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LETTER TO THE EDITOR

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Component and intrinsic motion integrate in 'dancing bar' illusion

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Abstract We introduce a new illusion that contradicts common assumptions in the field of visual motion perception. When an unoccluded bar moves at certain speeds and oscillates at certain frequencies, the perceived direction of the bar is not predicted by its intrinsic terminators but is biased to move in the direction orthogonal to its orientation. It appears that the veridical terminator motions are integrated with spurious component motion signals, generating an at times complex pattern of motion around an apparently closed loop path. In the absence of oscillation the effect does not occur. Several factors, including optimal angle, speed, and oscillating distance of the bar, are quantified and possible mechanisms are discussed. In a model, we suggest that the effect arises because of the failure to inhibit spurious component motion signals arising from contours that are nearly oriented along the direction of true motion.

Introduction

We introduce a new illusion that contradicts common assumptions in the field of visual motion perception. The illusion occurs when bars slanted slightly away from vertical are oscillated up and down. The effect only happens when the bars are oscillated. Although a veridical up and down motion is often initially perceived, the trajectories of the bars quickly become influenced by spurious component motion signals. This creates the impression that the bars are not only moving up and down, but also at the same time sideways, creating the impression that the bars are following a somewhat elliptical trajectory. The goal of this paper is to characterize the attributes of this new illusion, and present a preliminary model of the possible origin of this striking effect.

When an unoccluded bar moves within plain view, it is widely assumed that the rigid motion perceived is determined by the motion of its endpoints or terminators. For example, if these 'intrinsic' (i.e. belonging to the bar) terminators move upward, the bar will appear to move upward. However, if a bar is viewed through an aperture, then the motions of its visible terminators (where the bar is last seen before passing behind the occluder) are not indicative of the motion of the bar (Fennema and Thompson 1979; Adelson and Movshon 1982; Marr 1982; Nakayama and Silverman 1988). Such an 'extrinsic' (i.e., belonging to the occluder) terminator could move to the upper left when the bar in fact moves to the lower left, depending on the shape of the aperture (Wallach 1935). The visual system appears to be able to distinguish between these informative and non-informative classes of terminators when making a decision about the motion of a bar. If terminators are the intrinsic ends of a bar, the bar will be perceived to move in the direction of the terminators. However, if a bar is occluded, its non-intrinsic terminator motions are disregarded, and the motion that is perceived is

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the motion orthogonal to the orientation of the bar. Therefore, it must be that a stage of form analysis determines whether terminators are intrinsic or extrinsic, before the global motion of a bar is computed.

What might be the neural basis of the stage of form analysis that distinguishes intrinsic from extrinsic terminators in the context of moving bars? Lorenceau and colleagues have found that the motion perceived in a field of moving bars is initially perpendicular to the orientation of the bars, rotating to the actual direction of motion within about 200 ms (Lorenceau et al. 1993). After this initial integration period, however, the motions of the intrinsic terminators belonging to the moving bars largely determine the perceived direction of bar motion (Lorenceau and Shiffrar 1992; Wallach 1935). Recent neurophysiological data have shown that neurons in MT in the macaque respond more to terminator motion in a barber pole stimulus than to the ambiguous signals generated by portions of the contour away from terminators; Furthermore, they respond more to intrinsically owned terminators than to extrinsic terminators (Pack et al. 2004). It has also been shown that neurons in MT in the macaque will initially respond to the direction of motion that is perpendicular (component direction) to a moving line, independent of the actual direction of motion (Pack and Born 2001). These same neurons will, over a period of ∼60 ms, come to respond to the true motion of the line independent of its orientation, suggesting that the unambiguously moving endpoints of the line are quickly but not instantaneously exploited to generate a veridical motion solution. The response properties of these neurons match behavioral data that show that initial pursuit eye-movements will be in the direction perpendicular to the moving line, and then rapidly adapt to follow the direction of veridical motion as defined by the line terminators (Pack and Born 2001). There is also neurophysiological evidence of end-stopped neurons in V1 that respond to the motion of line-terminators independently of the line's orientation (Pack et al. 2003), suggesting that form-based trackable features such as line terminators can be directly extracted from the image as early as V1. Such cells are largely immune to the aperture problem.

