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Vision Research xxx (2006) xxx–xxx

Vision Research

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Mechanisms underlying the perceived angular velocity of a rigidly rotating object

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Received 21 December 2005; received in revised form 16 February 2006

Abstract

The perceived angular velocity of an ellipse undergoing a constant rate of rotation will vary as its aspect ratio is changed. Specifically, a “fat” ellipse with a low aspect ratio will in general be perceived to rotate more slowly than a “thin” ellipse with a higher aspect ratio. Here we investigate this illusory underestimation of angular velocity in the domain where ellipses appear to be rotating rigidly. We characterize the relationship between aspect ratio and perceived angular velocity under luminance and non-luminance-defined conditions. The data are consistent with two hypotheses concerning the construction of rotational motion percepts. The first hypothesis is that perceived angular velocity is determined by low-level component-motion (i.e., motion-energy) signals computed along the ellipse’s contour. The second hypothesis is that relative maxima of positive contour curvature are treated as non-component, form-based “trackable features” (TFs) that contribute to the visual system’s construction of the motion percept. Our data suggest that perceived angular velocity is driven largely by component signals, but is modulated by the motion signals of trackable features, such as corners and regions of high contour curvature.

Keywords: Contour curvature; Rotational motion; Component motion; Trackable features

1. Introduction

How the visual system constructs the perception of motion from the temporal dynamics of the retinal image is a fundamental question that continues to challenge vision scientists. This is true even for the perception of relatively simple stimuli such as those completely defined by a closed contour. At the heart of the problem is the fact that an infinite number of 3D velocity fields can generate the same 2D retinal sequence. The local motion information at any point along a contour is consistent with an infinite number of possible motions that all lie on a ‘constraint line’ in velocity space (Adelson & Movshon, 1982). The problem of interpreting this many-to-one mapping is commonly termed the ‘aperture problem’ (Adelson & Movshon, 1982; Fennema & Thompson, 1979; Marr, 1982; Nakayama & Silverman, 1988).

How the aperture problem is solved is perhaps the most fundamental challenge that must be met by any model of human motion perception. While there are several theoretical solutions to the aperture problem that account for many aspects of motion perception, no single general theory has yet emerged that can explain how the visual system actually processes motion in every instance. A majority of studies that have addressed the aperture problem have focused on translational motion and have provided models based on the integration of the locally generated component-motion signals. These models, involving vector summation or intersection of constraints (IOC), have provided reliable solutions to many of the percepts of translational motion (Adelson & Movshon, 1982; Bowns, 2001, 2002; Hildreth, 1984; Lu & Sperling, 1995, 2001; Yo & Wilson, 1992).

Here, we seek to understand the principles underlying rigid rotational motion. Few if any of the component-

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doi:10.1016/j.visres.2006.02.026

motion models that have succeeded in accounting for motion percepts under conditions of translational motion can be applied to objects undergoing rotational motion. The premise of IOC models is the observation that for translational motion, there exists a unique point of intersection in vector space for component vectors. However, the constraint-lines formed for each point along a contour undergoing rotation do not have a common intersection (see Fig. 1). They therefore do not provide a unique motion solution as they would in standard cases of translational motion.

A low, near-unity aspect ratio (i.e., almost circular) ellipse that undergoes rotation will be perceived to deform as though it were made of jelly (Musatti, 1924; Vallortigara, Bressan, & Bertamini, 1988; Wallach, Weisz, & Adams, 1956; Weiss & Adelson, 2000). This percept of non-rigid motion is fully consistent with the directions of the locally generated component motion signals along the contour. As the aspect ratio (height over width) of the ellipse increases, the ellipse will eventually appear to rotate rigidly in the 2D plane. Models that rely on local vector summation of component motion signals predict a non-rigid percept, no matter what the aspect ratio of the ellipse (Weiss & Adelson, 2000). Thus, traditional models, such as vector summation or intersection of constraints, are unable to account for rotational motion in principle.

While vector summation and IOC models cannot account for the case of rotational motion, there is one class of information that can in principle account for both the cases of translational and rotational motion. Certain regions of a contour move unambiguously, and are not subject to the aperture problem. Such regions include corners, regions of high curvature, junctions, and terminators. It has been hypothesized that such 'trackable features' (TFs) can be used to disambiguate ambiguous component motion signals that arise away from TFs (Ullman, 1979). In this paper we specifically examine the possible contribution of TF motion to the perception of rotational motion.

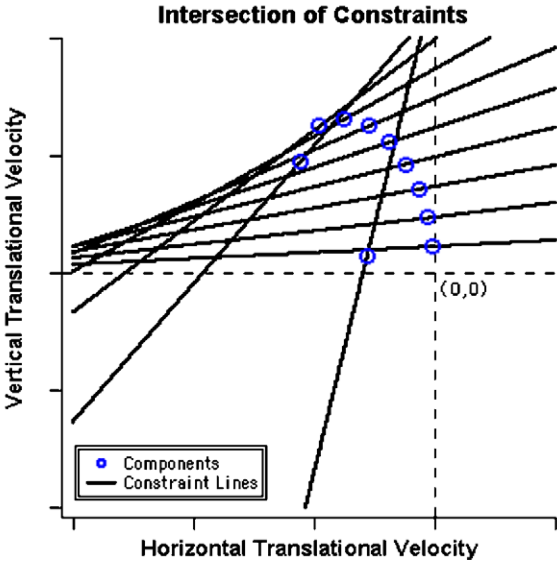

Fig. 1. IOC fails for rotational motion. The circles represent the direction and magnitude of component motion vectors in velocity space for various points along the leading edge of an ellipse undergoing clockwise rotation. The constraint lines represent all the possible "real-world" motions the corresponding contour location could be undergoing that would generate the same component magnitude. The intersection of constraints model applies to translational motion for which all constraint lines share a common point of intersection. As can be seen in this figure, the same in not true for rotational motion. There is no common point of intersection.

Our central aim here is to investigate the perceived angular velocity of a rotating ellipse. In particular we characterize a surprising illusion where angular velocity seems to change with aspect ratio. Specifically, a "fat" rigidly rotating ellipse with a low aspect ratio will in general be perceived to rotate more slowly than a "thin" rigidly rotating ellipse with a higher aspect ratio, when both in fact rotate at the same angular velocity. We explore the relationship between aspect ratio and perceived angular velocity, and seek to understand the mechanisms underlying this non-veridical perception, examining possible contributions from trackable feature and component motion signals. We limited our investigation to the domain of aspect ratios and angular velocities where all observers agree that ellipses are rotating rigidly. In none of our experiment did ellipses appear gelatinous at any time.

Subjects were presented with pairs of rotating luminance-defined stimuli (either ellipses, rectangles, or rounded rectangles) for 500 ms and asked to make a two alternative forced choice (2AFC) speed discrimination decision. In the first set of experiments, the basic relationship is characterized in terms of the perception of relative angular velocity for a rotating ellipse, rectangle, and rectangle with rounded corners. In the second set of experiments, non-luminance defined stimuli are used. These behavioral data are then compared to predictions made by locally computed component-motion signals.

2. Stimulus presentation

The visual stimulator was a 2 GHz Dell workstation running Windows 2000. The stimuli were presented on a 23-inch SONY CRT monitor with 1600 × 1200 pixels resolution and 85 Hz frame rate. Luminance values were measured using a Spectra® Spotometer® (Photo Research, Chatsworth, CA, USA) at a distance of 18 cm. Observers viewed the stimuli on a black background (0.55 cd/m^2) from a distance of 76.2 cm with their chin in a chin rest. Subjects were required to maintain fixation on a yellow square (93.88 cd/m^2) fixation spot that subtended 0.05° of visual angle. Fixation was ensured using a head-mounted eyetracker (Eyelink2, SR research, Ontario, Canada; Tse, Sheinberg, & Logothetis, 2002). Any time the subject's monitored left eye was outside a fixation window of 1.5° radius, the trial was automatically aborted, and a new trial was chosen at random from those remaining. The eyetracker was recalibrated whenever the subject's monitored eye remained for whatever reason outside the fixation window while the subject reported maintaining fixation. Once calibration was completed, the experiment resumed with a random trial.

3. Luminance-defined experiments

3.1. Experiment 1a: Aspect ratio and perceived rotational speed

The goal of Experiment 1a was to characterize the relationship between the aspect ratio of a luminance-defined ellipse and the relative angular velocity at which it is perceived to rotate. This was accomplished by repeatedly presenting a pair of rotating ellipses, one to the left and one to the right of fixation, and requiring subjects to make a 2AFC judgment of angular velocity by pressing one of two buttons to indicate which of the two ellipses was rotating faster. In each pair of stimuli, there was one control ellipse that had a fixed aspect ratio and fixed angular velocity across all trials, and one test ellipse whose aspect ratio and angular velocity varied from trial to trial in a pseudorandom manner counterbalanced for side of presentation.

3.1.1. Method

3.1.1.1. Observers. Eleven subjects (eight naïve Dartmouth students and the three authors) with normal or corrected-to-normal vision carried out the experiment. Naïve subjects were paid $5 for their participation.

3.1.1.2. Procedure. In each trial, subjects were presented with two grey (39.81 cd/m^2) rotating ellipses on a black (0.55 cd/m^2) background for 500 ms. Each ellipse was positioned so that its center was located nine visual degrees along the horizontal axis away from the central fixation spot. One ellipse (control) had the same aspect ratio = 5/3 and same angular velocity (126°/s) on every trial. The other ellipse (test) had an aspect ratio randomly selected from the following list which was generated by multiplying the length of the minor axis of the control ellipse by .8, .6, .4, respectively: 25/12, 25/9, 25/6. The test ellipse had an angular velocity randomly selected on each trial from the following list: 43, 63, 84, 105, 126, 147, 168, and 210°/s. Although both the control ellipse and test ellipse rotated in the same direction, the common direction of rotation was randomly determined for each trial. Subjects were required to indicate by pressing one of two buttons (2AFC) which of the two ellipses was rotating faster; the one on the left or the one on the right of fixation.

