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Form features provide a cue to the angular velocity of rotating objects

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Abstract

As an object rotates, each location on the object moves with an instantaneous linear velocity dependent upon its distance from the center of rotation, while the object as a whole rotates with a fixed angular velocity. Does the perceived rotational speed of an object correspond to its angular velocity, linear velocities, or some combination of the two? We had observers perform relative speed judgments of different sized objects, as changing the size of an object changes the linear velocity of each location on the object's surface, while maintaining the object's angular velocity. We found that the larger a given object is, the faster it is perceived to rotate. However, the observed relationships between size and perceived speed cannot be accounted for simply by size-related changes in linear velocity. Further, the degree to which size influences perceived rotational speed depends on the shape of the object. Specifically, perceived rotational speeds of objects with corners or regions of high contour curvature were less affected by size. The results suggest distinct contour features, such as corners or regions of high or discontinuous contour curvature, provide cues to the angular velocity of a rotating object.

Keywords

angular velocity; linear velocity; size; rotational motion

What determines how fast we perceive an object to rotate? Although a seemingly simple question, the motion of a rotating object poses distinct challenges that the visual system must overcome in order to construct its perceived speed. Consider for example a moving windmill, the tip of each blade travels a greater distance with each revolution than any other point along the blade's length. As such, the tips are in fact moving at a greater speed than other points on the windmill's blades. However, as part of a rigidly rotating object, the tip necessarily travels the same 360° degrees as each of those other points in the same amount of time. Thus, as a rotating object, the blade possesses a set of different instantaneous linear velocities that correspond to a single angular velocity. The primary question we address in this manuscript is whether the perceived rotational speed of a rotating object corresponds to the object's angular velocity, its linear velocities, or some combination of the two? In this paper, we describe a series of experiments designed to answer this question by examining how changes in the size of an object influence how fast it is perceived to rotate. Unlike instantaneous linear velocity, which depends upon a given point's distance from the center of rotation, angular velocity is size invariant. As such, the degree to which size differences influence an object's perceived speed of rotation can reveal the degree to which we can perceive an object's angular velocity.

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Why might the human visual system *not* perceive the angular velocity of a rotating object? After all, the size invariance of angular velocity can potentially serve as the basis for a kind of perceptual constancy (Fernandez, & Farell, 2007; Hochberg, 1978: MacEvoy, & Paradiso, 2001; Olkkonen, Witzel, Hansen, & Gegenfurtner, 2010) that would allow the perceived speed of rotation to hold constant across changes in size. Such changes in size could occur independently from any rotational motion, for example, due to changes in viewing distance. One likely limiting factor in constructing a percept of angular velocity is the aperture problem (Marr, & Ullman 1981; Adelson, & Movshon, 1982; Nakayama, & Silverman, 1988ab), a term used to describe the fact that the motion of an object, when viewed through a small aperture, is ambiguous: Irrespective of the actual motion of the object, only the motion component perpendicular to the local contour is detectable (component motion). Because early motion-detecting neurons have small receptive fields, they serve as local apertures and, as such, only the motion perpendicular to a moving contour's local orientation is detectable at early stages of visual processing (Marr, & Ullman, 1981; Adelson, & Movshon, 1982). Importantly, the magnitude of the component motion corresponding to the motion of a local portion of a rotating contour will be proportional to the instantaneous linear velocity of that contour location. In contrast, any computation of angular velocity based on the motion of this contour location must take into consideration the distance from the center of rotation, information that is not locally available (Barraza & Grzywacz, 2003). In order to determine the center of rotation, and ultimately angular velocity, motion, and perhaps form information, must be integrated from multiple locations along the object's contour (Porter et al., 2011). Due to this constraint, one may well ask if the human visual system is equipped to perceive angular velocity at all.

Past work investigating this question has yielded somewhat conflicting results. As angular velocity is size-invariant, the most straightforward strategy is to examine the relationship between size and perceived rotational speed. When simulated three dimensional cubes of varying sizes were rotated around an x and y axis, it was found that smaller objects had to be rotated faster in order to be perceived as rotating as fast as their larger counterparts (Kaiser, 1990). This result suggests that observers do not perceive the angular velocity of a rotating object, at least in three-dimensions. However, the size-speed relationship was not perfectly predicted by differences in the actual linear velocities of the differently sized cubes, suggesting that perceived rotational speed is not determined solely on the basis of the instantaneous linear velocities as well. The size invariance of perceived rotational speed has also been studied using dotted annuli. It was found that as the radius of rotation of 8 dots making up an annulus was increased, the dots were perceived to rotate faster (Werkhoven, & Koenderink, 1993). Consistent with the results obtained using rotating cubes, this observation strengthened the view that the human visual system lacks a specific mechanism to extract the size invariant information necessary to support the perception of angular velocity. However, there is some evidence to suggest that such mechanisms do indeed exist. For example, although size invariance was not demonstrated, it was found that angular velocities of rotating 3D objects could be discriminated with high accuracy (Kaiser, 1990). However, it has also been demonstrated that discrimination of the angular velocity of dotted annuli can be affected by a variety of factors such as the number of dots making up an annulus and their physical distribution (Werkhoven, & Koenderink 1991). Building upon these findings, it was demonstrated that varying the number of dots making up each rotating annulus could influence the relationship between size and perceived rotational speed (Barraza, & Grzywacz, 2002). Specifically, it was shown that when there are enough dots, and thus, the dots remain close enough together, changing the annulus radius did not alter its perceived rotational speed. Together, these results suggest that depending on the stimulus conditions, angular velocity can indeed be perceived.