Where and how intrinsic terminator motion signals are generated is not known. The processing of intrinsic or extrinsic terminator motion signals and the responses of end-stopped neurons cannot be understood within the linear systems approach (Zetzsche and Barth 1990; Barth and Watson 1990). One possibility is that these motion signals are computed in a nonlinear fashion outside of V1/V2 and then rapidly fed back to these early visual areas, modifying their initial response (Bullier 2001).

Here we demonstrate and quantify the existence of a new class of motion stimuli where the component of motion that is perpendicular to a moving bar influences perceived motion, even when the bars are unoccluded, and their intrinsic terminators are entirely visible and moving in a different direction. In particular, the intrinsic terminators move up and down, and the bars appear to move both upward and in the direction orthogonal to their orientation, deviating from vertical, often creating the impression that the bars are following a rather elliptical motion trajectory when they are in fact just moving upward and downward. Far from dissipating within 200 ms, this perpendicular component of bar motion dominates perception continually. We call this illusion, where bars appear to move in a nonveridical component motion direction rather than the direction dictated by their intrinsic terminators, the 'dancing bar' illusion, for reasons that are obvious when the effect is seen (see http://webster.dartmouth.edu/∼petertse/ for a demonstration).

Experiment 1

Here we determine the bar angle that optimally induces the dancing bar illusion as a function of stimulus speed.

In Experiment 1, we systematically change the speed of the target stimuli and let subjects adjust the angle of the bars in the target stimuli relative to the direction of motion in order to determine the optimal angle that can induce the strongest dancing bars illusion.

Methods

Observers

Five subjects (four naïve and one author) carried out all the experiments. All of them had normal or corrected-to-normal vision and were experienced psychophysical observers. Before each experiment, the subjects practiced several training trials until they were accustomed to the experimental procedure and were capable of fixating while conducting hand movements.

Stimuli and procedures

The stimulus configuration and experimental procedure used in Experiment 1 are shown in Fig. 1. Bars were white (71.1 lumen/m^2) on a black background (0.0 lumen /m^2). The fixation spot was a yellow (luminance: 285 lumen /m^2; CIE, $x = 0.402$, $y = 0.517$; measured using a Minolta 100LS colorimeter) square that subtended 0.05° of visual angle. The target stimulus was composed of 16