Fig. 2A illustrates the relative sizes of each of the stimuli used in this experiment. The color of the bounding box around each stimulus (not present during an experiment) is used in later figures to distinguish the stimuli. In addition to trials in which the three test stimuli (Fig. 2A(b–d)) were used, an additional "control" (Fig. 2A(a)) condition was presented in which a test ellipse with the same aspect ratio as the control was used. In these trials, the speed of rotation for this "test" ellipse was randomly selected from the list above. This condition, which compares two identical ellipses rotating at various speeds, can be used to test the efficacy of our 2AFC paradigm. The sizes in visual angle of the ellipses used in this experiment were as follows: 4.85° × 2.91°, 4.85° × 2.33°, 4.85° × 1.75°, and 4.85° × 1.16° corresponding to the stimuli shown in Fig. 2A(a–d), respectively. Trials were counter-balanced with respect to the side where the

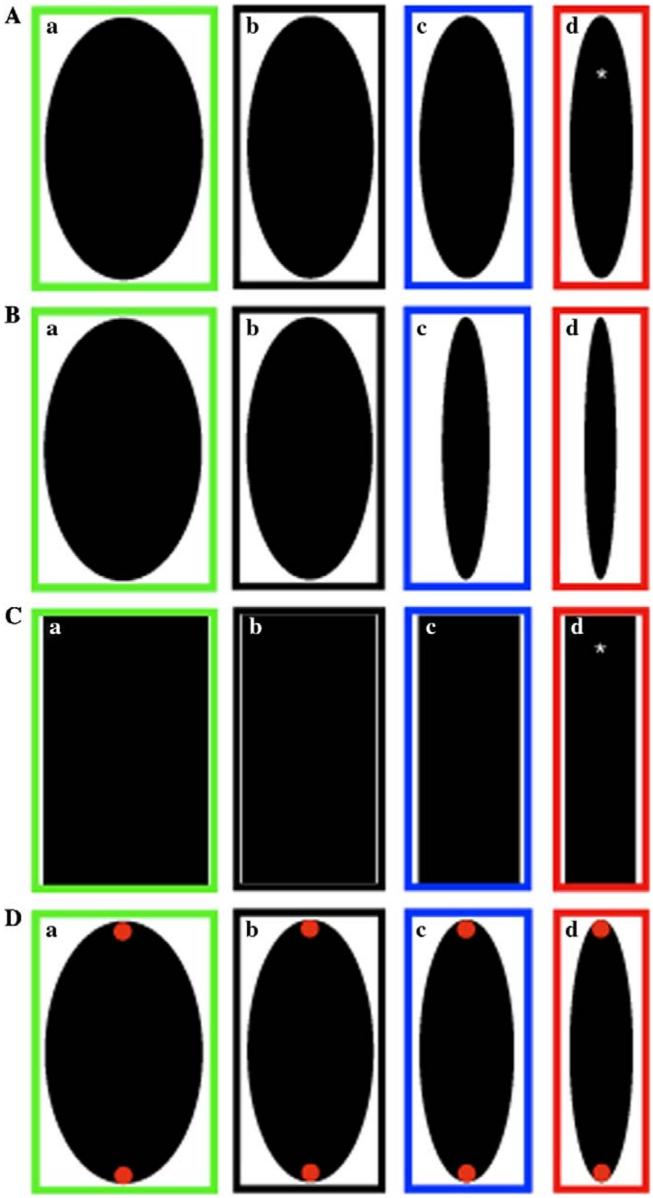

Fig. 2. Luminance-defined stimuli. (A) Experiment 1a, (a) The control stimulus with an aspect ratio = 5/3; (b), (c), and (d) are the test stimuli with aspect ratios = 25/12, 25/9, and 25/6, respectively. (B) Experiment 1b, (a) The control stimulus with an aspect ratio = 5/3; (b), (c), and (d) are the test stimuli with aspect ratios = 25/12, 50/9, and 25/3, respectively. (a) and (b) are the same as in Experiment 1a, (c) and (d) have double the aspect ratio of the corresponding (c) and (d) from Experiment 1a. (C) Experiment 2, the height/width of each rectangle is identical to the length of the major and corresponding minor axes of the ellipses used in Experiments 1a. (a) The control stimulus with an aspect ratio = 5/3; (b), (c), and (d) are the test stimuli with aspect ratios = 25/12, 25/9, and 25/6, respectively. (D) Experiment 4, red dots were added to the ellipses used in Experiment 1a. *, Indicates stimuli used in Experiment 3.

control ellipse was presented so that during an entire run (640 trials) 20 trials of each pairing were presented.

3.1.2. Results

The percentage of times that the test ellipse was perceived to rotate faster than the control ellipse was computed. Thus for each of the four test ellipses, eight values (one for each angular velocity) were calculated. The corresponding data were then fit using a logit function in MATLAB. These logit functions were then averaged across the 11 subjects. The point of subjective equality (i.e., the speed at which each test ellipse needs to be rotated to be perceived as rotating at the same speed as the control ellipse) was then computed. These values were determined by interpolating the 50% chance level from each of the logit functions fit to the data. These values were then averaged across subjects. This process is illustrated in Fig. 3. Data from an individual subject is illustrated in Fig. 3A, where each curve corresponds to a test ellipse of a given aspect ratio, and shows the percentage of trials in which the test ellipse rotating at the speed indicated along the x axis was perceived to be faster than the control ellipse. The color of the curve matches the color of the bounding box surrounding the test stimulus shown in Fig. 2. Group data is shown in Fig. 3B. To interpolate the point of subjective equality for each stimulus, logit functions were fit to the data from each subject. The mean logit function for each aspect ratio is shown in Fig. 3C. The point of subjective equality was then interpolated from the logit functions for each subject. Fig. 3D shows the mean point of subjective equality for each aspect ratio. The error bars represent the standard error of the mean across subject. The figure indicates that as the aspect ratio increases, so does the perceived angular velocity.

3.2. Experiment 1b

The goal of this experiment was to further characterize the relationship between aspect ratio and perceived angular velocity. It was also designed to determine if, beyond a certain aspect ratio, the parametric relationship between aspect ratio and perceived speed of rotation ceases to exist, as if perceived angular velocity asymptotes at some maximum. This was accomplished by replicating Experiment 1a while doubling the aspect ratio of the two “thinnest” ellipses (blue and red).

3.2.1. Method

3.2.1.1. Observers. Seven subjects (naïve Dartmouth students) with normal or corrected-to-normal vision carried out the experiment. Subjects were paid $5 for their participation.

3.2.1.2. Procedure. The same procedure used in Experiment 1a was used in this experiment, with the exception that the aspect ratios of the two thinnest ellipses (red and blue) were doubled from 25/9 and 25/6 to 50/9 ($4.85° \times 0.87°$) and 25/3 ($4.85° \times 0.58°$), respectively. The remaining two ellipses were kept at their original aspect ratios to serve as controls for global hysteresis effects of the experiment (i.e., to show that the perceived speed is not a function of the other stimuli used in the experiment). Fig. 2B illustrates the stimuli used in this experiment.

3.2.2. Results

The data were analyzed in the same manner as Experiment 1a. Fig. 3E illustrates the logit functions that were fit to the raw data. As in Experiment 1a, the thinner ellipses are perceived to rotate faster than the control ellipse. The results from the two ellipses that were also presented in Experiment 1a (green and black) are the same as in that experiment, indicating that the perceived angular velocity of a given ellipse is not influenced by the presentation of other ellipses of differing aspect ratios. Fig. 3F illustrates the perceived speed of subjective equality for the ellipses used in this experiment. As in Experiment 1a, there is no increase in perceived angular velocity beyond the next to highest aspect ratio ellipse. Furthermore, the perceived angular velocity of the high aspect ratio (Fig. 3D, blue and red) ellipses in Experiment 1a is statistically indistinguishable from that of the thin ellipses in Experiment 1b (Fig. 3F, blue and red).

3.2.3. Discussion

The data from Experiment 1 characterize the relationship between aspect ratio and perceived angular velocity of a luminance-defined rotating ellipse. The data corroborate the subjective experience that a “rounder” ellipse will appear to rotate more slowly than a “thinner” ellipse. Beyond an aspect ratio of 25/9, no further increase in angular velocity is perceived. In the next experiment we use rectangles with the same aspect ratios as the ellipses in Experiment 1.

3.3. Experiment 2: Rotating rectangles

In this experiment, pairs of luminance-defined rectangles were presented in a manner identical to that of the ellipses in Experiment 1. A fundamental difference between rectangles and ellipses of different aspect ratios is that unlike curvature that changes along with an ellipse’s aspect ratio, the defining “trackable features” of a rectangle, namely corners, are held constant across aspect ratio.

3.3.1. Method

3.3.1.1. Observers. Six subjects (four naïve Dartmouth students and two of the authors) with normal or corrected-to-normal vision carried out the experiment. Naïve subjects were paid $5 for their participation.

3.3.1.2. Procedure. The same procedure used in Experiment 1 was used in this experiment, with the exception that rectangles were used instead of ellipses. The aspect ratios and rotational speeds that were used for the test stimuli in this experiment were the same as those used in Experiment 1. The stimuli are shown in Fig. 2C.