Here, we further examine the conditions under which the angular velocity of a rotating object may be perceived. Specifically, we examine the role an object's shape plays in determining whether perceived rotational speed will be based upon angular or linear velocity. Our past work has demonstrated that the shape of a rotating object can influence how fast it is perceived to rotate (Caplovitz, Hsieh, & Tse 2006; Caplovitz & Tse 2007ab). In particular, objects such as rectangles and skinny ellipses with corners or regions of high curvature appear to rotate faster than those without. One hypothesis for why this is the case is that the motion of distinctive form features, such as contour discontinuities and areas of high contour curvature, can provide a cue to the angular velocity of the rotating object. In the absence of such features, the perceived speed of rotation will be based on local estimates of instantaneous linear velocity, which, due to the aperture problem, will likely underestimate the angular velocity of the object.

In the following experiments, we directly investigate whether the motions of such contour features provide a cue to angular velocity. We do this by investigating the relationship between the size and perceived rotational speed of a variety of object shapes with differing degrees of contour features. Across all object shapes, we find that larger objects tend to be perceived as rotating faster than corresponding smaller ones. This indicates that irrespective of shape, observers never fully perceived the angular velocity of a rotating object independent of linear velocity signals. However, the characteristics of this relationship depend on the shape of the object, and are never perfectly correlated with predictions based solely on linear velocity estimates. Importantly, objects with higher curvature relative to their size show less of an effect of size on perceived rotational speed. This suggests that these form features provide a cue to the angular velocity of the object to which they belong.

Additionally, we performed an analysis of how precisely participants are able to discriminate between the speeds of two rotating objects in the form of Weber coefficients. In this case, the Weber coefficients give an indication of what the percent difference must be between the rotational speeds of two objects before participants are able to distinguish between them. We find that participants are relatively poor at distinguishing the speeds of rotating objects, at least for the stimuli and speeds used in our studies. Also, unlike the significant effects of size and shape on perceived rotational speed, the precision with which the speed judgments are made is largely unaffected by size and shape.

Methods

Participants

Observers in each experiment (Experiment 1 Ellipses: N= 6; Rectangles: N= 5; Rounded Rectangles: N= 5; Experiment 2 Ellipses: N= 9; Rounded Rectangles: N= 5; Experiment 3 Stars: N= 6) consisted of student volunteers participating in exchange for course credit from the University of Nevada, Reno. Prior to participating, each observer provided informed consent according to the guidelines of the Department of Psychology, and the IRB of the University of Nevada Reno. All participants reported normal or corrected-to-normal vision and were naïve to the specific aims and designs of the experiments.

Apparatus and display

Stimuli were presented on a Dell Trinitron P991 monitor (19 inches, 1024 × 768) with an 85 Hz refresh rate. The stimulus computer was a 2.4 GHz Mac Mini with an NVIDIA GeForce 320M graphics processor (256MB of DDR3 SDRAM). Stimuli were created and presented with the Psychophysics Toolbox (Brainard, 1997) for MATLAB (Mathworks Inc., Natick, MA). The stimuli were black (.055 cd/m^2) shapes presented on a gray (20.5 cd/m^2)

background. Participants placed their head in a chin rest and viewed the stimuli binocularly from a distance of 57cm.

Stimuli & Procedure

In each experiment, the method of constant stimuli was applied to investigate the effects of size on perceived speed. The stimuli in the first two experiments consisted of ellipses, rectangles, or rectangles with rounded corners. In Experiment 3, the stimuli consisted of six pointed stars with varying degrees of corner angle. In each experiment, we examined the perceived speed of shapes with four different test sizes: 11.74°, 9.98°, 7.04° and 4.11° in height. The perceived speed of each test size was compared to that of a reference stimulus that always had a height of 11.74°.

Changing the size of an object will necessarily change the distribution of eccentricities of its contour locations. For the largest to the smallest test shapes used, shapes extended maximally 3.32°–15.06°, 4.2°–14.18°, 5.67°–12.71°, and 7.14°–11.25° horizontally from fixation. It is known that changes in eccentricity can influence the perceived speed of a moving object (Mckee & Nakayama, 1984). Here we held the distance between fixation and the center of rotation for each stimulus constant: 9.19°. As such, the average eccentricity of each object was held constant across object category and size. Moreover, the starting orientation for each object was randomly determined on each trial. In past research, it has been shown that changes in perceived speed as a function of object shape are independent of eccentricity (Porter, Caplovitz, Kohler, Ackerman and Tse, 2011). Taken together, it is unlikely that changes in eccentricity that coincide with changes in object size play a significant role in determining the perceived speed of the objects tested here.

The width of each shape depended on the experiment in which it was displayed and will be described later. In each experiment, pairs of stimuli (a test and a reference) were presented such that their centers were positioned to the left or right of fixation along the horizontal axis. The reference shape always rotated with an angular velocity of 120°/sec. For Experiments 1 and 2, the angular velocity of the test shape was pseudorandomly chosen from the following list: 40°, 60°, 100°, 110°, 120°, 130°, 140°, 180°, and 200° per second. For Experiment 3, the following speeds were used: 51°, 100°, 110°, 120°, 130°, 140°, and 190° per second.

Trial Presentation

As illustrated in Figure 1, on a given trial, participants were presented with a test and reference stimulus on either side of fixation for 500 ms. Although the brief presentation time of 500 ms made the task difficult, it was used to reduce the possibility of participants using additional strategies to judge relative speed and to minimize the likelihood of a blink or eye-movement being made while the stimuli were on the screen. Each shape began at a random orientation and rotated continuously either clockwise or counterclockwise (randomly determined on each trial). A central circular fixation point (radius = 0.14°) was present for the duration of each experiment and the sides of fixation on which the test and reference stimuli were presented were random across trials. Participants were instructed to indicate which shape appeared to rotate faster, the one on the left or the one on the right of fixation, via a keyboard press. Participants received no feedback during any experiment as to the accuracy of their responses.