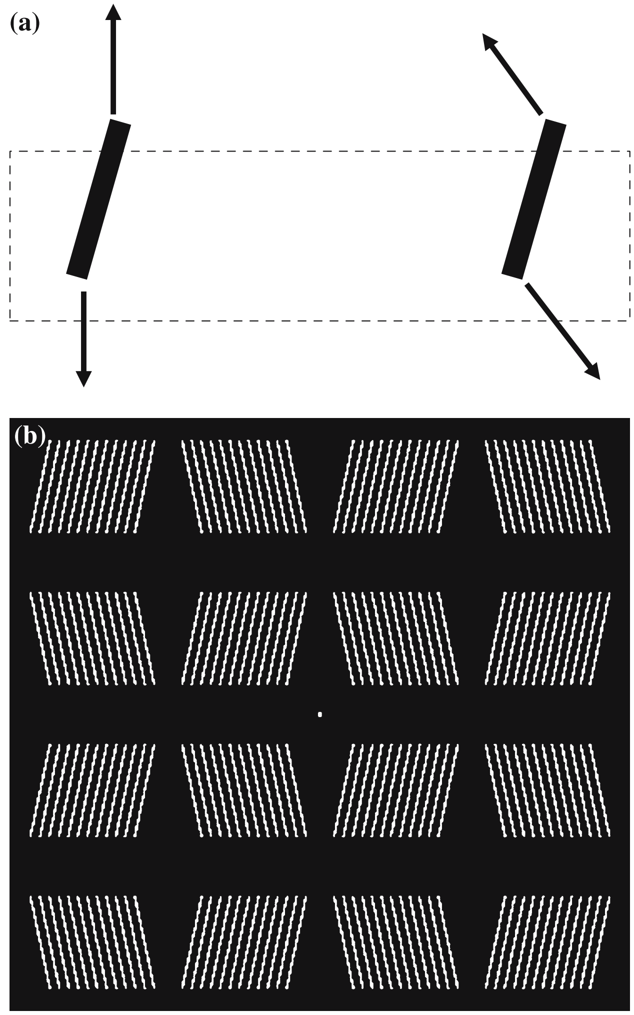

Fig. 1 **a** A schematic drawing, on the left, of the true stimulus directions traversed as the *slanted bar* moves up and down, and on the right, the approximate mean directions perceived as the bar appears to move in a direction influenced by the component motion signal. The actual perceived path is often curved. **b** The configuration of the stimuli used in the experiments

"squares" comprised of 12 bars each. Each individual bar subtended 0.1° of visual angle in width and 2.3° of visual angle in height. The distance between each bar within a "square" was 0.1° of visual angle. All squares oscillated up and down at a constant speed within a constant range (0.2° of visual angle). There was no acceleration or deceleration in either the upward or downward trajectory of the bars. The centers of the 16 squares were located ±2.2° or ±5.2° visual degrees from vertical midline and ±1.7° or ±5.2° from the horizontal midline. All the stimuli were viewed with both eyes. The total size of the visual field was 40 cm × 30 cm, viewed from a distance of 57 cm. Subjects had their chin in a chin rest. The visual stimulator was a 2 GHz Dell workstation running Windows 2000. The stimuli were presented on a 23-in. SONY CRT gamma-corrected monitor with 1,600 × 1,200 pixels resolution and 85 Hz frame rate.

Subjects were presented with the stimuli and required to adjust the angle of the bars in the target stimuli by pressing two buttons to find the angle that induced the strongest effect of figures moving away from the true vertical direction of motion. One button increased and the other decreased the angle of the bars. The speed of the target stimulus was randomly assigned to be one of the following values (0.8, 1.12, 1.28, 1.68, 1.92 or 2.0 visual degrees/s), and the starting angle of the bars was randomly assigned to be either 2°/360° or 15°/360°. All conditions were counterbalanced across 24 trials. Subjects were required to rest after each trial until any potentially existing afterimage had disappeared. Eye movements were monitored using a head-mounted eyetracker (Eyelink2, SR research, Ontario, Canada). Trials during which the subject's monitored left eye was outside a fixation window of 1.5 visual degrees radius were excluded and repeated later in the experiment. Thus all data reported here were carried out under conditions of fixation.

Results Results of Experiment 1 are shown in Fig. 2a. Stimulus speed does not affect the optimal angle at which the effect is perceived to be strongest. Among the six tested speeds, the optimal angle (relative to the direction of motion) to perceive the illusion remains constant at about 14° (of 360°) slanted away from the vertical.

Experiment 2

Here we determine the time that it takes to perceive the illusion as a function of stimulus speed.

In Experiment 2, we systematically change the speed of the target stimuli and ask subjects to determine the time it takes to perceive the illusion after the stimulus onset.

Methods

Stimuli and procedures

In Experiment 2, the stimuli and procedure were very similar to Experiment 1 except that the angle of the bars was always fixed at 6°/360°. The optimal angle of 14° from vertical determined in Experiment 1 was not used in order to prevent the possibility of a floor effect, where the illusion would be perceived to commence equally quickly at all speeds. Subjects were presented with the stimuli and required to press a button at the moment they first started to perceive the illusion. The speed of