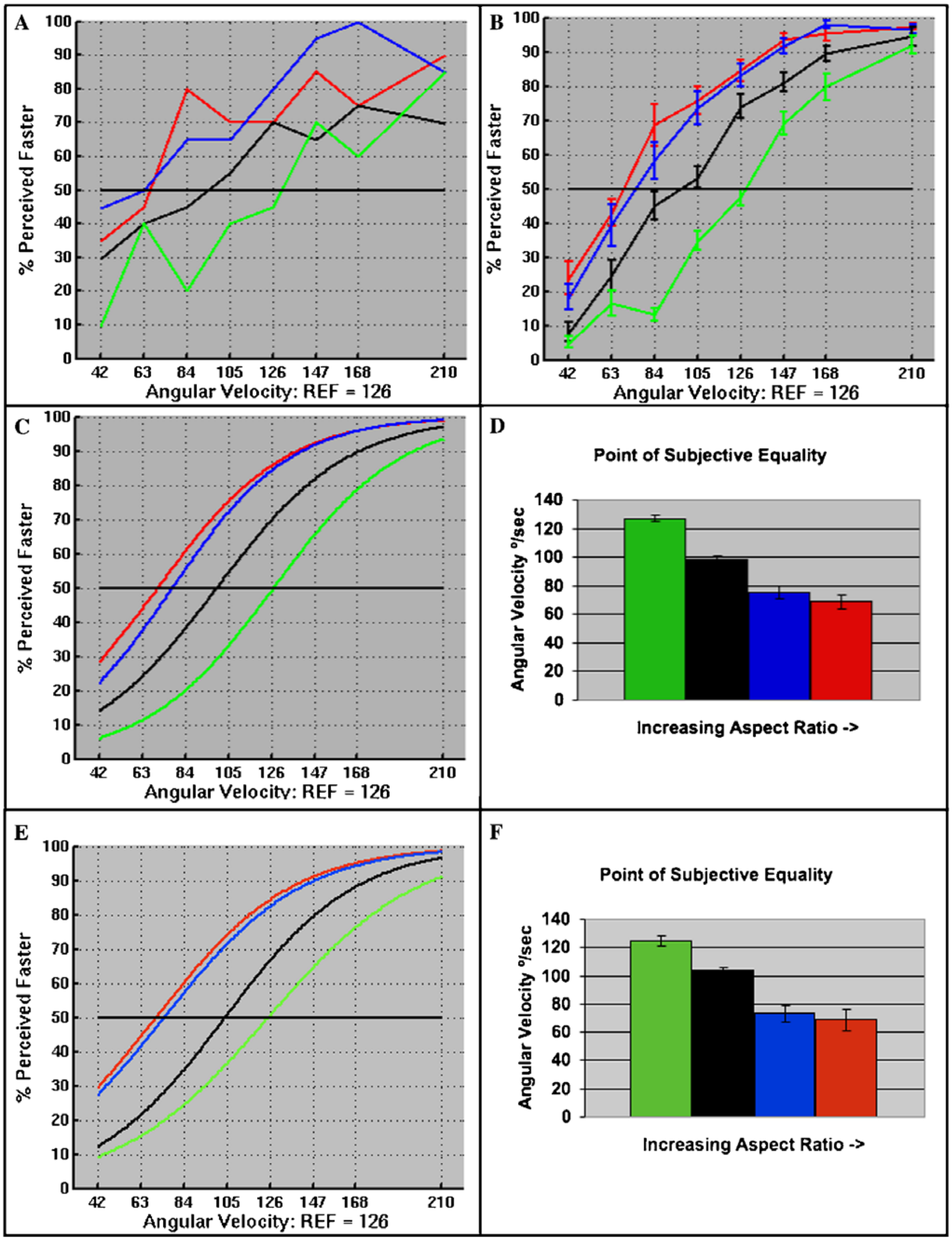

Fig. 3. Results of Experiment 1. (A) Individual data from a single subject (Experiment 1a): each curve represents the percentage of trials for which the test ellipse (corresponding to the same color of the bounding box in Fig. 2A) was perceived to rotate faster than the control ellipse (always rotating at a speed of 126°/s). The green curve represents the control condition in which both the control and test ellipse had the same aspect ratio. In this condition, it can be observed for this subject, that when the two ellipses were rotating at the same angular velocity (126°/s) the subject, as expected, performed at the 50% chance level. The upward/leftward shift of the curves relative to the control condition (green) indicates that as the aspect ratio was increased, the perceived angular velocity also increased. (B) Mean data from across all subjects (Experiment 1a): the mean data across all 11 subjects who participated in Experiment 1a. Error bars represent the standard error of the mean across subjects. (C) Mean fit of the data to a logit psychometric function (Experiment 1a): the individual data from each subject was fit with a logit function using MATLAB. The mean of the individual psychometric function is shown. The upward/leftward shift of the curves relative to the control condition (green) indicates the perceived increase in angular velocity with increasing aspect ratio. Error bars are not included because the psychometric functions are interpolated over hundreds of data points and would obscure the curves. (D) Point of subjective equality (Experiment 1a): for each subject the point at which their corresponding psychometric functions crossed the 50% chance level was interpolated. The ratio of each of the values to the reference speed of the control stimulus (126°) was used to compute how fast each stimulus would need to rotate to be perceived as rotating at the same speed as the control rotating at 126°/s. As would be expected from the psychometric functions, the high aspect ratio ellipse needs to rotate much slower than the 126°/s to be perceived as rotating at such a velocity. The error bars represent the standard error of the mean across subject. (E) Mean fit of the data to a logit psychometric function (Experiment 1b): the psychometric curves (corresponding to the color of the bounding boxes in Fig. 2B) for Experiment 1b are very similar to those of Experiment 1a. This suggests that beyond a given aspect ratio, no further increase in angular velocity is observed. (F) Point of subjective equality (Experiment 1b): the points of subjective equality for Experiment 1b are very similar to those of Experiment 1a.

3.3.2. Results

In the case of rotating rectangles, varying the aspect ratio had no effect on the perception of rotational speed, unlike the case of rotating ellipses. As can be seen in Fig. 4A, all of the test stimuli were perceived to rotate at the same relative angular velocity.

3.3.3. Discussion

Unlike the ellipses used in Experiment 1, the rectangles did not elicit illusory underestimations of angular velocity as a function of their aspect ratio. Instead, each of the rectangles was observed to rotate at the same relative speed.

3.4. Experiment 3: Perceived speed of a rotating ellipse

The two thinnest ellipses appear to rotate at the same relative speed as measured by our experimental procedure. This experiment was designed to test whether the motion of these ellipses is perceived as being the same as that of the rectangles used in Experiment 2. In this experiment the speed of rotation of one of these two ellipses (stimulus D, Experiment 1a) is compared with a rectangle of the same aspect ratio (stimulus D, Experiment 2). This will determine the degree to which the angular velocity of the ellipses is underestimated relative to that of the rectangles.

3.4.1. Method

3.4.1.1. Observers.

Eight subjects (six naïve Dartmouth students and two of the authors) with normal or corrected-to-normal vision carried out the experiment. Subjects were paid $5 for their participation.

3.4.1.2. Procedure.

This experiment followed the same general procedure as that used in the previous experiments. A rotating test and control stimulus were presented for 500 ms on either side of fixation, and subjects were asked to respond via a button press which of the two stimuli was perceived to rotate faster. The control stimulus, a rectangle (stimulus D, Experiment 2) rotating at 126°/s was present in all trials. The test stimulus, an ellipse (stimulus D, Experiment 1a) was also present in all trials. The speed of rotation of the test ellipse was randomly selected from the same list of speeds as was used in the previous experiments. The experiment consisted of 160 trials, such that 20 trials of each speed were presented. The side on which the control stimulus was presented was randomly selected on each trial.

As in previous experiments, logit functions were fit to the data from each subject. From these functions, the point

