experiment 2, this time testing two different contrast conditions. In a dim-disc condition, we reduced the contrast of the disc by one half, and in a dim-rail condition, we reduced the contrast of the rails by one half.

Method

Subjects. Forty subjects were tested. Ten were randomly assigned to each of four conditions.

Apparatus, procedure, and design. The methods were identical to those used in Experiment 2, with the exception that for half of all subjects, the disc appeared in a reduced contrast gray (78.5 cd/m^2) relative to the white rails (157.5 cd/m^2). For the other half of the subjects, the rails appeared in a reduced contrast gray (78.5 cd/m^2) relative to the white disc (157.5 cd/m^2). Thus, there were four conditions formed from the factorial combination of display size and relative contrast.

Results and Discussion

Subjects failed to respond on less than 0.9% of all trials. The percentage of trials on which subjects perceived the disc as moving in phase with the rails is shown in Figure 6, which includes the data from Experiment 2 (disc and rails of equal contrast) for comparison purposes.

Figure 6 shows that an illusion of assimilation was again observed with small displays: For both dim-disc and dim-rail conditions, in-phase motion was the most frequently reported perception in the condition with a wiggle amplitude of 0 (over 70%). In addition, motion perception was affected by the relative contrast of the disc and the rails, particularly when the disc was moving straight or out of phase from the rails.

An ANOVA revealed a main effect of wiggle amplitude, $F(6, 108) = 265.13$, $MSE = 142.38$, indicating that subjects were far more likely to perceive in-phase motion when the disc was moving in phase with the rails relative to when the disc was moving out of phase with the rails. Moreover, there was a significant interaction between wiggle amplitude and relative contrast, $F(6, 108) = 5.89$, $MSE = 142.38$, indicating that the effect of relative contrast varied across the wiggle conditions. Simple effects *t* tests at each of the wiggle conditions revealed a significantly greater perception of in-phase motion in the dim-disc than in the dim-rail condition at wiggle values of 0, $t(18) = 2.63$, $SED = 8.28$, and -1, $t(18) = 3.34$, $SED = 10.17$, but not at wiggle values of -2 or -3 ($ts < 1.4$).

Figure 6 also shows that with large displays there was again an illusion of opposition, with motion typically perceived as being out of phase with the curved rails at a wiggle amplitude of 0 (less than 30% in-phase responses). Unlike for the small displays, however, there was no effect of contrast variations in the disc and the rails. An ANOVA revealed only a main effect of wiggle amplitude, $F(6, 108) = 670.45$, $MSE = 74.34$. A *t* test for the effect of relative contrast conducted on data from the condition with a wiggle amplitude of 0—the only wiggle value in which performance was not at floor or ceiling in the large-display condition—found no

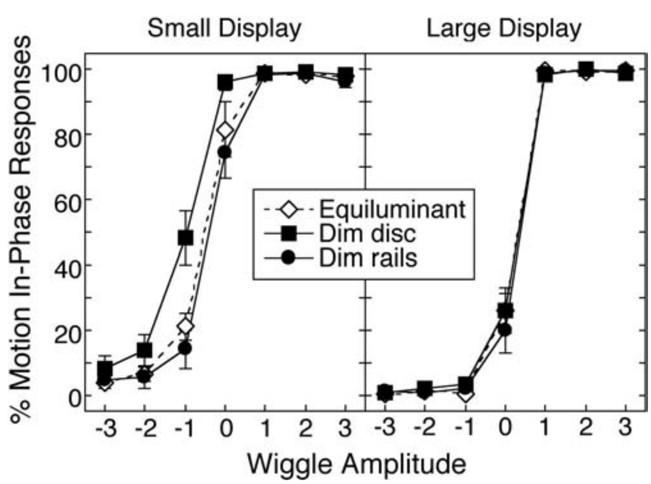

Figure 6. Percentage of trials in the small- and large-display conditions in which the disc was perceived as moving in phase with the rails as a function of display size and wiggle amplitude of the disc in Experiment 3. Amplitude 0 indicates the disc was moving in a straight line, positive numbers indicates the disc was moving in phase with the rails, and negative numbers indicate the disc was moving out of phase with the rails. Data in the equal contrast condition are from Experiment 2. Error bars indicate one standard error of the mean; some bars are smaller than the symbols.

effect ($t < 1$), despite having power of over .85 to detect an effect of the magnitude seen in the small-display condition at a wiggle amplitude of -1 (in which performance was also not at floor or ceiling).