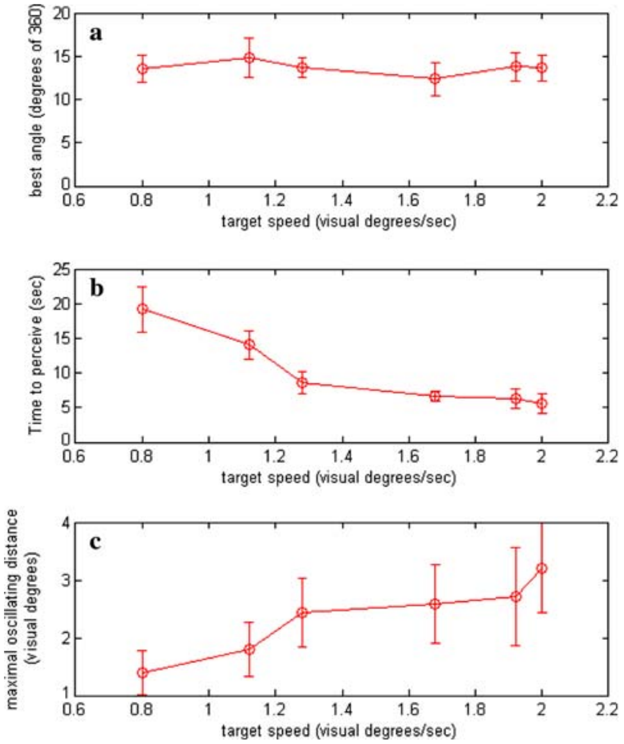

Fig. 2 Optimal angle and the time it takes to perceive the illusion as a function of target speed ($n = 5$). **a** The speed does not affect the best angle to perceive the illusion. **b** Among the six tested speeds, the time it takes to perceive the illusion is negatively correlated with the speed of the tested motion pattern. **c** Among the six tested speeds, the maximal oscillating distance at which the subjects can still perceive the illusion is positively correlated with the speed of the tested motion pattern

the target stimulus was randomly assigned to be one of the following values: 0.8, 1.12, 1.28, 1.68, 1.92 or 2.0 visual degrees/s. All conditions were counterbalanced across 24 trials. Subjects were required to rest after each trial until the afterimage had disappeared.

Results Results of Experiment 2 are shown in Fig. 2b. Among the six tested speeds, the higher the speed, the shorter the amount of time it takes to start perceiving the illusion.

Experiment 3

Here we determine the maximal oscillating distance to perceive the illusion as a function of the stimulus speed.

The illusion depends critically on the oscillation of the bars. If the bars travel continually in either the upward or downward direction, no illusion is perceived, and the motion perceived is vertical, which it in fact is. Here we determine the outer bounds of changes in direction as a function of speed. In Experiment 3, we systematically change the speed of the target stimuli and ask subjects to answer the maximal distance at which they can still perceive the illusion.

Methods

Stimuli and procedures

In Experiment 3, the stimuli and procedure were very similar to Experiment 1 except the angle of the bars was always fixed at 14°/360°, the angle determined to lead to the strongest effect in experiment 1. Subjects were presented with the stimuli and required to press a pair of buttons to increase or decrease the oscillating distance until they found the maximal oscillating distance at which they could still perceive the illusion given unlimited looking time. The speed of the target stimulus was randomly assigned to be one of the following values (0.8, 1.12, 1.28, 1.68, 1.92 or 2.0 visual degrees/s) on each trial and the starting oscillating distance was either 0.2 or 2 visual degrees. All conditions were counterbalanced across 24 trials. Subjects were required to rest after each trial until any potential afterimage had disappeared.

Results Results of Experiment 3 are shown in Fig. 2c. Among the six tested speeds, the time it takes to perceive the illusion is positively correlated with the speed of the tested motion pattern. As stimulus speed increases, the maximal oscillating distance that still permitted the perception of the illusion increases correspondingly.

Discussion

It is likely that motion processing areas generate two motion solutions for a moving bar stimulus; a local one consistent with the perpendicular direction of motion that one would obtain by viewing the bar through the “aperture” of a receptive field in primary visual cortex, and a global one consistent with the motion of the terminators. Usually the intrinsic terminator solution ‘wins’ or dominates perception within about 200 ms, as shown by Lorenceau et al. (1993), and the aperture or component solution loses, generating an unambiguous percept of motion in the direction specified by the intrinsic terminators. However, when the bars are oscillated back and forth, the component solution appears to ‘win’ anew after each turnaround, or at least continues to contribute to the overall perceived motion to a degree that is not possible in the absence of oscillation. We hypothesize that this is because it takes a finite amount of time for terminator motion to dominate the component motion solution. If a new motion begins before the intrinsic terminator solution has had a chance to