Data Analyses

In each experiment, the percentage of times that the test stimulus was perceived to rotate faster than the reference stimulus was computed independently for each condition. Thus, for each of the four test stimulus sizes, nine values (one for each angular velocity) were calculated. Because the 2AFC task has two categorical responses, the following sigmoidal-shaped binomial-logit function was then fit to the corresponding data for each of the two test arrays using the MATLAB (glmfit() command): $f(x)=100\times\left\lfloor\frac{e^{b_1+xb_2}}{1+e^{b_1+xb_2}}\right\rfloor$ (Wichmann & Hill, 2001). For statistical analyses related to the perceived speed of the rotating objects, the point of subjective equality (PSE) (i.e. the angular velocity at which each test stimulus needs to rotate in order to be perceived as rotating at the same angular velocity as the reference stimulus) was computed for each subject. These values were determined by interpolating the 50% chance level from the functions fit to the data: PSE, $x = -b_1/b_2$. For statistical analyses related to the precision with which the rotational speeds of two objects can be discriminated, Weber fractions were derived from the psychometric curves. The Weber fraction was calculated by taking the difference between the speeds at which observers reported the test stimulus moving faster 75% and 25% of the time and dividing this difference by two times the 50% point (PSE). This gives an indication of the precision with which participants were able to judge the relative speeds of the stimuli. For each experiment, separate one-way repeated measures ANOVAs (with size as a factor) combined with *a-priori* linear contrasts were performed in order to determine whether or not perceived rotational speed and the precision with which speed judgments were made were parametrically modulated by size. We note that in the case of precision, the factor of size reflects the ability to discriminate between two different sized objects, and it is the degree to which they differ in size that reflects the levels of this factor. For example, is it more difficult to discriminate the speed of a large and small object than two same sized objects? The design of the experiments does not inform the question of how discrimination ability between two same-sized objects may be influenced by their overall size. For example, is it more difficult to discriminate between two same-sized large objects than two same-sized small objects?

Across experiments, two-way mixed design repeated measures ANOVAs with between subject factor: shape (across experiment) and within subject factor: size, were performed in order to determine interactions between size and shape on perceived rotational speed and speed discrimination ability. For each ANOVA we report partial eta squared (η_p^2), a standardized measure of effect size (Richardson, 2011).

Experiment 1

Stimuli

In Experiment 1, the shapes used were ellipses, rectangles and rounded rectangles. These shapes were chosen to extend observations made using similar stimuli in previous research into shape influences on perceived rotational speed (Caplovitz, Hsieh, & Tse, 2006). These stimuli allow parametric manipulation of basic form characteristics such as contour curvature to be made without dramatically changing the overall shape (i.e. a skinny ellipse is still an ellipse).

To be consistent with past research (Caplovitz, et al., 2006), each shape had an aspect ratio of 5/3 (thus the reference shape subtended 11.74° x 7.04°). Rounded rectangles were constructed by replacing the corners of a rectangle with circular portions of contour (see Figure 5: Caplovitz et al., 2006). The corner replacing circles each possessed a radius equal to 2.93°, 2.49°, 1.76°, and 1.03° for the largest to smallest sized shape. In the case of ellipses and rectangles, participants completed 720 trials in two 360 trial blocks, and all 720 trials in one block in the case of rounded rectangles. In each block, trials were presented in pseudorandom order with the same size and speed combination for the test shape appearing ten times for the ellipses and rectangles, and twenty times for the rounded rectangles.

Results

The raw data along with curve-fits for one subject in the ellipses condition are shown in Figure 2A. The curves show that when the ellipses were rotating much slower than the reference, they were judged as slower, and that when they were rotating much faster than the reference, they were judged as rotating faster. Also, the rightward shift in the curves indicates that as the shapes grew smaller, their perceived speed became slower. This trend is present for all three shapes and is reflected in the PSE graphs shown in Figures 2B–2D. A repeated measures ANOVA revealed a significant main effect of size on perceived speed for ellipses: $F(3,15) = 14.886$, $p < 0.001$, $\eta_p^2 = 0.749$, rectangles: $F(3,12) = 18.172$ $p < 0.001$, $\eta_p^2 = 0.82$, and rounded rectangles: $F(3,12) = 8.789$ $p = 0.002$, $\eta_p^2 = 0.687$. The linear contrast revealed a significant parametric relationship between size and perceived speed as well for ellipses: $F(1, 5) = 19.381$ $p = 0.007$, $\eta_p^2 = 0.795$, rectangles: $F(1, 4) = 24.38$ $p = 0.008$, $\eta_p^2 = 0.859$, and rounded rectangles: $F(1, 4) = 12.213$ $p =0 .025$, $\eta_p^2 = 0.753$. As a measure of precision, the average Weber fraction for all ellipses was 18.65%, for rectangles was 17.77%, and for rounded rectangles was 22.92%.

Comparable statistical analyses were performed on the Weber fractions both here and in the comparisons and experiments that follow. With few exceptions, no significant effects were observed in these analyses of precision. A complete presentation of the precision data and corresponding statistical analyses is included as supplemental material and is briefly discussed towards the end of the manuscript.