The results of Experiment 3 support the hypothesis that the assimilation effect seen in the bicycle illusion is dissociable from the well-known opposition illusion of induced motion. Varying the relative contrast of the disc and the rails had a strong influence on the assimilation illusion in small displays, such that reducing the relative signal strength of the disc increased the illusion and reducing the relative strength of the inducing stationary rails reduced the illusion. These same factors had no measurable influence on the opposition illusion produced by large displays. If anything, the opposition illusion responded to relative contrast in the opposite way to the bicycle illusion; namely, the opposition illusion was slightly stronger when the disc had higher contrast than the rails.

Readers should also note that a reduction in the relative contrast of the disc had the same effect of increased blur that we noted in Demonstration 2 on our website (www.psych.ubc.ca/~ennslab/research/research_index.html) and that both of these effects are similar to that seen for parafoveal viewing. That is, parafoveal viewing is akin to viewing a display with reduced contrast. Thus, when parafoveal viewing reduces the edge contrast of the moving disc even further, the illusion is enhanced. Conversely, if parafoveal viewing selectively reduces the contrast of the rails (as it can when the rails are relatively weak to begin with), the illusion is reduced.

This interpretation is also supported by our informal observations of the illusion when the moving disc and the rails are displayed in opposite contrast polarity (white disc with black rails on a gray background). This sharply reduces the illusion of assimilation in the small display, whereas the illusion of opposition in the large display is unaffected. This is an important point because it is consistent with a reduction in confusion about the position of the disc's edge relative to the rails, just as confusion is reduced when the disc is depicted with greater absolute contrast relative to the rails. It is not the overall contrast level that is important, but rather the ability of the visual system to determine that the disc's edges are unique.

Experiment 4: Just Another Tilt Illusion?

One alternative account that should be considered before engaging in a broader discussion is the possibility that motion is not a critical ingredient. Perhaps two cyclists of equal height, one standing in the center of the sagging rails and one standing by a post, would also appear to be different in height. If so, then the illusion should be considered an instance of the large family of *tilt illusions*. These include the Ponzo illusion (Gregory, 1970), the rod-and-frame illusion (Asch & Witkin, 1948), the simultaneous tilt illusion (Dyde & Milner, 2002), and the distortions of angles and sizes seen in mystery cabins (Shimumura & Prinzmetal, 1999) and gravity hills (Bressan, Garlaschelli, & Barracano, 2003). In a study using displays of obliquely oriented lines, Swanston (1984) reported a version of the tilt illusion that involved moving a dot over the lines. The dot seemed to make the largest illusory vertical "blip" when it crossed lines that were tilted upward about 12 deg away from the horizontal.

In brief, tilt illusions occur when background edges in a scene are mistaken for the horizon (or for the gravitationally defined vertical), whereas they are in reality tilted away from these references. Smaller edges that are viewed in these contexts tend to be judged with reference to these assumed visual landmarks, and so a truly flat bar seen against a background of slightly tilted background contours will appear to tilt in a direction opposite to background contours. Tilt illusions are, therefore, illusions of opposition, in which the relative angle between two display contours (the inducing background and the smaller test edges) is mistaken for the absolute angle between the test edge and gravity-defined horizontal or vertical.

The immediate problem of trying to understand the bicycle illusion as an instance of this class is that tilt illusions always seem to involve mechanisms of opposition. Perhaps no one has ever tested a very small version of the tilt illusion, or viewed the existing displays from a great distance, to see whether the tilt illusion reverses. In Experiment 4, we did this, testing a range of conditions intended to bridge the bicycle and the simultaneous tilt illusion, as shown in Figure 7. In addition to varying display size (small, large), we tested the perceived tilt of a pair of discs (a) in a curved-rails condition that was analogous to the conditions we tested using a single moving disc in Experiments 2 and 3, (b) in a curved-texture condition that involved a larger background of the