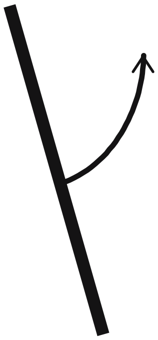

Fig. 3 The *curved arrow* depicts an exaggerated rendition of the motion path expected upon an upward vertical sweep of the slanted bar if the initial motion direction is dominated by contributions from the component vector orthogonal to the orientation of the bar, and the later motion direction is dominated by contributions from the vertical terminator motion signals. Upon a downward sweep the oppositely curved path would be expected, completing a pseudo-elliptical path before the next upward sweep

dominate the component solution, the component solution will not be suppressed as it would given uninterrupted motion in a single direction. In the absence of sufficient suppression of aperture motion by intrinsic terminator motion, the visual system may integrate component and terminator motions to generate a perception of motion.

Because component motion signals dominate immediately after a switch in motion direction, the bars will appear to move in a direction orthogonal to the orientation of the bars. However, as the terminator signals come to dominate, the bars will appear to move in an increasingly vertical (i.e. veridical) direction. Upon the next reversal in direction this pattern of motion directions will again be followed, causing the bars to move along an approximately elliptical trajectory, when in fact moving simply up and down. If it is true that component motion signals dominate immediately after each turnaround, followed by an increasingly strong terminator motion signal with time, we would expect the motion path followed by the bars to be shaped in approximately the manner shown in Fig. 3, assuming that the terminator motion signal grows exponentially stronger with time and that the component motion signal grows exponentially weaker with time. Initially the motion of the bars is orthogonal to the orientation of the bars upon an upward motion. By the end of the upward motion, the motion path is vertical, consistent with the direction of the terminator motion. Upon a turnaround, the component signal again initially dominates, followed by an increasing contribution from the terminator motion signals.

In sum, perpendicular component motion dominates upon motion onset. However, before the intrinsic terminator motions can come to dominate the signal, the oscillating bars change direction, whereupon the perpendicular component motion signals dominate again. That this effect occurs suggests that the motion system does not have a memory of past motions. Instead motion trajectories are computed anew upon each new motion onset. In particular, it appears that terminator motion is computed from ‘scratch’ each time the line changes motion.

It must be noted, however, that it may take several seconds before the component solution can win at all. Many observers report that the illusion takes several seconds to kick in. Initially, the veridical up and down oscillatory motion is typically perceived. This suggests that the motion system that tracks the motion of the line terminators fatigues with time, making the relative strength of the component solution stronger.

A model

Let Φ be the angle of the bar relative to vertical. The maximum displacement Δs of the bar within a duration Δt in the direction of component motion will be proportional to $\sin(\Phi)$. Let us call this displacement over Δt the ‘perpendicular component motion,’ shown as the red arrow in Fig. 4. Note that the direction perpendicular to the bar is not the horizontal direction (i.e. the direction orthogonal to the true direction of motion). The motion that is perpendicular to the orientation of the moving contour has both vertical and horizontal components. We are not interested in the vertical component of the perpendicular component motion, since it will not deviate from the true direction of motion. We are only interested in the horizontal component of this perpendicular component motion. Given these simple facts, as a first pass, we might think that the horizontal component of motion would be given by $\mathbf{v}\sin(\Phi)\cos(\Phi)$, where $\mathbf{v}$ is the velocity of the vertically moving bar. This is plotted in Fig. 5 as a function of angle, where $\mathbf{v}$ has the value 1. If the peak horizontal component of perpendicular component motion were given by $\mathbf{v}\sin(\Phi)\cos(\Phi)$, we would expect to have a peak illusion at $\Phi = 45°$ for all values of $\mathbf{v}$. However, our peak is empirically found to be 14° from vertical. Why might this be the case?