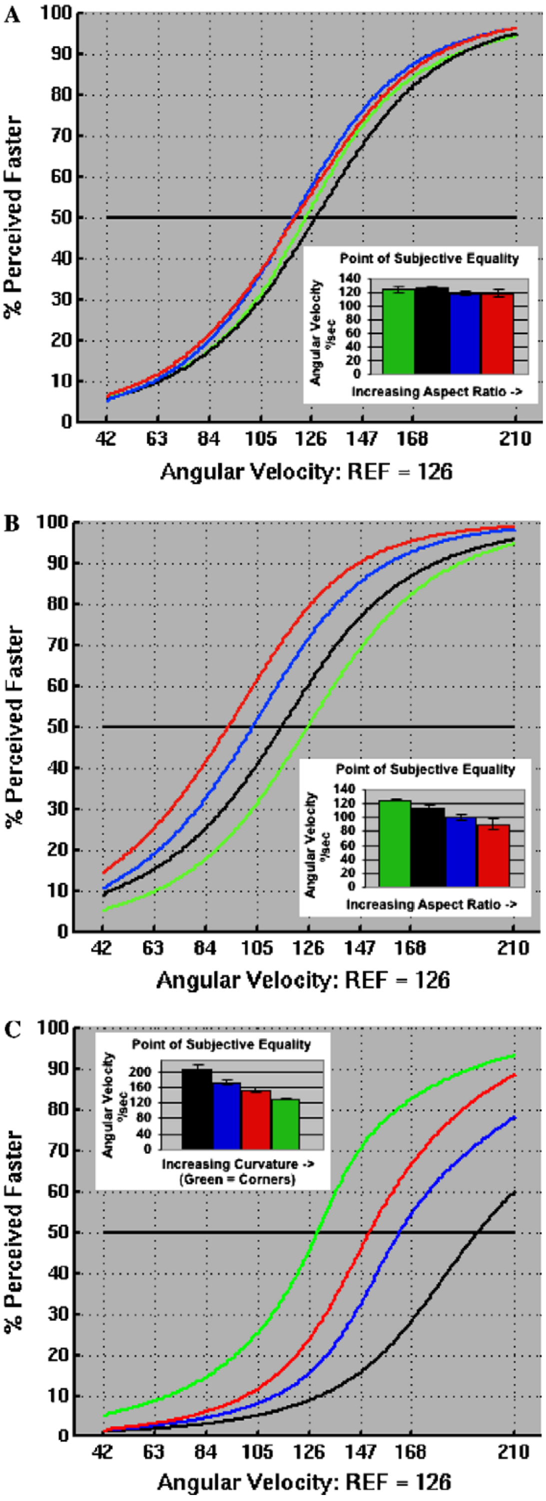

Fig. 4. Results Experiments 2, 4, and 5. (A) Experiment 2: the psychometric functions (corresponding to the colors of the bounding boxes in Fig. 2C) and points of subjective equality (inset) for the rotating rectangles used in Experiment 2. Unlike the ellipses used in Experiment 1, there is no change in perceived angular velocity with changing aspect ratio. (B) Experiment 4: the addition of red dots at the ends of the major axes of the ellipses, reduced the degree to which angular velocity was underestimated as a function of aspect ratio. However, the presence of the unambiguously moving red-dots was not sufficient to completely override the illusory percept. (C) Experiment 5: the perceived angular velocity of rounded rectangles (curves correspond to the colors of the bounding boxes shown in Fig. 5D) closely matches that of the ellipses. As the contour curvature of the rounded rectangles increased, so did its perceived angular velocity. Because the control stimulus (rectangle) was in general perceived to rotate faster that each of the test stimuli, the psychometric functions are shifted downward/rightward relative to the control condition (green).

of subjective equality was computed to determine the speed at which the test ellipse needed to rotate to be perceived at the same speed as the control rectangle.

3.4.2. Results

The mean speed of subjective equality was 138.9°/s (SE = 5.55°/s). A one sample, two tailed t test ($t = 2.33$, $df = 7$, $p < .053$) demonstrated that the ellipse was perceived to rotate slightly slower than the rectangle. Thus, despite the fact that the curvature of the high-aspect ratio ellipse is itself high in magnitude, the perception of its angular velocity is still underestimated.

3.5. Experiment 4: Explicit trackable features

This experiment was designed to examine how additional TFs interact with the perception of rotational motion. In particular, in this experiment, the ellipses used in Experiment 1 were modified by adding a red (22.65 cd/m^2) spot to either end of the ellipses' major axes, as shown in Fig. 2D. This adds an additional source of explicit TF motion information in the sense that a low-level 'red spot detector' could respond to the speed and direction of the red spot regardless of shape and speed information from elsewhere in the image. The dots each subtended 0.485° of visual angle and were positioned so that the outer edge of the dot was tangent to the outer edge of the ellipse.

3.5.1. Method

3.5.1.1. Observers. Nine subjects (six naïve Dartmouth students and the three authors) with normal or corrected-to-normal vision carried out the experiment. Naïve subjects were paid $5 for their participation.

3.5.1.2. Procedure. The same procedure used in Experiment 1 was used in this experiment, with the exception that the ellipses were modified to include the red dots. The aspect ratios and rotational speeds that were used for the test stimuli in this experiment were the same as those used in Experiment 1.

3.5.2. Results

Fig. 4B indicates that the effect that aspect ratio has on perceived angular velocity is reduced in the presence of the red-dot TFs. A repeated measures ANOVA performed on the data from this experiment and Experiment 1a demonstrated a statistically significant interaction between aspect ratio and the presence of the red dots ($F(3, 54) = 6.206$, $p < .001$, $\eta_p^2 = .256$). In Experiment 1, lowest aspect ratio ellipses had to be rotated approximately 85% faster than the highest aspect ratio ellipse to be perceived as rotating at the same angular velocity. With the presence of the red-dot trackable feature, that relationship was reduced to approximately 40%.

3.5.3. Discussion

Consistent with the hypothesis that TFs contribute an additional source of motion information that the visual system can use to construct a perception of rotational motion, the presence of the red-dot trackable features substantially reduced the effect that aspect ratio has on perceived angular velocity. Of particular interest is that despite the presence of the red-dot trackable features, there remains, albeit reduced, an effect of aspect ratio on the perceived angular velocity. This suggests that the additional motion information provided by the presence of the red dots is contributing to rather than completely overriding or supplanting component motion information arising from the contour of the ellipse used to generate perceived angular velocity.

The results of this experiment can also be interpreted conversely in terms of the effect that the ellipse has on the perceived speed of the red dots. In the absence of any ellipse, there would be no basis for perceiving any difference in the rotational speed of the red dot pair, since, in the absence of any ellipses, all red dot pairs would in fact be identical at the level of the stimulus. Changing the context in which the red dot pair is embedded can be viewed as changing the perceived rotational speed of the red dots.

3.6. Experiment 5: Rounded rectangles

Here, we use modified rectangles where corners have been replaced by round segments of contour (rounded rectangles). By preserving aspect ratio and manipulating only the corner regions of the contour, this manipulation specifically seeks to answer whether corners and regions of high curvature are unique form features for the processing of motion, independent of the rest of the contour.

3.6.1. Method

3.6.1.1. Observers. Six naïve Dartmouth students with normal or corrected-to-normal vision carried out the experiment. Each of the subjects was paid $5 for their participation.

3.6.1.2. Procedure. As in Experiments 1, 2, and 4, one control and three test stimuli were used. The control stimulus was a rectangle with the same aspect ratio as the control rectangle used in Experiment 2. The three test stimuli were constructed by replacing the corners of a rectangle identical to the control with circular regions of contour. Each of the test stimuli had a different curvature at the corner, that was controlled for by varying the radius of the circular replacement. The top row of Fig. 5 illustrates an example of how the test stimuli were constructed. The bottom row of Fig. 5 shows the rounded rectangles used in this experiment. The radii of the circular replacements for each test stimulus ranging from highest curvature to lowest are as follows: 0.56°, 0.84°, 1.12° of visual angle.

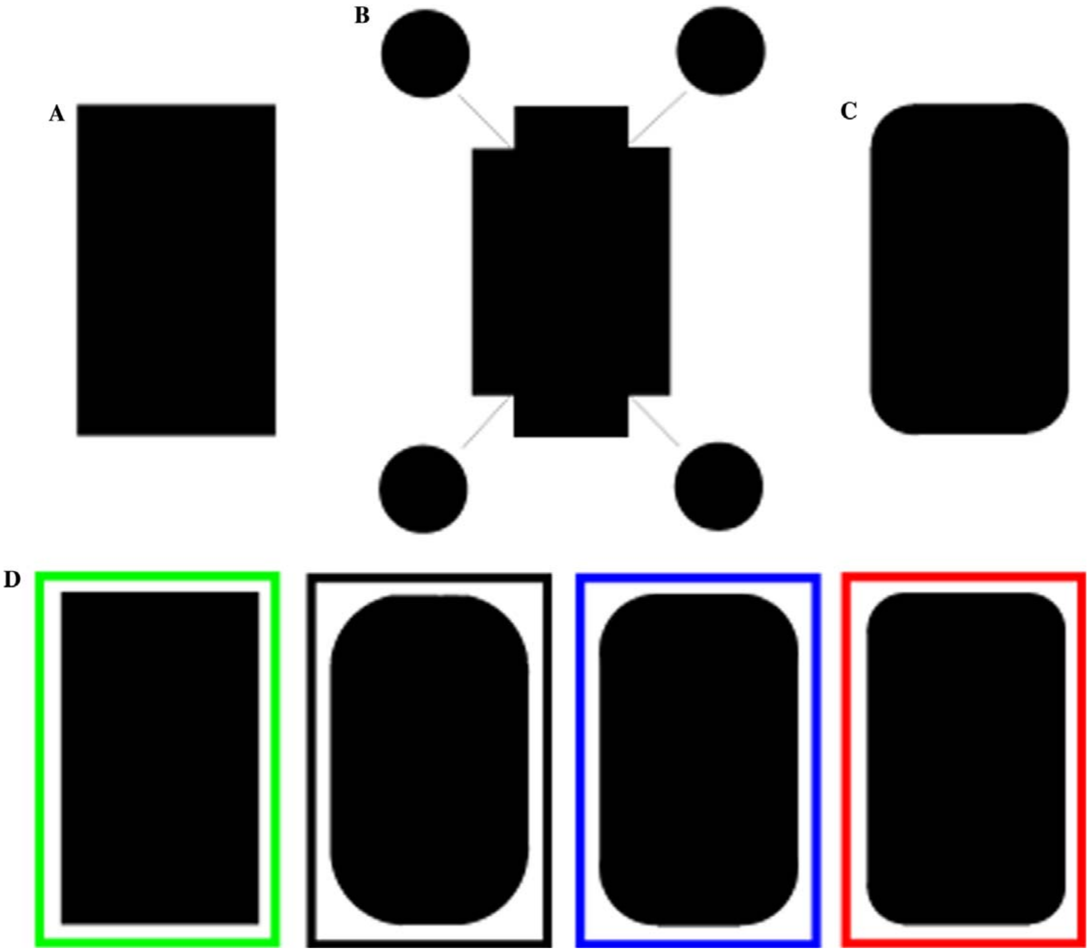

Fig. 5. Rounded rectangles. The rounded rectangles were constructed by modifying a rectangle (A) identical to the one used as the control in Experiment 2. Corners were replaced by circular regions (B) to construct a rounded rectangle (C). The amount of curvature used in each test stimulus (bottom row) was controlled for by changing the radii of the circles used to replace their corners.

3.6.2. Results

The results of this experiment are shown in Fig. 4C. They demonstrate that the perceived angular velocity, as in Experiment 1, varies parametrically with the degree of curvature located along the rounded rectangle's contour.