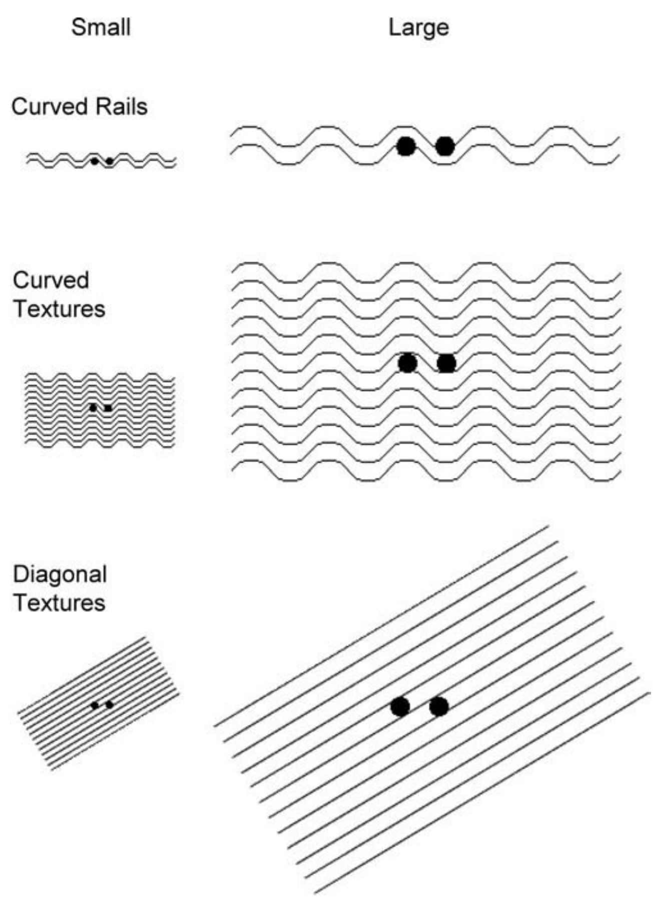

Figure 7. Displays used in Experiment 4 to test for a stationary tilt illusion.

same curved lines, and (c) in a diagonal-texture condition that was intended to replicate a strong stationary tilt illusion (Shimumura & Prinzmetal, 1999).

Subjects discriminated the direction in which the pair of discs was tilted ("Which side is lower?"). Discs were placed to coincide with the peak and trough in the curved rails to maximize any illusion that might be present. The actual tilt of the discs varied from 3 pixels higher on the left to 3 pixels higher on the right, in 1-pixel steps. The critical condition for the measurement of an illusion was at 0 tilt, where the discs were perfectly horizontal.

If the bicycle illusion is just another tilt illusion, there are two critical predictions. First, the opposition illusion found with relatively large displays should reverse and become an illusion of assimilation when they are reduced in size. This outcome would help explain why the bicycle illusion reversed in direction with viewing distance. Second, the static tilt illusion assessed in the small curved-rails condition (see Figure 7) should be similar in magnitude to the assimilation illusion measured for the moving disc in the small displays in Experiments 1–3. If this is the case, then the reference confusion that we believe to be the basis of the bicycle illusion could be ascribed to the geometric differences between the discs and the rails. There would be no need to propose an interaction between shape and motion processing in understanding the illusion.

Method

Subjects. Forty subjects were tested, with 10 subjects assigned to each of four groups: (a) the small curved-rails (with small straight rails as a comparison) group, (b) the large curved-rails (with large straight rails as a comparison) group, (c) the small curved-texture and small diagonal-texture (with small straight-texture as a comparison) group, and (d) the large curved-texture and diagonal-texture (with large straight-texture as a comparison) group. For each group, there were 280 trials in each display condition (560 trials for the first two groups and 840 trials for the second two groups).

Apparatus, procedure, and design. The experiment was controlled by an eMac with a 43-cm VGA monitor (89 Hz). There were six display conditions, involving the factorial combination of display size (small, large) and stationary background lines (curved rails, curved textures, and oblique textures). In all conditions, subjects responded by depressing the "z" key if the left disc appeared lower than the right or the "/" keys if the right disc appeared lower.