Comparison across shape

While all three stimulus types revealed a systematic effect of object size on perceived rotational speed, we wanted to know whether the magnitudes of these effects were the same or different across the three shape categories. That is to say, does size influence the perceived speed of an ellipse, rectangle or rounded rectangle to the same degree? Visual inspection of the PSEs shown in Figures 2B, C and D suggests that, size indeed interacts with stimulus type in determining how fast an object will appear to rotate. For example, the smallest rounded rectangle needs to rotate well over 200°/sec in order to appear to move as fast as the reference rounded rectangle, whereas the smallest regular rectangle only needs to rotate at ~160°/sec in order to appear to move as fast as the reference rectangle. To quantify this observation, we performed a mixed-design 3×4 repeated measures ANOVA with the size of the test stimulus used as a within subject factor, and stimulus shape (ellipse, rectangle, rounded rectangle) used as a between subject factor. As expected, the analysis revealed a significant main effect ($F(3,39) = 23.299$ $p < 0.001$, $\eta_p^2= 0.642$) and parametric relationship ($F(1, 13) = 33.023$ $p < 0.001$, $\eta_p^2 = 0.718$) between size and perceived speed. In addition, a significant main effect was also demonstrated for the shape used in each experiment ($F(2,13) = 6.401$ $p = 0.012$, $\eta_p^2 = 0.496$). Importantly, there was a significant interaction between shape and size demonstrating that the effect of size on the perceived speed of a rotating object is modulated by the shape of that object ($F(6,39) = 3.918$ $p = 0.004$, $\eta_p^2 = 0.376$).

Discussion

The results of this experiment provide clear and compelling evidence that the size of an object influences how fast it is perceived to rotate. For each of our three stimulus classes, the smaller the object, the slower it was perceived to rotate. Based on these observations, we can conclude that people do not perceive the angular velocity of a rotating object independent of linear velocity signals. Instead, people perceive an estimate of rotational speed that is dependent on the size of the object. We also find that the perceived rotational speed also depends on shape of the object.

The shape-dependency observed in the PSE analyses demonstrates that perceived rotational speed does not depend solely on the instantaneous linear velocities, nor even the detected linear velocities (i.e. component motion) (Adelson & Movshon, 1982) of the object’s contour. These linear velocities will always scale parametrically with size independently of shape. For example: if an object is rotating with an angular velocity at ω, then every point along its contour is travelling with a linear velocity of $r\omega$ where r is the distance of the contour location from the center of rotation. As the size of the object changes so will the linear velocity. Importantly, the amount of change depends solely on the change of size and not on the shape of the object.

This fact allows us to derive what the PSEs for each of the test stimuli would be if perceived rotational speed were based solely on the linear velocities of an object’s contour. We can then compare these values with the PSEs derived from Experiment 1. For completeness sake we can also compare the empirically derived PSEs to those that would be predicted if people perceived angular velocity (in this case all PSEs should be equal). As can be observed in Figure 3, for all three shapes the derived PSEs all lie somewhere between what would be expected from linear or angular velocity. However, as suggested by the significant interaction between shape and size revealed above, there are differences between the shapes of the objects. Specifically, the perceived speed of the rounded rectangles very closely matches that expected from linear velocity, whereas the perceived rotational speed of rectangles is much closer to angular velocity. The ellipses on the other hand, lie somewhere in between the rectangles and rounded rectangles.

These results motivate the hypothesis that there are two distinct sources of motion information that are used to construct the perceived speed of a rotating object. The first source of information is derived from the local motion signals detected along the object’s contour (Marr & Ullman 1981; Adelson, & Movshon, 1982; Nakayama & Silverman, 1988ab). These aperture-problem constrained motion signals convey speed information that covaries with linear velocity. For example, for a contour location moving with linear velocity $r\omega$, the detectable component motion (Adelson & Movshon, 1982) will be $r\omega\cos(\theta)$ where θ is the angular difference between the vector normal to the contour at that location and the instantaneous direction of the linear velocity. Because ω and θ will be constant for a given contour location, the magnitude of the component motion signal will scale proportionally with size (i.e. be proportional to linear velocity). The results obtained thus far suggest that the motions of form features, such as corners and regions of high contour curvature provide a second source of information that represents the angular velocity of the object (i.e. size invariant). According to the hypothesis, the perceived speed of a rotating object is dependent upon both of these sources of information. If an object less distinctive contour features, as is the case with the rounded rectangles, then its perceived speed will be dominated by the local motion information and co-vary with size. In contrast, if an object has highly distinctive contour features such as the corners of the rectangles, then its perceived speed will be closer to that predicted by the perception of angular velocity. This two-sources of motion information hypothesis is analogous to those that are thought to underlie a number of perceptual phenomena related to translational motion (Castet, Lorenceau, Shiffrar, & Bonnet, 1993; Gori, Giora, Yazdanbakhsh, & Mingolla, 2011; Gori, & Hamburger, 2006; Gori, & Yazdanbakhsh, 2008; Tse & Hsieh, 2007; Yazdanbakhsh & Gori, 2011). However, the current hypothesis differs from these in that the motion of the form-defined features must be combined with an analysis of the center of rotation in order to represent angular velocity.

In the following experiment, we further test this hypothesis by slightly altering two of the stimuli used in Experiment 1. In Experiment 2 we used rounded rectangles with corners defined by smaller circles and ellipses with higher aspect ratios. These manipulations increase the maximal contour curvature (k) of both classes of stimuli (Sokolov, 2001). The logic behind this manipulation is that in each case the features of these objects will have less ambiguous 2D motion signals (Weiss, Simoncelli, and Adelson, 2002) and thereby contribute more to a size invariant motion signal. In both cases, the hypothesis predicts that changes in size should have less of an effect on perceived rotational speed (i.e. perception closer to that of angular velocity).