3.6.3. Discussion

Because the aspect ratio of the rounded rectangles was preserved across the three test stimuli, the majority of the contour remained constant across the stimuli. As such, the results of this experiment suggest that the perception of angular velocity arises from motion signals originating from specific locations, namely corners and regions of high curvature along the rotating contour. These data suggest that the corners present in Experiment 2 are the source of the accurate percept of rotational motion. In the absence of the rectangle's corners, the angular velocity, as is the case for a rotating ellipse, is underestimated.

4. Experiments using non-luminance defined stimuli

These experiments were carried out to determine whether the illusory speeding up of perceived angular velocity with increased ellipse aspect ratio persists even when the ellipses presented are not defined by luminance contrast. In the following sets of experiments, both chromatically defined and motion-defined stimuli are used to examine the relationship between aspect ratio and perceived angular velocity.

4.1. Presentation of chromatically defined stimuli

Luminance values were measured using a Spectra® Spotometer® (Photo Research, Chatsworth, CA, USA) at a distance of 18 cm. Observers viewed the stimuli on a grey background (10.313 cd/m^2) from a distance of 76.2 cm with their chin in a chin rest. Subjects were required to maintain fixation on a yellow square (93.88 cd/m^2) fixation spot that subtended 0.05° of visual angle. Fixation was ensured using a head-mounted eyetracker (Eyelink2, SR research, Ontario, Canada; Tse et al., 2002). Any time the subject's monitored left eye was outside a fixation window of 1.5° radius, the trial was automatically aborted, and a new trial was chosen at random from those remaining. The eyetracker was recalibrated whenever the subject's monitored eye remained for whatever reason outside the fixation window while the subject reported maintaining fixation. Once calibration was completed, the experiment resumed with a random trial. In Experiments 6 and 7, green stimuli were used that were subjectively equiluminant with the grey background.

4.2. The determination of subjective equiluminance

The luminance of the green stimuli used in Experiment 6 was adjusted to become subjectively equal to the grey background for each subject using the minimal flicker technique (Anstis & Cavanagh, 1983). Before the experiment, we presented a green flashing (30 Hz) square that subtended 1.5° visual angle in the center of a grey background (10.313 cd/m^2) and let the subjects adjust the green component of the square's color until minimal subjective flicker was reported. The color of the square was then fixed and applied to the stimuli for the duration of the experiment. The CIE color coordinate of the green square was approximately (.290, .608).

4.3. Experiment 6: Aspect ratio and perceived angular velocity

The goal of this experiment was to characterize the relationship between the aspect ratio of a chromatically defined ellipse and the relative angular velocity at which it is perceived to rotate. In particular, we were interested in making a comparison to the results of Experiment 1. As such, the same experimental parameters and procedures were used as in Experiment 1 with the only exception being that the stimuli were chromatically defined rather than luminance-defined (See Fig. 6A).

4.3.1. Method

4.3.1.1. Observers. Five subjects (four naïve Dartmouth students and one of the authors) with normal or corrected-to-normal vision carried out the experiment. Naïve subjects were paid $5 for their participation.

4.3.2. Results

The results of this experiment, shown in Fig. 7A, indicate that the perceived angular velocity increases as a function of aspect ratio, as was the case with luminance-defined stimuli.

4.3.3. Discussion

The data from this experiment characterize the relationship between aspect ratio and perceived angular velocity of a rotating chromatically defined ellipse. The data corroborate the subjective experience that a "rounder" ellipse will appear to rotate more slowly than a "thinner" ellipse. These data are very similar to those found in Experiment 1. Limitations in the determination of subjective equiluminance preclude the current observation from ruling out the possibility that the perception of rotating objects, even under luminance-defined conditions, is driven solely by the integration of locally generated luminance-defined component motion signals. Because subjective equiluminance is a function of both eccentricity (Bilodeau & Faubert, 1997) and spatial frequency (Cavanagh, MacLeod, & Anstis, 1987; Cushman & Levinson, 1983; Dobkins, Gunther, & Peterzell, 2000; Logothetis & Charles, 1990), the method used to determine subjective equiluminance was unable to ensure that residual luminance contrast did not remain in the stimuli. Indeed, the method used in this experiment can only ensure that the luminance contrast was relatively low compared to the stimuli used in Experiment 1. Despite this limitation, it is apparent that the illusory underestimation of angular velocity is still present in the absence of high-contrast luminance edge information, and suggests that the illusory percept may not be driven solely by low-level luminance-defined sources. This result does not, however, rule out the possibility that chromatic stimuli could be processed by low-level motion detectors in an analogous fashion to luminance-defined stimuli. In fact both physiological (Dobkins & Albright, 1994) and psychophysical (Cavanagh & Anstis, 1991) studies argue for the existence of such low-level chromatically tuned motion detectors.

4.4. Experiment 7: Luminant vs. chromatically defined ellipses

This experiment compared the perceived angular velocity of a luminance-defined ellipse with an ellipse that was chromatically defined.

4.4.1. Method

4.4.1.1. Observers. Five Dartmouth students (four were naïve and one had participated in Experiments 1 and 2) with normal or corrected-to-normal vision carried out the experiment. All observers were paid $5 for their participation.

4.4.1.2. Procedure. The procedure for this experiment was similar to that used in Experiment 1a. Pilot data indicated that the chromatically defined ellipses were perceived to rotate more slowly than the luminance-defined ellipses. To better characterize this relationship, the set of angular velocities tested in this experiment was changed from that used in Experiment 1 to: 21, 42, 63, 84, 105, 126, 147, and 168°/s. Unlike the procedure for Experiment 1, one of the ellipses on each trial was chromatically defined (control) and one was luminance-defined (test). Furthermore, on each trial the control and test ellipses had the same aspect ratio, chosen in a pseudorandom fashion from the list of aspect ratios used in Experiment 1a. The control ellipse was rotated at an angular velocity of 126°/s on every trial. The luminance-defined test ellipse was rotated at an angular velocity chosen in a pseudorandom fashion from the list of eight velocities listed above. Trials were counter-balanced with respect to the side where the control ellipse was presented. As in Experiment 1, an entire run consisting of 640 trials contained 20 trials of each pairing.

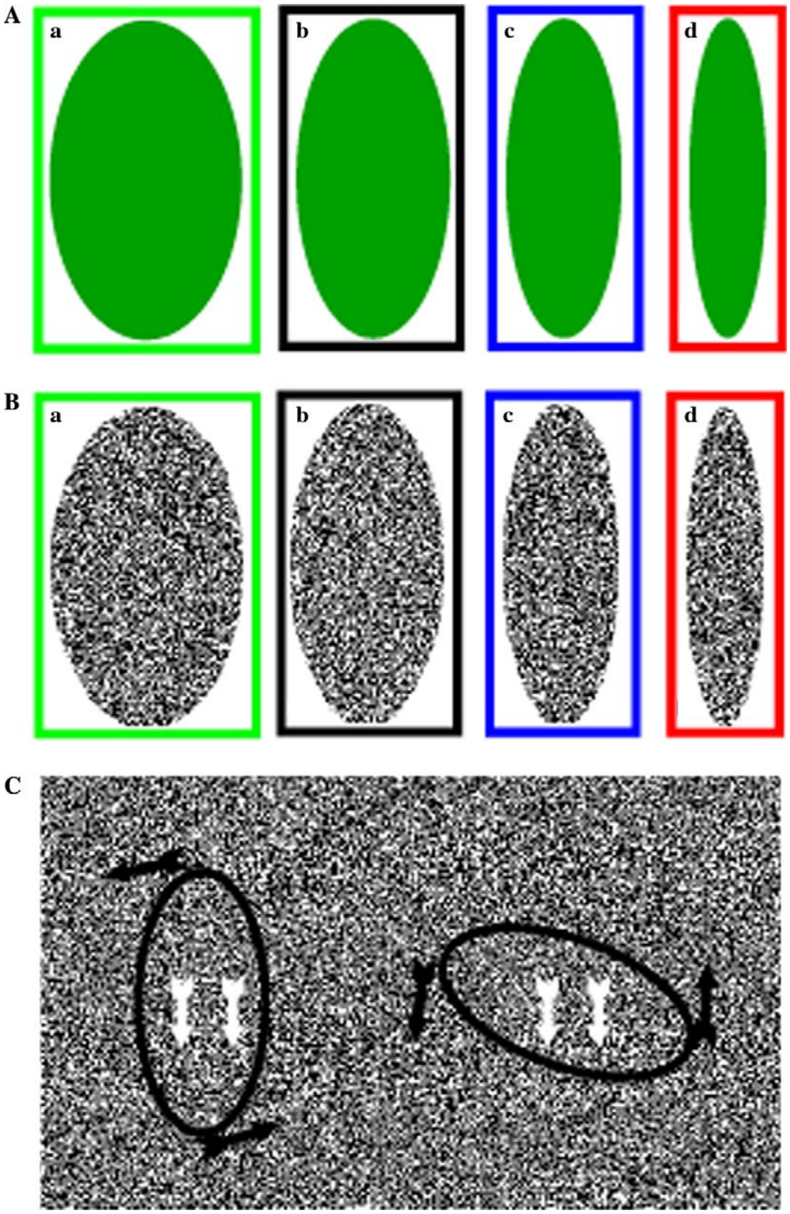

Fig. 6. Non-luminance defined stimuli. (A) chromatically defined ellipses: as in Experiment 1a the control stimulus (a) had an aspect ratio = 5/3. (b), (c) and (d) were the test stimuli with aspect ratios = 25/12, 25/9, and 25/6, respectively. (B) Form from motion ellipses: the aspect ratio of each of the elliptical apertures was identical to the aspect ratios of the ellipses used in Experiment 1a. (C) Defining the form from motion stimuli: the motion (vertical translation relative to a stationary background) of the random dots was uncorrelated with the rotational motion of the elliptical apertures. Note: the black contours shown in these figures was not present in the actual stimulus display.