On each trial, two black discs (4 min, 34 s in diameter in the small-display condition and 9 min, 8 s in diameter in the large-display condition; 6.5 cd/m^2), separated horizontally by a distance equal to one half the wavelength of the curved lines, appeared against a background of black lines on a white background (157.5 cd/m^2). In the curved-rails condition, these lines consisted of a pair of sinusoidal lines separated by 3 min, 15 s in the small-display condition and by 6 min, 30 s in the large-display condition. The small rails were 3 deg, 41 min in horizontal extent and separated vertically from one another by 3 min, 15 s (the sinusoidal rails had amplitudes of 2 min, 36 s per wave). The large rails were 7 deg, 22 min in horizontal extent and separated vertically from one another by 6 min, 30 s (the sinusoidal rails had amplitudes of 5 min, 12 s per wave). The discs were separated horizontally so that one was aligned vertically with the peak in the wave and the other was aligned vertically with the trough.

The comparison stimuli for the curved rails consisted of a pair of equally long, horizontal, straight lines, also separated by 3 min, 15 s in the small-display condition and by 6 min, 30 s in the large-display condition. The horizontal separation of the discs in the straight-rails condition was identical to that in the curved-rails condition. The tilt judgments subjects made in this condition were used as the reference for the tilt judgments made in the curved condition, so that we could estimate a total illusion magnitude for each subject, just as we had done in Experiment 1.

The curved-texture condition consisted of the same sinusoidal lines as in the curved-rails condition, except that five more of these lines were added above the rails containing the discs and five were added below them (see Figure 7). The diagonal-texture condition consisted of the same number of lines, but these lines were straight and oriented at a 25 deg angle with respect to horizontal. Randomly, this orientation was to the right or the left from trial to trial. This orientation was chosen because it has been reported to result in the largest tilt illusion (Shimumura & Prinzmetal, 1999). The comparison stimuli for both of these conditions consisted of a texture of 12 horizontal straight lines, also separated by the diameter of the discs.

The discs in all of these conditions were presented in one of seven relations that differed in the vertical displacement of one dot away from the horizontal. We refer to these relative disc positions as *tilt*. On a random one half of trials, the left disc remained vertically centered in the space between two rails, and the position of the right disc was varied in one of three steps (tilt = 1, 2, or 3). On the other half of trials, the right disc remained centered between two rails, and the position of the left disc was varied in the same way. When tilt = 0, the discs were horizontally aligned, with both discs vertically centered between two rails. Tilts 1–3 corresponded to vertical displacements of 1 min, 18 s; 2 min, 36 s; or 3 min, 54 s in the small condition and of 2 min, 36 s; 5 min, 12 s; or 7 min, 48 s in the large condition.

Results and Discussion

Subjects failed to respond on less than 0.3% of trials in any condition. For simplicity, our analyses examined the direction and magnitude of the illusion when the disc pair was horizontally aligned (tilt = 0) in the display. Other tilt conditions (tilt = 1, 2, or 3) were treated as filler trials in which differences in vertical placement would be detected by subjects with varying degrees of ease. Judgments in the tilt = 0 displays were used to compute the direction and size of the tilt illusion by comparing a critical condition (e.g., curved rails) with its comparison condition (e.g., straight rails). The direction of the illusion was determined by whether subjects responded that the disc aligned with the trough in the curved conditions (or the lower portion of the diagonal textures) was the lower of the two discs, which corresponded to an illusion of assimilation, or instead responded that the disc aligned with the peak in the curved conditions (or on the uphill side of the diagonal textures) was the lower disc, which corresponded to an illusion of opposition. Illusion magnitude was estimated for each subject by taking the percentage of trials on which he or she classified the disc at the peak (or the disc on the uphill side) as the lower disc and subtracting the percentage of trials on which he or she reported the corresponding (i.e., left or right) disc in the straight comparison display as the lower disc. A positive score therefore reflected an illusion of opposition, a score of 0 meant no illusion, and a negative score was an illusion of assimilation.

The mean illusion score for each of the display conditions is shown in Table 2. Only an illusion of opposition was found, with the largest illusion observed for the large diagonal texture, consistent with previous research on the simultaneous tilt illusion (Dyde & Milner, 2002; Shimumura & Prinzmetal, 1999). There was a slightly smaller illusion of opposition in the curved-textures condition and a considerably smaller one in the curved-rails condition. This opposition illusion was reduced in each case in the smaller displays, but even these displays failed to yield an illusion of assimilation.