Experiment 2

Stimuli

The methods used in this experiment were identical to those used in Experiment 1, with the exception that an aspect ratio of 25/6 was used for the ellipses (thus the reference ellipse subtended 11.74° x 2.82°) and the circles replacing the corners of the rounded rectangles each possessed a radius equal to 1.17°, 0.99°, 0.70°, and 0.41° for the largest to smallest sized shape (compared to 2.93°, 2.49°, 1.76°, and 1.03° in Experiment 1). Participants completed all 720 trials in one block for each shape.

Results

The same data analysis procedures as described in Experiment 1 were used yielding the results presented in Figure 4. As was the case with the previous experiment, the smaller high aspect ratio ellipses and smaller small corner rounded rectangles were systematically perceived as rotating slower than the larger reference shapes. The corresponding repeated measures ANOVA revealed a significant main effect of size on perceived speed for high aspect ratio ellipses: $F(3,24) = 24.888$ $p < 0.001$, $\eta_p^2 = 0.757$ and small corner rounded rectangles: $F(3,12) = 4.014$ $p = 0.034$, $\eta_p^2 = 0.501$ as well as a significant linear contrast for the ellipses of $F(1, 8) = 28.829$ $p < 0 .001$, $\eta_p^2 = 0.783$ but not for the rounded rectangles: $F(1, 4) = 4.272$ $p = 0 .108$, $\eta_p^2 = 0.516$. The average Weber fraction for all high aspect ratio ellipses was 20.098% and 17.443% for the small corner rounded rectangles.

Rounded Rectangles Comparison

Visual inspection of the mean PSEs derived for the rounded rectangles in Experiments 1 and 2 (Figures 2D and 4B) suggests that increasing the curvature of the rounded corners leads the perception of rotational speed to be closer to that of angular velocity. This qualitative observation was quantified by performing a mixed design 2×4 repeated measures ANOVA with the size of the test stimulus used as a within subject factor, and the rounded rectangle corner size (small radius circles, high radius circles) used as a between subject factor. The analysis revealed a significant main effect ($F(3, 24) = 12.113$ $p = 0.001$, $\eta_p^2= 0.602$) and parametric relationship ($F(1, 8) = 16.308$ $p = 0.004$, $\eta_p^2 = 0.671$) between size and perceived speed, as well as a significant main effect for the corner size of the rounded rectangle used in each experiment ($F(1,8) = 5.882$ $p = 0.042$, $\eta_p^2 = 0.424$). More importantly, a significant interaction was observed between corner size and object size ($F(3,24) = 4.231$ $p = 0.016$, $\eta_p^2 = 0.346$).

These data are consistent with the hypothesis that increasing the curvature of the corner regions would shift the balance between form-derived motion signals and local component motion signals leading to percepts of rotational speed that are more consistent with angular velocity.

Ellipses Comparison

The analysis of the ellipse data from both experiments revealed a systematic effect of size on perceived rotational speed. Visual inspection of the PSEs shown in Figures 2B and 4A indicates there may be small interaction between ellipse aspect ratio and size in determining how fast an object will appear to rotate. For example, the mean PSE for the smallest ellipse shown in Figure 2B is 197.25 °/s whereas the corresponding PSE shown in Figure 4A is 180.19 °/s. However, a mixed-design 2×4 repeated measures ANOVA with the size of the test stimulus used as a within subject factor, and ellipse aspect ratio (low, high) used as a between subject factor, suggested that these small differences may be due to chance. While the analysis revealed the expected main effect of size ($F(3, 39) = 39.298$ $p < 0.001$, $\eta_p^2 = 0.751$) and parametric relationship ($F(1, 13) = 48.661$ $p < 0.001$, $\eta_p^2 = 0.789$) between size and perceived speed, there was no significant main effect for the aspect ratio used in each experiment ($F(1,13) = 0.695$ $p = 0.419$, $\eta_p^2 = 0.051$) and no significant interaction between aspect ratio and size ($F(1,13) = 0.914$ $p = 0.443$, $\eta_p^2 = 0.066$). As such, although the data from this experiment are qualitatively consistent with the above hypothesis, this is not born out in the statistical analysis.

Discussion

The results of this experiment have provided somewhat conflicting results regarding the hypothesis that contour features provide a size-invariant cue to perceived rotational speed. The hypothesis predicted that for both the higher-aspect ratio ellipses and higher curvature rounded rectangles, the perceived rotational speed would be closer to the perception of angular velocity. While this was qualitatively the case for both sets of objects, only increasing the curvature of rounded rectangles showed a statistically significant effect on perceived rotational speed. It is possible that this asymmetry may reflect a floor effect in that the perception of the ellipses in Experiment 1 was already well away from linear velocity.

It is also possible that our simplified notion of what constitutes the critical characteristic of a contour-feature in determining the degree to which it will contribute to perceived rotational speed is incomplete. For example, although the contour curvature (k) was increased in Experiment 2 for both the ellipses and rounded rectangles, it was increased by a greater degree for the ellipses (Reference stimuli: $k_{Exp1} = 1.35$; $k_{Exp2} = 8.45$) than the rounded rectangles ($k_{Exp1} = 0.97$; $k_{Exp2} = 2.44$); however, a greater effect was observed for the rounded rectangles across the two experiments.