We hypothesize that the motion processing system is able to discount perpendicular component motion with less success as Φ (i.e., the angle between a contour and the global direction of motion) becomes very small, as schematized in Fig. 6. We suggest that low spatial frequencies of moving patterns determine the

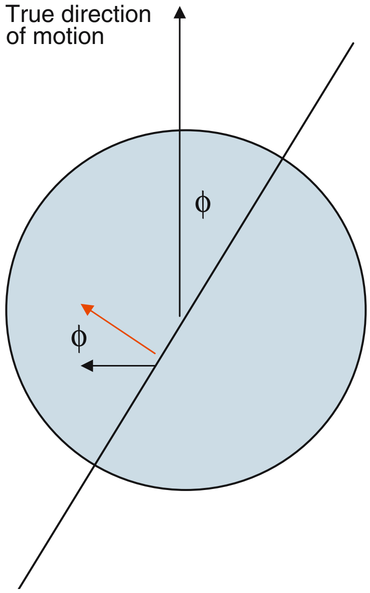

Fig. 4 Φ is the angle of the bar relative to the true direction of motion. The perpendicular component motion, shown as the *red arrow*, is $\sin(\Phi)$ multiplied by the motion vector describing the true direction of motion. The angle between the perpendicular component motion and the true direction of motion is also Φ. The horizontal component of perpendicular component motion, which is the only component that could lead to the illusion, will be given by $\cos(\Phi)$ multiplied by the motion vector describing the perpendicular component motion

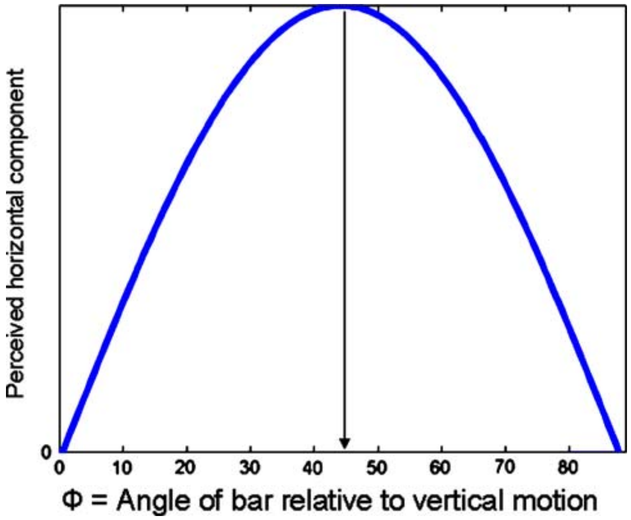

Fig. 5 As a first pass, we might think that the horizontal (spurious) component of motion is given by $\sin(\Phi)\cos(\Phi)$. This is plotted here as a function of angle. If the peak horizontal component of perpendicular component motion is given by $\sin(\Phi)\cos(\Phi)$ we would expect to have a peak illusion at $\Phi = 45°$. However, our peak is empirically found to be 14° from vertical

global direction of motion. To inhibit spurious motion signals due to the aperture problem, we hypothesize that motion signals derived from high spatial frequency sources such as contours oriented at an angle relative to this global direction of motion receive inhibitory feedback such that perpendicular component motions from these contours are suppressed. However, we hypothesize that there are either angular or temporal limits on the computation that determine whether a moving contour is oriented relative to its direction of motion. If these limits are reached at small angles, inhibition of perpendicular component motion of these contours would presumably be correspondingly weaker in this domain. In other words, if it cannot be determined whether a bar is oriented relative to its direction of motion, the spurious component motion signals arising from this bar would not be suppressed. If the degree to which a moving contour's spurious component motion signals are not suppressed decreases exponentially as a function of Φ (i.e. the angle between the oriented contour and its true direction of motion), then the optimal angle for seeing spurious motion perpendicular to the real direction of motion would follow from $\mathbf{v}\sin(\Phi)*\cos(\Phi)*\exp(-k\Phi)$. For an appropriately chosen value of k chosen to lead to a peak at $\Phi = 14°$, where $\mathbf{v} = 1$, the shape of this function is that shown in Fig. 7. In the domain of large values of Φ, where suppression of spurious component motion signals is strong, this function approaches zero, as evident on the right side of the curve shown in Fig. 7. It also approaches zero where the component signals themselves would be close to zero, namely where the bar is oriented parallel with the direction of motion, as is evident on the left side of the curve.