An overall ANOVA conservatively treated the two size and three background conditions as between-subject factors. It revealed a significant main effect of condition, $F(2, 54) = 16.42$, $MSE = .030$. Simple effects indicated that the opposition illusion was larger for both the diagonal texture and the curved texture than for curved rails, but that the difference between the diagonal and curved texture was not significant. There was also a main effect of display size, $F(1, 54) = 5.71$, $MSE = .030$, reflecting the larger opposition illusion on the large displays, and this effect did not interact with condition, $F < 1$. The differences between each of the background conditions were significant when considered individually: Diagonal textures versus curved textures were tested with a repeated measures comparison, $F(1, 18) = 8.07$, $MSE = .009$, and curved textures versus curved rails with a between-subjects comparison, $F(1, 36) = 12.47$, $MSE = .038$.

In the curved-rails condition, which approximated most closely the conditions of the bicycle illusion, the tendency toward an opposition illusion was not significant for either display size, although an illusion in the direction of opposition was experienced by 7 of the 10 subjects shown small displays and by 8 of 10 subjects shown large displays. Statistical power to detect an illusion of 30% (the approximate assimilation illusion magnitude measured in Experiments 1 and 2) in the small curved-rails condition was greater than .95.

The results of Experiment 4 did not support the hypothesis that the bicycle illusion is another tilt illusion. First, although the illusion in the tilted-texture condition was one of opposition, replicating the well-known effect, this illusion did not reverse when the same displays were reduced in size. Second, when only a pair of curved lines was used in the background, to resemble the small-display conditions in our motion experiments, there was no measurable illusion at all. Taken together, the data here suggest that the tilt illusion is robust as an illusion of opposition in both small and large displays. Furthermore, it is weakened or eliminated when only a pair of lines is used rather than a texture. The bicycle illusion cannot be understood as merely a moving version of a stationary tilt illusion.

Table 2
Mean Percentage of Trials (and Standard Errors) on which Subjects Reported an Illusion of Opposition (Positive Numbers) or Assimilation (Negative Numbers) in Experiment 4 When the Disc Pairs Were Horizontal (Tilt = 0)

	Display size	
Variable	Small	Large
Curved rails	+3.4 (6.0)	+16.7 (8.6)
Curved textures	+25.6 (5.3)	+38.2 (3.8)
Diagonal textures	+37.5 (4.1)	+43.8 (10.8)

General Discussion

Our purpose in this article was first to describe a visual illusion discovered in a natural setting. In the bicycle illusion, a cyclist viewed from a distance, riding beside a fence consisting of two strands of chain strung between posts, is seen not only as moving forward, but also as bobbing up and down in phase with the contour of the chains. Second, we wished to document with psychophysical procedures that this illusion provides an opportunity for understanding the way human vision integrates information from multiple sources, in this case information from a stationary shape (the fence) and the spatial position of an object in motion (the cyclist).

Our experiments revealed that the elements for the bicycle illusion are actually capable of generating two illusions, with the type of illusion depending critically on viewing distance (or, equivalently, the size of the viewing angle). With a small display, a moving disc appears to bob up and down in phase with curved background lines, creating an illusion of assimilation. With a large version of the same display, the disc moves in opposition to the shape of the stationary curves, producing an illusion of opposition. These two illusions are influenced in different ways by variation in relative contrasts of the moving disc and the stationary curves. For the illusion of assimilation, reducing the quality of spatial information from the disc increased the magnitude of the illusion, whereas increasing the quality of that information reduced illusion magnitude. These results are consistent with our proposal that the illusion of assimilation involves confusion about the spatial position of the disc.

Finally, we tested a stationary version of the bicycle illusion to determine whether it could be understood as a variant of the larger family of tilt illusions. Our various attempts to instantiate the bicycle illusion in a stationary display resulted only in illusions of opposition.

Relation to Other Illusions

Taken together, these data imply that the bicycle illusion originally seen in a natural setting is distinct from previously described illusions of motion. Here, we briefly summarize research on several of these illusions, both to highlight their possible links to the bicycle illusion and to help direct attention to the unique window on visual processes provided by the bicycle illusion.