As a next step in furthering our understanding of a contour-features contribution to perceived angular velocity, we conducted an additional experiment to test the effect of corner angle on perceived rotational speed. There is evidence to suggest that changes in corner angle can influence both perceptual (Troncoso, Macknik, & Matrinez-Conde, 2005) and neural (Troncoso, et al., 2007) representations of objects. Thus far, the 90° angles that define the rectangles in Experiment 1 lead to the smallest effects of size on perceived rotational speed. Is it the case that making the corner angle more acute with further decrease the effect of size on perceived rotational speed; will making the corner angle obtuse conversely increase the effect? Or is it the case that contour discontinuities in general represent a limit to which contour features may contribute to perceived rotational speed? In the following experiment, we test these possibilities by creating a set of stimuli consisting of six pointed stars with corners that are either acute, right or obtuse angles.

Experiment 3

Stimuli

This experiment was conducted to determine if the angle of the corners making up a rotating object would affect the perception of its rotational speed. The procedures used in this experiment were similar to those used previously. However, the shapes in this experiment consisted of six pointed stars. The outer radii of the different sizes of stars were 11.74°, 9.98°, 7.04° and 4.11°, with the reference star always having an outer radius of 11.74°. Thus, as with the previously used shapes, for the largest to the smallest test stars used, stars extended maximally 3.32°–15.06°, 4.2°–14.18°, 5.67°–12.71°, and 7.135°–11.245° horizontally from fixation. In this experiment, participants viewed stars with three different corner angles: 14.25° (acute), 90°(right), and 126.86° (obtuse). The reference and test star always possessed the same corner angle on each trial. In this experiment, the reference star always rotated at 120° per second, and the test star rotated at a speed pseudorandomly chosen from seven possible speeds: 51.43°, 100°, 110°, 120°, 130°, 140°, and 189.47° per second. Participants completed a total of 840 trials with each size, corner angle, and speed combination being presented ten times.

Results

The same data analysis procedures as described in Experiment 1 were used in this experiment. Similar to previous experiments, as can be seen in Figure 5 the smaller stars were systematically perceived as rotating slower than the larger reference star. We performed a two-way repeated measures ANOVA with the size of the test stimulus and corner angle used as a within subject factors. The results revealed a significant main effect of size on perceived speed: $F(3, 15) = 3.860$ $p = 0.031$, $\eta_p^2 = 0.436$, but a non-significant linear contrast of $F(1, 5) = 4.851$ $p = 0.079$, $\eta_p^2 = 0.492$. Moreover, the main effect of corner angle was not significant, $F(2,10) = 1.535$ $p = 0.262$, $\eta_p^2 = 0.235$, and importantly there was no significant interaction between star size and corner angle: $F(6,30) = 1.429$ $p = 0.236$, $\eta_p^2 = 0.222$. The average Weber fraction for all stars was 17.135%.

Discussion

The results of Experiment 3 demonstrate that like the rectangles, the perceived rotational speed of the star-stimuli with contour discontinuities has a strong angular velocity component. We note that the 90° angle used in the star condition yielded very similar results to the rectangles in Experiment 1 that also have 90° corners (comparing Figures 3 and 5) suggesting that increasing the number of contour discontinuities does not significantly contribute to the effect of size on perceived rotational speed. Importantly, neither increasing nor decreasing the corner angles of the stars had a significant effect on the influence of size on their perceived rotational speed. As such the results suggest that at least in the range of corner angle tested here, the presence of a contour-discontinuity represents a limiting case of feature-distinctiveness in the context of perceived rotational speed. It may be the case that for objects with smooth continuous contours (i.e. ellipses and rounded rectangles) it is the degree to which their features approximate discontinuities such as corners that determine how size invariant their perceived rotational speed will be.

Overall Analysis

As a final analysis, we ran a 6×4 repeated measures ANOVA with size as a within subjects factor and shape as a between subjects factor for the PSEs. Because of the within subject nature of Experiment 3, for the purposes of this analysis, mean PSEs and Weber fractions were taken across all corner angles for stars, such that there was one value for each participant for each star size. For the case of the effect of shape and size on perceived speed, there was a significant main effect for size $F(3,90) = 46.391$, $p < 0.001$, $\eta_p^2 = 0.607$, a significant linear contrast $F(1,30) = 61.969$, $p < 0.001$, $\eta_p^2 = 0.674$, a significant main effect for shape $F(5,30) = 4.879$, $p = .002$, $\eta_p^2 = 0.448$, and a significant interaction between size and shape $F(15,90) = 3.636$, $p < 0.001$, $\eta_p^2 = 0.377$. The overall analysis of the PSEs reconfirms the previous findings of the effects of size and shape on the perceived speed of rotating objects: the degree to which size influences perceived rotational speed is shape-dependent.

In the case of the calculated effect of size and shape on precision, a significant main effect of size was only observed in the case of the first set of rounded rectangles, and no significant main effects for shape, or interactions were observed (See Supplementary Material for full Weber statistics).

General Discussion

The purpose of this study was two-fold: first to determine the degree to which observers perceive the angular velocity of rotating objects independently from effects of local linear velocities and second: to determine the role, if any, object shape may play in determining the balance between perceived angular and linear velocities. To accomplish these goals we examined the effect object-size had on the perceived speed of rotating objects, and how this effect was influenced by the shape of the object itself.

With respect to the first goal, the results of each experiment provide unequivocal evidence that the perceived speed of a rotating object is size variant. Specifically, smaller objects appear to rotate more slowly than larger ones. Thus, human observers do not perceive the angular velocity of rotating objects independent of linear velocity signals. The demonstration of size variance highlights the important influence of local component motion signals (Adelson & Movshon, 1992) on perceived rotational speed. However, this is not the whole story. For all objects but rectangles with large rounded corners, results were inconsistent with a sole contribution of component motion signals to perceived speed. For rectangles, ellipses, rounded rectangles with sharper corners and six-pointed stars, the degree to which perceived speed scaled with size was significantly less than what would be predicted by perception of component motion alone, indicating a perception closer to that of angular velocity.