4.4.2. Results

There are two observations to be made from the data shown in Fig. 7B. The first is that chromatically defined ellipses are perceived to rotate at a significantly slower angular velocity than their luminance-defined counterparts. While there is a large amount of between-subject variability on the magnitude of this effect (as evidenced by the size of the error bars in insert of Fig. 7B), on average (across subject and aspect ratio) a chromatically defined ellipse is perceived to rotate ~40% slower than an equivalent luminance-defined ellipse. The second observation is that there is an interaction between aspect ratio and the ‘cost’ of perceived angular velocity observed between the two classes of stimuli. Specifically, as the aspect ratio of an ellipse increases (gets thinner), the perceived angular velocity of a chromatically defined ellipse becomes closer to that of a luminance-defined ellipse. To quantify this effect, a repeated-measures ANOVA was carried out testing the effect of aspect ratio on perceived speed of subjective equality ($F(3,12) = 9.23$, $p < .002$, $\eta_p^2 = 0.698$) . A post hoc, linear contrast revealed a statistically significant ($F(1,4) = 29.96$, $p < .005$, $\eta_p^2 = .882$), linear relationship between aspect ratio and perceived speed of subjective equality.

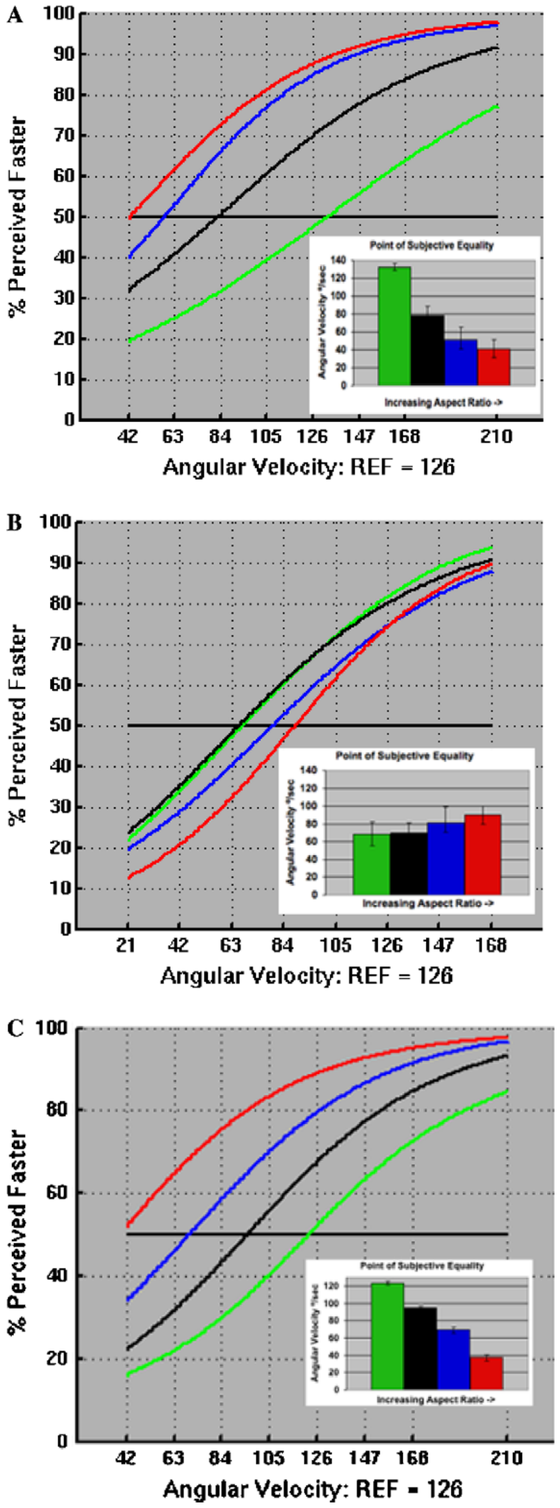

Fig. 7. Results Experiments 6–8. (A) Chromatically defined ellipses: the psychometric curves (corresponding to the color of the bounding boxes in Fig. 6A) and points of subjective equality (inset) show a similar increase (upward/leftward shift of the curves relative to the control condition) in perceived angular velocity as a function of aspect ratio as the luminance-defined ellipses used in Experiment 1a. (B) Chromatic vs. luminance-defined ellipses: each of the psychometric curves is shifted well to the left of the reference velocity of 126°/s. This indicates that no matter what the aspect ratio, the chromatically defined ellipse was perceived to rotate much slower than the luminance-defined ellipse against which it was compared. Furthermore, this underestimation appears to be a function of aspect ratio indicated by the fact that the red and blue curves are to the right of the green and black ones. (C) Relative motion-defined ellipses: like the chromatically defined and luminance-defined ellipses, the ellipses defined by relative motion also exhibit increased perceived angular velocity with aspect ratio. While it is commonly believed that low-level motion energy detectors may exist for chromatically defined stimuli, there is greater debate concerning whether the same is true for relative-motion-defined stimuli. These data imply that the mechanism that drives the percept of angular velocity is common across the processing of a wide variety of stimulus classes, including those for which no low-level detectors are thought to exist.

4.4.3. Discussion

The two observations yielded by this experiment provide valuable information towards understanding the relationship of aspect ratio and the perception of rotational motion. Chromatically defined ellipses are perceived to rotate more slowly than their luminance-defined counterparts. While this observation is not new (Cavanagh, Tyler, & Favreau, 1984), what is novel is the result that the degree to which angular velocity is underestimated under chromatically defined conditions is a function of aspect ratio. Specifically, the higher an ellipse's aspect ratio, the more its perceived angular velocity under chromatically defined conditions matches that under luminance-defined conditions. Together, these interactions of aspect ratio and perceived angular velocity under luminance and chromatic conditions suggest that component signals alone are not the sole contributing factor to the determination of perceived angular velocity, since the component signals should at least be proportional across the luminance- and color-defined ellipses.

4.5. Experiment 8: Form from motion

The preceding experiment probed the perception of non-luminance-defined motion using chromatically defined stimuli. There is evidence that color information alone can trigger the responses of motion-energy detectors (Cavanagh & Anstis, 1991; Dobkins & Albright, 1993a, 1993b, 1994, 1995). Cavanagh has argued that there must exist motion-energy detectors which take luminance, color, and texture as input, but that there are no first-order motion-energy detectors for motion information provided by disparity, or relative motion-defined motion (for review see: Cavanagh, 1995). Thus, the stimuli used in Experiment 6 may trigger responses within a low-level processing system (sensitive to chromatically defined motion energy) even though they were subjectively equiluminant. In addition, limitations in the calculation of subjective equiluminance make it virtually impossible to rule out the possibility of residual luminance information present in the chromatically defined stimuli.

The motion signal arising from trackable features would remain even when stimuli are not defined by luminance, color, or texture. Thus, to make a more general assessment, the perception of rotating ellipses defined by coherent motion (form from motion) was examined. In this experiment, the background against which the ellipses were rotated was made up of a stationary random-dot noise field. The ellipses themselves were defined by the presence of coherent motion within a rotating elliptical aperture. The direction of coherent motion of the random dots used in this experiment was uncorrelated with the direction of the rotation of the ellipse they defined. Thus, local modulations in luminance within the coherently moving dot field could not provide motion information about the speed and direction of the rotation motion of the defined ellipse.

If perceived angular velocity still varies with aspect ratio using stimuli to which low-level motion-energy detectors are blind, we will be able to conclude that the motion signals that drive the illusion are not derived from low-level motion-energy detectors in all cases.

4.5.1. Method

4.5.1.1. Observers. Six naïve Dartmouth students with normal or corrected-to-normal vision carried out the experiment. All observers were paid $5 for their participation.

4.5.1.2. Procedure. In this experiment, motion-defined ellipses rotated against a static background composed of random-dot noise. The background field was composed of 1024 × 1024 randomly distributed (white-noise distribution) pixels defining a square subtending 20° of visual angle in each direction away from central fixation. The intensity of each pixel was randomly selected between white and black. Each ellipse was defined by rotating an elliptical aperture in which random dots moved coherently in a direction uncorrelated with the rotation of the aperture. The random dots within each rotating elliptical apertures underwent either upward or downward translation (Fig. 6C) at a rate of 0.33°/s of visual angle. In each trial the direction of translational motion (either upward or downward) was the same for both ellipses, and alternated from trial to trial. The aspect ratios, and angular velocities were identical to those used in Experiment 1 (Fig. 5B).

4.5.2. Results

As can be seen in Fig. 7C, the illusory underestimation of perceived angular velocity was again observed. As the aspect ratio of the ellipses increased, the perceived angular velocity also increased. This illusory percept has now been shown to exist for luminance-defined, chromatically defined and form-from-motion-defined ellipses.

4.5.3. Discussion

When the motion of the random dots that defined the ellipses was uncorrelated with the rotational motion of the elliptical apertures, the perceived angular velocity was underestimated as a function of aspect ratio. The results of this experiment closely match those observed for the chromatically defined ellipses used in the preceding experiment. From this we conclude that the observations made in Experiment 6 are likely not due to residual luminance information present in the stimuli, since there could be no luminance-defined cues in the present experiment. Furthermore, the illusion of form-dependent angular velocity changes cannot be solely due to low-level luminance or color-driven motion-energy signals.

5. General discussion

As a rigid ellipse rotating at a fixed angular velocity thins, it appears to rotate more quickly. Although the motion processing system is making a fundamental error in assessing motion here, the misperceived angular velocities examined in this series of experiments provide a window into the possible mechanisms that may give rise to these illusory percepts. As such, they may provide insight into the nature of motion processing more generally.