One family of illusions that resembles the bicycle illusion is referred to as *motion integration*. In a typical task used to study this illusion, a central stationary grating, small disc, or sprinkle of random dots is surrounded by another set of gratings, a larger disc, or a larger sprinkle of random dots. When the surrounding stimulus moves, the central stationary stimulus sometimes also appears to move, either by motion opposition (also called induced motion), in which the central stimulus appears to move in the direction opposite to the surrounding stimulus, or by motion capture (also called motion assimilation), in which the central stimulus appears to move in the same direction as the inducing stimulus.

Research on these two illusions of motion indicates that viewing size is a critical factor in determining which one occurs, with motion capture more likely for smaller central stimuli and motion opposition increasing in likelihood as the size is increased (Murakami & Shimojo, 1993; Nawrot & Sekuler, 1990). The factors of spatial frequency and luminance contrast also tend to differentiate these two illusions, with motion capture more likely to occur with surrounding stimuli of a lower frequency and central stimuli of a lower contrast (Ido et al., 1997, 2000), especially when they can be perceptually grouped with one another (Mussap & Prins, 2002). Motion opposition is more likely to occur with central and surrounding stimuli of similar frequencies that are perceptually distinct (Murakami & Shimojo, 1996). The theoretical interpretation usually involves a two-stage model, with local motion detectors early in the system (e.g., area V1) simply averaging their responses within a small local region (e.g., a receptive field) and more global motion detectors later in the system (e.g., human area MT or monkey area V5) either integrating these local signals on the basis of other analyses and supporting a perceptual grouping interpretation (i.e., leading to motion assimilation or capture) or differentiating these local signals on the basis of an interpretation of perceptual segmentation (i.e., leading to motion opposition or contrast; Braddick, 1993).

The bicycle illusion is also size and luminance contrast dependent, and as such, seems to have much in common with motion integration. The most notable difference, however, is that the inducing stimulus in the bicycle illusion is entirely stationary. This fact implies that the analysis of motion is being influenced at a relatively early stage by an analysis of the stationary shape of the background in which the motion of the test stimulus (the bicycle) is occurring. This makes the bicycle illusion distinct from other known illusions of motion integration and raises the interesting theoretical possibility that the bicycle illusion is a preparation for studying the interaction between shape perception (considered to be a ventral stream or parvocellular function) and motion perception (considered to be a dorsal stream or magnocellular function).

A family of illusions closely related to motion integration, and one that seems to involve the influence of stationary shape on motion perception, is that of "motion streaks" (Burr & Ross, 2002; Geisler, 1999). These are neural signals generated by the visual system in response to a moving edge (Geisler, Albrecht, Crane, & Stern, 2001; Krekelberg, Dannenberg, Hoffmann, Bremmer, & Ross, 2003), and they correspond roughly to the "speedlines" used by cartoonists to depict and convey motion in stationary pictures (Burr, 2000; Kim & Francis, 1998). Research has shown these neural signals can be used to perceptually organize visual patterns even when there is no objective motion signal in a display (Edwards & Crane, 2007; Ross, Badcock, & Hayes, 2000). Their existence has been interpreted both as support for a channel interaction framework involving cross-talk between the dorsal and the ventral stream (Ross et al., 2000) and as support for two independent signals for motion registered by cortical neurons in the earliest stages of processing (Burr, 2000).

To the extent that motion streaks can be considered a contribution of "shape" to the perceived direction of motion, they are similar in their effect to the bicycle illusion. The perceived direction of motion is assimilated to the orientation of the motion streaks. We note, however, that motion streaks are a shape generated internally by the brain, not one that exists in the physical stimulation. The fence rails in the bicycle illusion act more like the physical speedlines used in cartoons than like the motion streaks purported to be generated internally (Kim & Francis, 1998). Also, it is critical that speedlines have not been reported to reverse their direction of effect, like the bicycle illusion does, as the viewing angle is increased.