With respect to the second goal, the combined results of each experiment provide strong evidence that the degree to which the perceived speed of a rotating object is modulated by its size is in part dependent on the shape of the object. For example, the perceived speed of a rotating rectangle was scaled by size to a lesser degree than the perceived speed of a rotating ellipse. Similarly, increasing the curvature of the rounded-rectangles reduced the degree to which their perceived speeds scaled with size.

Taken together, these results suggest that the visual system makes use of two sources of motion information in constructing the perceived speed of rotational motion. The first is size variant and the second is size invariant. As suggested above, one likely source of size variant motion information is component motion: local estimates of instantaneous velocity that are constrained by the aperture problem (Adelson & Movshon, 1982; Caplovitz et al. 2006). Component motion signals, by their very nature, are local, and as such will necessarily scale in magnitude with the size of a rotating object. This is because points along a rotating object’s contour move with instantaneous velocities that are a function of their distance from the center of rotation. As such, as an object increases in size, corresponding points will travel greater distances in the same amount of time and will thus move faster at any given moment in time.

The second source of motion information is size invariant and depends upon specific shape characteristics of the object. The data presented here suggest that the motions of corners or regions of high curvature are the source of this size invariant information. One possible neural mechanism that may underlie such form-defined motion information is the activity of motion sensitive end-stopped neurons (Pack & Born, 2001; Pack, Livingstone, Duffy, & Born, 2003). These neurons signal the velocity of line-ends independent of the orientation of the line they belong to. As such, the motion signals they provide are unambiguous with respect to the aperture problem. Corners and regions of high curvature approximate line-ends. Because the local velocity estimates of such form features are unambiguous with respect to the aperture problem, it has been hypothesized that they can provide a strong cue as to the true motion of an object (Ullman 1979; Caplovitz et al. 2006; Caplovitz & Tse, 2007a).

However, local processing of the motion of form features is insufficient to provide a size invariant estimate of a rotating object's speed. Such size invariance requires the integration of local velocity estimates with their distance from the center of rotation (Bertamini & Proffit, 2000; Porter et al., 2011). Relative to the rest of the object, the center of rotation is the one point on the object that is not moving, a fact that may provide some clue to the visual system as to its location (Bertamini & Proffit, 2000). The importance of correctly identifying the center of rotation is highlighted by the fact that when the center of rotation is misperceived, predictable errors in perceived speed are made (Barraza & Grzywacz, 2003). Previous research also indicates that the visual system makes use of low-level contour discontinuities in constructing rotational motion percepts, as top-down assumptions of object rigidity are not sufficient to produce a veridical percept of a rotating rigid object under circumstances such as object occlusion (Shiffrar & Pavel, 1991).

In the case here where an object rotates about its own center, the problem of localizing the center of rotation simplifies to the localization of the object's center. There is evidence to suggest that the center of an object is directly perceived. For example, observers can accurately identify the center of a triangle and will do so even when instructed to identify the midpoint of its height (Anstis, Gregory, & Heard, 2009). Moreover, observers tend to use the center of individual elements that make up an array in determining the size of the array (Boswell & Caplovitz, 2012).

We did not find a similar pattern of results in regards to the Weber fractions, with only size potentially having a significant effect. We found average Weber fractions ranging from 18% to 23% (See supplementary material). These values are higher than some reported in the literature for other types of motion perception (Kaiser, 1990; Orban et al., 1985) indicating that people are in general relatively poor at discriminating the perceived speed of rotating objects. It is possible that this difficulty may be in part explained by task difficulty: the stimuli were presented in the periphery, for brief periods of time, and the size of the test object varied pseudorandomly from trial to trial. Also, the observers in this study were naïve undergraduate volunteers and not trained or experienced psychophysicists.

The literature describes a wide range of Weber fractions for various perceptual tasks. In some cases, such as for the detection of changes in the relative spacing between stimuli, Weber fractions may be as low as <1% (Lappin & Craft, 2000; Lappin, Donnelly, & Kojima, 2001). A wide variety of visual perceptual tasks, such as those involving the perceived rotational velocities of simulated 3-D shapes, the perceived velocities of objects at different eccentricities, the relative bending of objects, the detection of speed changes in moving objects, and the detection of directional changes in moving patterns, have yielded Weber Fractions in the 5%–15% range (Haarmeier & Their, 2006; Kaiser, 1990; Mateeff et al., 2000; Norman et al., 2007; Orban et al., 1985). Other tasks, such as those involving the discrimination of trajectory curvature and velocity discrimination in non-directional stimuli have produced Weber fractions in the >20% range (Authie & Mestre, 2012; Cropper, 1994). Our Weber fraction results appear to fall within the latter categories; however, it must be noted that we only describe Weber fractions for judgments made with one constant reference velocity. Often, when examining perceptual thresholds using the Weber fraction, a range of stimulus levels will be tested often producing a curved "dipper" function describing at what levels observers are most and least sensitive to relative stimulus changes (Cropper, 1994;

Daar, Or, & Wilson, 2012; Mateeff et al., 2000; Orban et al., 1985). Given the nature of our tests, it remains unknown whether the Weber fractions we report represent an upper-bound, lower-bound or intermediate measure of rotational speed discrimination.