5.1. Summary of results

In the experiments presented here, we characterize the relationship between the aspect ratio of an ellipse and the angular velocity at which it is perceived to rotate. Specifically we observe three main findings. The first of these findings is that as an ellipse's aspect ratio increases, thereby increasing its maximum of positive curvature, so does its perceived angular velocity. This aspect ratio dependent underestimation of angular velocity persists whether the ellipses are luminance-defined, chromatically-defined, or defined by coherent random-dot motion. The second of these findings is that the illusion does not persist for rectangles whose aspect ratio varies. This suggests that aspect ratio per se is not the driving force behind the illusory percept. The third principal finding is that motion signals arising from different sources can contribute to each other to generate a single percept of angular velocity. This was demonstrated by the results of Experiment 4 in which a common motion signal arising from a highly salient red dot placed at the ends of the ellipse's major axis, lessened rather than eliminated the degree to which angular velocity was underestimated. This was also demonstrated by the results of Experiments 6 and 7, where chromatically defined ellipses appeared to rotate more quickly than expected based solely upon component signals, as aspect ratio increased.

5.2. Component motion signals

To investigate the role of component vectors in the perception of angular velocity, we calculated the magnitudes of the component motion signals arising at each point along one leading edge of each ellipse used in Experiment 1, each rectangle used in Experiment 2, and each rounded rectangle used in Experiment 5. Component magnitudes were computed at each point along the contour by projecting the translational velocity vector corresponding to 126°/s onto the vector normal to the contour at that point. The right hand column of Fig. 8, illustrates the magnitudes of

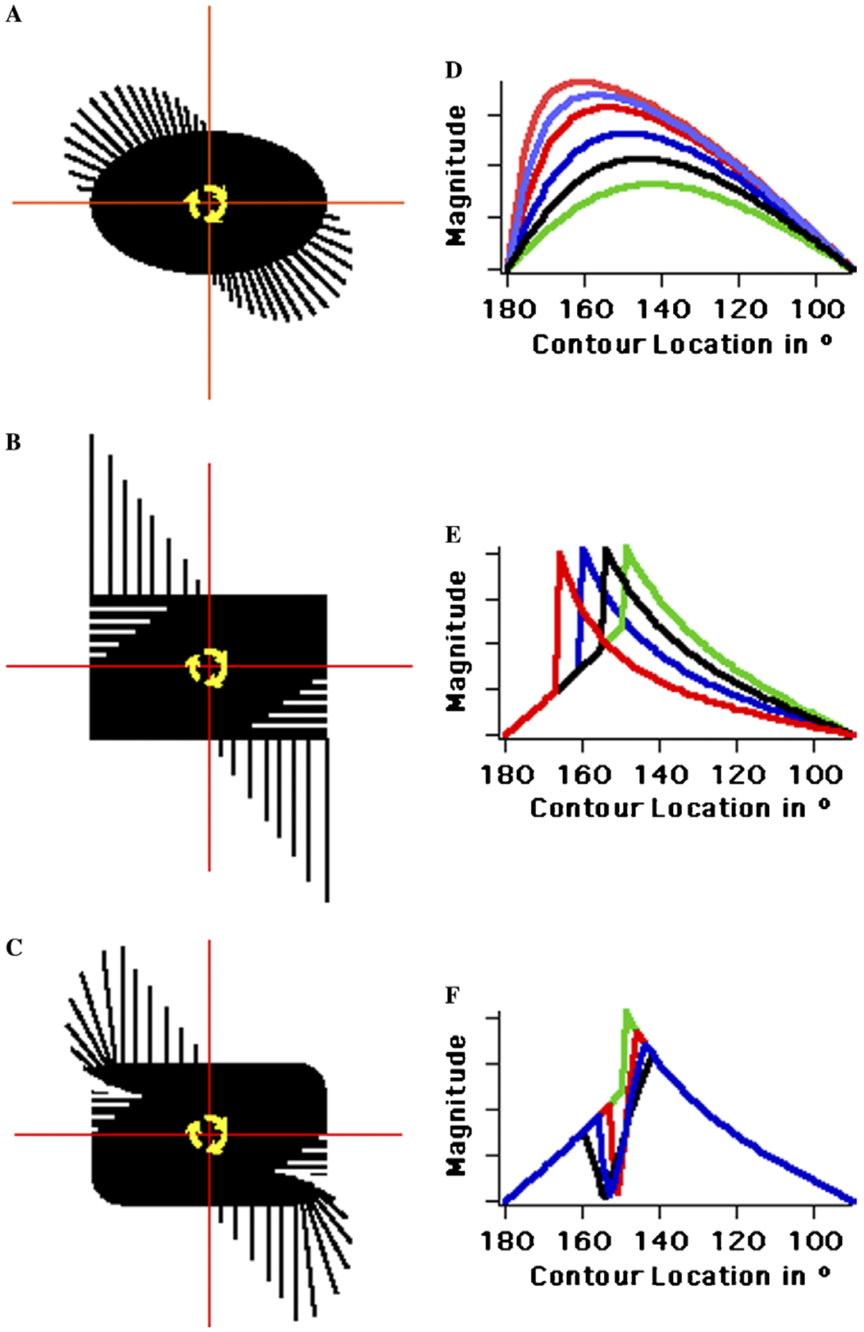

Fig. 8. Component vectors for the stimuli of Experiments 1, 2, and 5. Left column: here, component vectors corresponding to continuous rotational motion in the clockwise direction are plotted along the contours of the control stimuli used in Experiments 1(A), 2(B), and 5(C). The component vector at a particular contour location is computed by projecting the instantaneous translational vector of that location onto the normal vector (or vector perpendicular to the contour) at that point. The magnitude and direction of the component vectors varies along the contours off each stimulus type. A challenge for any component-integration model is to combine these vectors in a fashion that produces a percept of rigid rotational motion that exhibits the illusory motion percept described in this paper. Right column: here, the magnitudes of the component vectors generated from continuous clockwise rotational motion for the leading edge of each stimulus (color corresponds to the associated bounding boxes shown in Figs. 2 and 5) in Experiments 1(D), 2(E), and 5(F). In each plot the magnitudes are plotted as a function of angle sweeping from horizontal location (180°) up and around to the vertical contour location(90°). A clear generalized increase of component magnitude as a function of aspect ratio can be observed in the case of the ellipses. In contrast, no generalized increase is observed in the case of the rectangles. For the rounded rectangles, the component magnitudes are identical across stimulus for extended portions of the contour. This is because outside the rounded regions the contours of the different stimuli are actually the same. Within the rounded regions, some of the components are larger for the lower-curvature stimuli while others the higher-curvature components are larger.

the component vectors for each of the stimuli used in Experiments 1, 2, and 5. The left-hand column in Fig. 8, illustrates the actual component vectors for the control stimulus used in each experiment.

No single model integrating component motion signals yet exists that can explain all motion percepts. It is therefore impossible to quantitatively judge whether or not the component vectors accurately predict the data collected in our experiments. However, inspection of Fig. 8D shows a consistent increase in the magnitudes of the component vectors as a function of increasing aspect ratio. This observation is consistent with the data from Experiment 1. Furthermore, unlike the case for the ellipses, inspection of Fig. 8E shows no such systematic increase in the component magnitudes for the case of rotating rectangles, which again is consistent with the data collected in Experiment 2.

The component magnitudes for the rounded rectangles do not tell as clear a story. Because extended portions of contour for each of the stimuli are identical, so are the magnitudes of the component vectors at these locations. In fact the only place where the contours differ is in the rounded regions. There is no systematic relationship between the component magnitudes in these regions and the data collected in Experiment 5. For example, in portions of the rounded regions, the magnitudes of the components of the lower curvature stimuli are larger than for the higher curvature ones, yet in other portions, the opposite is observed. It is remarkable that the magnitudes of the component vectors shown in Figs. 8D and F can be so radically different while the perceptual experiences observed in Experiments 1 and 5 are so similar. However, despite this discrepancy, even simple models based on component magnitudes do an excellent job predicting the perception of angular velocity. For example, Fig. 9 illustrates the predicted point of subjective equality for each of the stimuli used in Experiments 1, 2, and 5 (Figs. 9A–C, respectively) based solely on the magnitude of the maximum component vector. While it is unlikely that the maximum component vector would be the sole contributing factor in the computation of angular velocity, that such a simplistic model can accurately predict the data strongly supports the hypothesis that the perception of angular velocity is largely driven by the magnitudes of the component vectors.

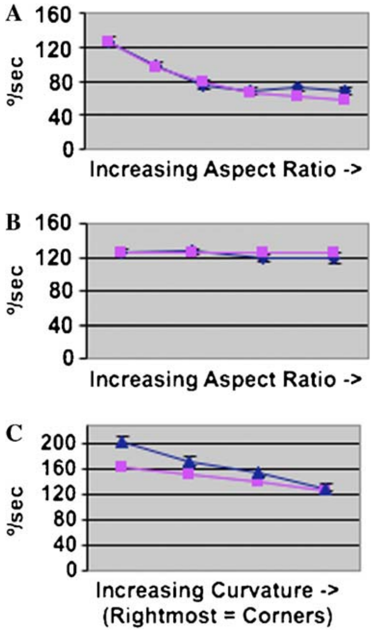

Fig. 9. Maximum component vectors predict perceived angular velocity. In each plot the blue curve represents the point of subjective equality computed from the psychometric curves generated for Experiments 1(A), 2(B), and 5(C). The pink curve represents the predicted point of subjective equality based on taking the ratio of the maximum component vector of the control stimulus and each of the corresponding test stimuli. Despite the overly simplistic nature of this model, the magnitudes of perceived angular velocity are very accurately predicted for all three experiments.