A third class of illusion that seems relevant is the barber pole illusion, originally described by Hans Wallach (see Wuerger, Shapley, & Rubin, 1996). Here, a set of oblique stripes moving vertically (either up or down) inside an elongated frame appears to be moving orthogonally to the oblique edge, giving the appearance of a twirling, three-dimensional cylinder. The standard interpretation of this illusion is illustrated in Figure 8. Local motion-detecting mechanisms in the visual system are sensitive to only a small portion of the entire visual field, illustrated by the circular white window in the figure. The direction of any moving edge inside this window is inherently ambiguous. For instance, the bar in the window in Figure 8 could be moving downward, toward the right, or at an angle orthogonal to the moving edge. This is known as the *aperture problem*. Motion detecting mechanisms have a strong bias under such circumstances to signal the motion in the direction orthogonal to the edge. Only if this edge is perceptually grouped with another edge that is moving in the same direction, elsewhere in the visual field, is the bias for motion orthogonal to the edge overcome. Thus, we see the factors of perceptual grouping at work in this illusion in much the same way we described in the illusions of motion integration.

A natural way to think of the bicycle illusion in this context is that the wheels of the bicycle are being viewed through the "aperture" of the sagging chain rails. As such, the leading edge of the wheel may appear to be oriented with a negative slant in the upward-going portion of the rails and then oriented with a positive slant in the downward-going portion of the rails, as illustrated in Figure 9. This explanation alone cannot account for the bicycle illusion, however, because it would predict the same illusion for small and large displays, namely, an illusion of assimilation. The

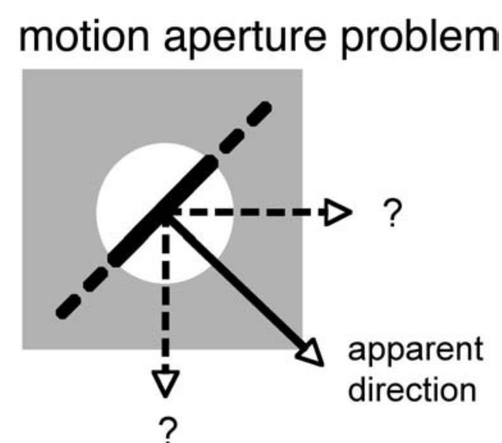

Figure 8. Illustration of the motion aperture problem. The direction of movement of an edge inside an aperture, representing the information available to a local motion detection region in visual cortex, is ambiguous.

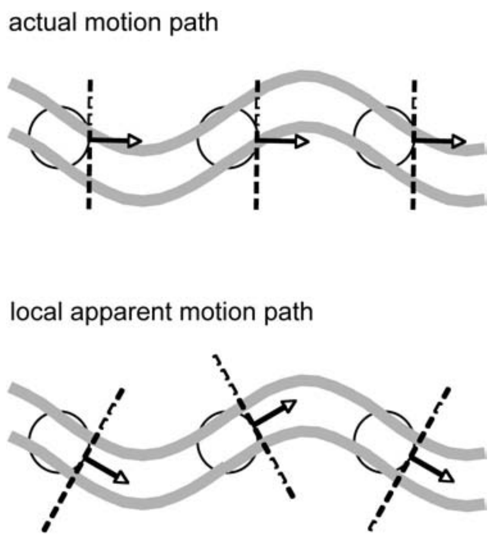

Figure 9. Application of the aperture problem to the bicycle illusion. Movement of the leading edge of the wheel is slanted and perception of motion is biased to be orthogonal to the leading edge.

fact that the bicycle illusion is specific to small displays (or distant viewing) means that an additional factor must be brought to bear in a complete account.

A fourth class of motion illusion of possible relevance is the so-called *stepping feet* illusion. In brief, the apparent speed of a moving object depends on the difference in relative luminance contrast between its own surfaces and those of the background on which it is moving (Thompson, 1982). Specifically, an object moving at a constant velocity will appear to speed up when moving against a background that differs sharply in luminance and to slow down when the luminance of the background is more similar. This means that a dark gray shape moving over a series of black and white stripes will appear to slow down every time a black edge is encountered and to speed up when a white edge is crossed. If a pair of shapes, one dark gray and the other light gray, is moved in tandem over the same stripes, the dark gray shape will appear to slow down at the same time that the light gray shape appears to speed up, giving the appearance of "footsteps" rather than simultaneous motion of the two shapes (Anstis, 2001, 2003, 2004).