The experimental results are accounted for by this simple model. According to this model, the optimal angle for perceiving the dancing bars illusion remains constant as a function of speed, as found in experiment 1, because the peak of the relationship shown in Fig. 7, described by $\mathbf{v}\sin(\Phi)*\cos(\Phi)*\exp(-k\Phi)$, is purely a function of k and Φ. The peak of this curve is the same for all values of $\mathbf{v}$ for fixed values of k and Φ. The time it takes to perceive the illusion is negatively correlated with the speed of the tested motion pattern, as found in experiment 2, and the maximal oscillating distance at which the subjects can still perceive the illusion is positively correlated with the speed of the tested motion pattern, as found in experiment 3, because the magnitude of the spurious component signal increases as the speed of the bar increases, making it harder to inhibit. According to this model, the perceived direction of motion of a moving bar would then be given by the ongoing vector summation of the vertical component motion plus the spurious horizontal component of the perpendicular component motion, leading to the illusion. Because the relative size of the vertical and spurious component motion vectors changes as the hypothesized inhibi-

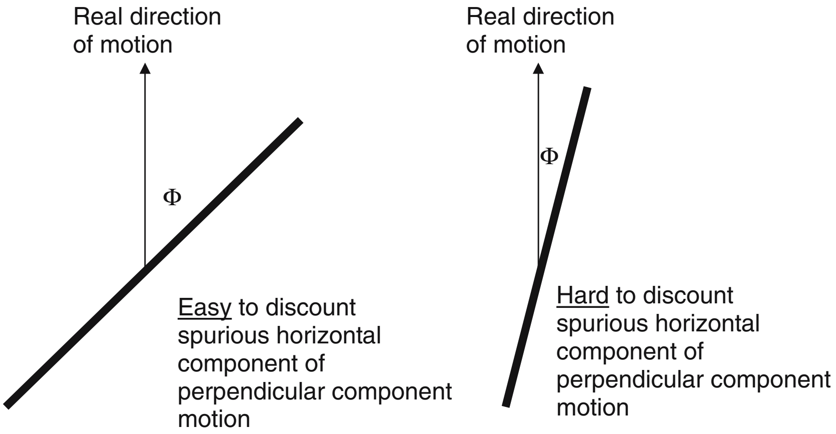

Fig. 6 We hypothesize that the motion processing system is able to discount perpendicular component motion with less success as Φ becomes very small. We suggest that filters tuned to low spatial frequency components of motion determine a global direction of motion. To inhibit spurious motion signals due to the aperture problem, motion signals derived from contours oriented relative to the global direction of motion receive inhibitory feedback such that perpendicular component motions from these contours are suppressed. However, the limits of this inhibitory process are reached at small angles (i.e. the angle between a contour and the global direction of motion), and inhibition of perpendicular component motion for small values of Φ is correspondingly weaker

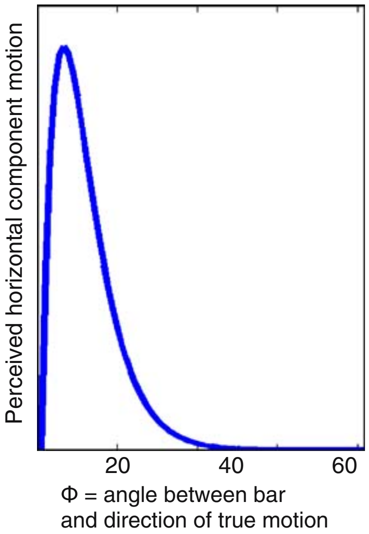

Fig. 7 The optimal angle for seeing spurious motion perpendicular to the real direction of motion is given by sin(Φ)*cos(Φ)*exp($-k\Phi$). For an appropriately chosen value of k, chosen so that the function peaks at 14°, the shape of the function is that shown here

tion of component motion signals strengthens over time, the perceived direction of the dancing bars appears to change with time.

Conclusions

Spurious motion signals perpendicular to the real direction of bar motion appear to contribute to the global perceived motion of the vertically oscillating bars at small Φ (i.e. small deviations from the direction of motion). We find that the maximum effect occurs when the angle between a contour and the true direction of motion equals approximately 14°, regardless of the speed of the moving bar. We hypothesize that spurious component motion signals must be successfully inhibited for large Φ, but that inhibition of spurious component motion signals (arising from the horizontal component of the perpendicular component motion) decreases when the angle Φ is small.

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