Inspection of the left-hand column of Fig. 8 makes apparent that each of the three stimulus types has a unique distribution of component vectors, yet qualitatively each stimulus is perceived to rotate rigidly in the 2D plane. While it is possible that a model for integrating component vectors may yet be found that can reconcile these observations, to our knowledge such a unifying model does not yet exist. It is possible that no such model exists. It may not be possible to reconstruct a rigidly rotating shape from the integration of such disparate and continually changing component vectors. Instead, object rigidity may arise from the outputs of a non-component analysis. One possibility is that there is a process of form analysis that decides whether an object has deformed, translated, or rotated, and that the outputs of this process are combined with the outputs of component motion processing to create a final percept of rigid rotation.

It has been shown that very low aspect ratio ellipses will be perceived to deform non-rigidly in the 2D plane as they rotate. Weiss and Adelson (2000) demonstrated that the non-rigid percept is completely compatible with the magnitudes and directions of the component motion signals themselves. In the case of rigidly rotating ellipses that appear to rotate non-rigidly, it is as though the common direction of rigid-motion (rotation) is not made explicit to the visual system. In stark contrast to the low aspect ratio gelatinous ellipses examined by Weiss and Adelson, all of the stimuli used in this study had relatively high aspect ratio and were thus perceived to rotate rigidly.

Because our stimuli appear to rotate rigidly, it can be concluded that the true direction of motion for each point along the contour is made explicit somewhere in the visual system. However, if the direction of motion is known at each point along the contour, then the correct speed should in principle be easily computable from the magnitude of the component motion signal at that point. It would simply be the projection of the component onto the true motion direction existing at each point. In the case of ellipses that are perceived to rotate rigidly in the 2D plane, the visual system has at its disposal all the information necessary to produce accurate velocity estimates. If the visual system were computing the magnitude of component motion lying in the direction tangent to the circular path dictated by object rigidity, there would be no illusion. All ellipses would be perceived to rotate at the same angular velocity. Since there is an illusion of perceived angular velocity, we can conclude that the visual system is not carrying out this simple computation, and is therefore not taking advantage of all the information available to it in computing angular velocity. Instead, the perception of angular velocity appears to be driven in large part by the magnitudes of component motion signals. However, as the red dot experiment makes clear, perceived angular velocity is not solely due to the magnitudes of component signals. It appears to also be modulated by motion signals derived from trackable features.

While the component motion processing system is driven by motion-energy signals, the illusion persists even with relative motion-defined stimuli, for which no motion-energy detectors exist (Cavanagh, 1995). One possibility is that component motion processing is itself not solely driven by standard motion-energy detectors. For example, it is possible that second-order motion computations (e.g., Ledgeway & Smith, 1994, 1995; Mather & West, 1993; Seiffert & Cavanagh, 1998) contribute to the generation of component motion signals. Another possibility is that the illusion is not solely driven by component signals, but is instead also driven by signals from trackable features. The interaction between form and motion observed in Experiment 4 suggests that this is the case.

5.3. *Trackable features*

Depending upon the shape characteristics of a moving contour, there are contour locations along a contour that generate unambiguous motion signals. For example, corners, terminators, and junctions move unambiguously when they are intrinsically part of the moving object. It has been hypothesized that such 'trackable features' (TFs) can be used to disambiguate ambiguous component motion signals that arise away from TFs (Ullman, 1979). An alternative solution to the aperture problem than that provided by the appropriate integration of component signals thus lies in exploiting TFs.

Relying solely on TFs, however, creates new problems that are in some ways as problematic as the component-motion solutions to the aperture problem. For one, corners, terminators, and junctions can arise in the image for reasons of occlusion that have nothing to do with the motion of the stimulus. These 'extrinsic TFs' give rise to spurious motion signals that can lead to incorrect conclusions about what motion is actually taking place in the world (Shimojo, Silverman, & Nakayama, 1989). As such, for a trackable feature to provide an accurate source of motion information, it must first accurately be assigned to the appropriate contour. The visual system appears to get around the ambiguities of motion stimuli by having multiple motion systems that process different characteristics of the moving stimulus (motion energy, form, and salience). As the present illusion of misperceived angular velocities makes apparent, however, even having two or more complementary motion systems in place can lead to incorrect judgments of motion.

The results of the experiments conducted in this study are not only consistent with component models, but are also consistent with the trackable feature hypothesis in which the motion of the trackable corners and regions of high curvature is extrapolated to the rest of the object's contour. In Experiments 1 and 5, as contour curvature increases, thereby presumably increasing the strength of the motion signal these TFs produce, perceived angular velocity increases. In the case of rotating rectangles, the trackable features (corners) are held constant across aspect ratio, and the percept of angular velocity remains constant as a function of aspect ratio. The trackable feature hypothesis is also consistent with the observation that perceived angular velocity is underestimated under chromatically-defined conditions (Experiment 6) and when motion is defined by relative motion (Experiment 8). Accounting for these results in terms of a purely component-based solution is difficult because there is debate as to whether low-level component motion signals can be generated by such stimuli (Cavanagh, 1995).

The results of our experiments provide an important insight into the way trackable features may be processed. In Experiment 2, the trackable features are corners that remain constant across each of the different rectangles. Because the aspect ratio of each rectangle is different, the distance from the center of rotation to the corner of each rectangle is different. Specifically, the distance from the center to the corner of the fatter rectangles will be greater than that of the skinnier rectangles. As such, the actual instantaneous translational velocity of the corners is inversely proportional to the aspect ratio of the rectangle. If the visual system computed angular velocity from the translational velocities of the corners, the fatter rectangles would be perceived to rotate faster than the thinner ones. Because this is not the case, we can conclude that the perception of angular velocity is not driven directly from the translational velocity of the trackable features.

In contrast to the rectangles used in Experiment 2, the regions of high curvature assumed to provide the trackable features of the ellipses used throughout the study are all the same distance away from the center of rotation independent of the aspect ratio. Thus the actual translational speed of the trackable features is identical across aspect ratio as is their distance from the origin. Because the illusion occurs in the case of ellipses, we can again conclude that the perception of angular velocity is not driven directly from the true translational velocity of the trackable features. It is possible that in the absence of high curvature, the translational velocity is underestimated, leading to a perception that low aspect ratio ellipses rotate slower than high aspect ratio ellipses.

The data presented in this paper are consistent with the hypothesis that corners and regions of high curvature can serve as trackable features. The detected motion of these form-features can then be propagated to the rest of the contour. However, the current data do not establish the degree to which the illusion of perceived angular velocity is due to trackable features or component motion signals.

5.4. *Neurological basis for trackable features*

The evidence described here suggests that component motion signals dominate in the generation of the percept of angular velocity, although how this precisely occurs is unclear. However, we cannot and do not wish to conclude that the motions of trackable features are not used to generate a motion signal that constrains or even wholly specifies object motion. Quite to the contrary, 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 intermediate contours. Furthermore, they respond more to intrinsically owned terminators than to extrinsic terminators (Pack, Gartland, & Born, 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 & Born, 2001). These same neurons will, over a period of approximately 60 ms, shift their response properties so that they 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 are in the direction perpendicular to the moving line, and then rapidly adapt to follow the direction of veridical motion as defined by the terminators of the lines (Pack & 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, Livingstone, Duffy, & Born, 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. Indeed, contour discontinuity information may be extracted even before V1, since circular center-surround receptive fields will respond more to corners than to edges, and more to bar terminators than corners (Troncoso, Macknik, & Martinez-Conde, 2005).

While trackable feature motion may strongly constrain perceived translational motion, this does not appear to be the case for rotational motion, where component signals appear to dominate perceived angular velocity. Why might this be? Note that rotational motion presents an entirely different set of computational problems to the visual system than translational motion. For the case of translational motion, it is useful to shift to the direction dictated by trackable features such as terminators because these trackable features indeed do carry information about global translational motion that is immune to the aperture problem, assuming global shape rigidity. Note that all trackable features should share the same motion direction and magnitude, assuming object rigidity. In a sense, it is as if global translational motion direction and magnitude is computed 'for free' from the motion of trackable features. In contrast, the motion of local trackable features contain no 'free' information about global rotational motion, even assuming rigid rotation, because the instantaneous direction and motion magnitude of a trackable feature can vary dramatically with its placement along an object's contour, even at a fixed angular velocity. Indeed, every trackable feature on a rigidly rotating object would have a different instantaneous direction and magnitude of translational motion. Thus, even if angular velocity were derived from the motion signals of trackable features, angular velocity would have to be computed by integrating motion signals from trackable features located around an object's contour. Because of the potential complexity of this computation, the visual system may rely primarily on some unknown function of the magnitudes of detected component signals when determining the magnitude of perceived angular velocity, even if it relies more heavily on trackable features in the case of determining the magnitude of translational motion.

6. Conclusion

The data provided in this paper, quantify the subjective impression that objects with corners or high contour curvature appear to rotate faster than objects with lower contour curvature rotating at the same objective angular velocity. We show that this is true for both luminance-defined, chromatically-defined, and relative motion-defined objects. The data are consistent with two alternative hypotheses for how the perception of rotational motion is generated, namely the integration of component motion signals, and the tracking of unambiguously moving contour features. Our data suggest that both trackable features and component signals contribute to perceived angular velocity, although component signals appear to dominate. How these motion signals are combined remains unresolved. A focus of future research will be to dissociate trackable feature motion from component motion to determine their relative contributions to perceived angular velocity.

Acknowledgments

We thank Heather Kiefer, Patricia Olszynski, and Kendra Vierbickas for their assistance in collecting the data for this project. This project was funded by NIH Grant R03 MH0609660-01 grant to P.U.T. and by a predoctoral NSF fellowship 2005031192 to G.P.C.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.visres.2006.02.026.

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