The influence of luminance contrast on the perceived speed of motion becomes especially relevant to the bicycle illusion when the bicycle (or disc) and the rails are similar to one another in their luminance relations, as they usually were in our experiments. As such, the motion signal coming from the regions of the display where the disc and the rails intersect may be considerably weaker than the signal coming from the leading edge of the moving disc that is seen between the rails and that forms a strong contrast with the background. This difference could have the effect of reducing the coherence of the motion signals coming from various local mechanisms associated with the disc, leaving open the possibility that other factors, including the stationary shapes, could have an influence on how these local signals are combined.

Possible Mechanisms

This brief survey of related illusions suggests that the bicycle illusion may involve a combination of mechanisms, including those involved in motion integration (combining local motion signals through perceptual grouping), the aperture problem (motion direction determined by the orientation of local edges), and the stepping feet illusion (motion speed determined by luminance contrast). Figure 10 illustrates how these three factors can combine in a very simple way to produce the bicycle illusion. The oriented edge in the upper part of Figure 10 has a graded luminance contrast that reaches its peak in the middle of the bar and tapers off at either end. This has the effect of providing the visual system with a graded set of local signals with regard to the speed of the moving edge. The perceptual consequence of moving such an edge horizontally across the visual field is that it appears also to be moving obliquely downward, in keeping with the bias of the local motion mechanisms at the center where the signal is strongest (Anstis, 2003). Note that as soon as the same bar has equal luminance contrast across its edges, as illustrated in the lower part of Figure 10, its actual motion can again be interpreted correctly, because now local motion detectors can be integrated over a larger region of the visual field to provide a consistent signal. Anstis (2003) aptly referred to the illusion in Figure 10 as an aperture problem "without an aperture" (p. 935).

The bicycle illusion observed in our small displays can be interpreted as another version of this problem, as illustrated in Figure 9. Instead of the weak signals at the edges of the disc deriving from the reduced edge contrast relative to the background, these signals are weaker for the disc because its edge contrast is similar to that of the rails. As such, the strongest local motion signals are coming from between the rails, and so the edge will appear to move along the direction given by the sagging rails, rather than only horizontally, as they are actually moving.

The one remaining question is why these same principles do not apply to the larger displays in which the illusion becomes one of opposition. We propose that opposition is experienced because at

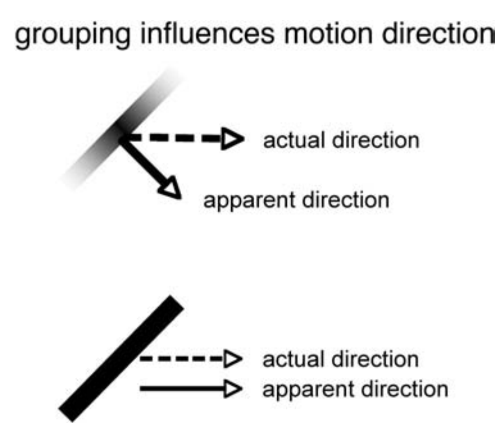

Figure 10. Grouping influences perception of the direction of motion. The edge with graded luminance provides graded local signals regarding speed, leading to apparent movement orthogonal to the highest contrast region of the edge. Movement of an edge with uniform luminance is interpreted correctly because local motion detectors can be integrated over a larger region of the visual field.

larger viewing angles, the contours of the disc and the contours of the rails are more readily differentiated due to the increased acuity that comes with their larger size. Viewing the small displays has the effect of minimizing the subtle differences between the edges of the disc and the edges of the rails. The fact that the edges of the disc are in motion reduces their acuity even further (Long & May, 1992), helping to tilt the interpretation in favor of the local motion direction signaled most strongly from between the curved rails. As the elements of the display are enlarged and the individual contours are represented with greater fidelity, the confusion arising from the neighboring edges of the disc and rails is also reduced, permitting global grouping mechanisms of the kind involved in motion integration to link the motion signals emanating from the contours of the disc above, below, and between the rails. Once these elements of the disc are linked (perceptual grouping) and differentiated from those of the rails (perceptual segregation), these individual object representations are available to engage in the competition usually undertaken for separate representations in a lateral inhibitory network. As we described earlier, those mechanisms serve to exaggerate the differences between objects, and in this case, such an exaggeration about their relative spatial position leads to the illusion of motion opposition.

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