The perceived speed results of the experiments presented here add to a growing body of evidence that motion perception in general is mediated by the integration two sources of motion information: component and form-defined. Early work demonstrated that the perceived speed of a translating line is dependent upon the relationship between the orientation of the line (modulates component motion) and the line's ends (form-defined) (Castet, et al., 1993). Moreover, the integration of moving line segments into a coherently moving global object depends in part on the relative strength of the motion derived from the line ends (Lorenceau & Shiffrar, 1992). The integration of component and form-defined motion also underlies a number of visual illusions including the Rotating Tilted Lines Illusion (Gori & Hamburger 2006, Gori & Yazdanbakhsh, 2008), the Accordion Grating Illusion (Gori, Giora, Yazdanbakhsh & Mingola, 2011) and the Dancing Bars Illusion (Tse & Hsieh, 2007). However, unlike these previous studies, the results presented here demonstrate that in the context of rotational motion, the motion of form-defined features gets integrated with the center of rotation to generate a size-invariant cue to the angular velocity of the object.

The above examples and the data presented here all describe two dimensional motions. Areas of high contour curvature and contour discontinuity play an important role in three dimensional motions as well. For example, if fixation is maintained in a given depth plane, disparity and velocity relationships between the two eyes will change as an object moves in depth. It has been shown that 3D motion information can be derived by tracking changes in disparity over time or computing interocular velocity differences (Harris, Nefs, & Grafton, 2008; Nefs & Harris, 2010; Cumming & Parker, 1994; Brooks, 2002; Brooks & Stone, 2004; Harris & Watamaniuk, 1995; Rokers, Czuba, Cormack, & Huk, 2011). Form-features can provide an important source of disparity and velocity information for representing the relative depth of an object. In the case of a horizontal line segment, the line-ends provide the only unambiguous source of disparity information. As such, it has been argued that form-features may serve as an important input to the mechanisms that track an object's motion in depth (Lages & Heron, 2010). However, recent work has suggested that these mechanisms are poor at tracking 2D motions (Zannoli, Cass, Alais and Mamassian, 2012). Form features can also play an important role in constructing the three dimensional structure of an object rotating in depth. For example, if a back-lit bent wire is rotated, its two dimensional project shadow can be perceived to deform in two dimensions. However, if the bending of the wire creates contour discontinuities or regions of high curvature, rigid rotation will most likely be perceived (Kinetic Depth Effect: Wallach and O'Connell, 1953; Sinha and Poggio, 1996). In these cases, the discontinuity serves as a feature that can be used to construct the three dimensional rigid rotation and structure of the object (Ullman 1979). We note that as the feature moved in depth, its 2D motion velocity will change as will its retinal size. It is possible that integrating this velocity with an estimate of the center of rotation to represent the angular velocity of the object helps maintain the rigidity of the object's form and motion.

How and where in the brain form-defined motion information gets integrated with the center of rotation remains unknown. Various brain areas have been identified in macaques and humans that show a preferential response to rotational motion. One such area identified in macaques is the dorsal section of MST (MSTd), which receives projections from macaque MT (Saito et al., 1986; Tanaka, Fukada, & Saito, 1989; Tanaka & Saito, 1989). Areas of human MT have also been identified that show similar patterns of activation (Wall, Lingnau, Ashida, & Smith, 2008). However, high-level motion areas such as MST tend to respond preferentially to full field optic flow, as opposed to the motion of individual objects (Tanaka, Fukada, & Saito, 1989).

To further complicate matters, effects of form features on the perceived speed of rotational motion have been observed both for luminance and non-luminance defined objects (Caplovitz, Hsieh & Tse, 2006). This suggests that the processing of the motion of form features may not be mediated by the neural projection from V1 to MT that underlies much of the elementary processing of motion information. Although many of the neurons in layer 4B of V1 that project to MT are end-stopped (Orban, 2008), these neurons themselves receive input from the magnocellular layers in the LGN, and are thus primarily responsive to spatiotemporal changes in luminance (Levitt, et al., 2001; Schiller & Colby, 1983). This, combined with the fact that the computation of angular velocity requires the non-local processing of both the form-defined motion signal and the center of rotation, suggests that the extraction of the size invariant motion signal arises from processing beyond V1. Promising fMRI results suggest a role for neurons within in human area V3A, which has shown preferential activity for rotational motion (Wall et al., 2008) as well as activity specifically contingent on the degree of contour curvature present on rotating objects, (Caplovitz & Tse, 2007b) even when the objects are non-luminance defined (Caplovitz, Hsieh, & Tse, 2005).

A number of computational models have demonstrated and theorized as to how form features influence perceived motion (i.e. Lu and Sperling, 2001; Weiss, et al., 2002). Notably, the model proposed by Weiss et al. 2002 posits that the perceived velocity of an object is derived by integrating information derived from the linear velocities of local motion signals with the information derived from the linear velocities of form-defined features. This model can account for a number of veridical and illusory motion percepts including the perceived non-rigid deformation of low aspect ratio rotating ellipses. Indeed, the fact that the perceived speed of an object covaries with size follows naturally from this model. This is because the linear velocities of both local motion signals and form features will covary with size. However, the model cannot readily account for the shape dependent nature of these size-related changes in perceived. The data presented here would suggest that before the perceived speed of a rotating object is fully represented, the linear velocity of a form feature is converted to a size invariant representation of angular velocity.

The current data fall short in providing a full description of what constitutes the critical factors that determine the degree to which a form feature will contribute to a representation of angular velocity. Clearly, contour curvature and contour discontinuities play an important role; however, a formal quantitative description of how they contribute to representations of angular velocity is beyond the scope of this paper. The observations drawn from the data presented here provide a rich set of constraints that can help guide future research into the matter.

In conclusion, the processing of form and motion has long been considered to be largely independent, serving to solve distinct perceptual problems: what is the object and where is it going? The results presented here add to a growing body of evidence that suggests the processing of form plays an integral role in motion perception. Specifically, the identification and processing of distinct form features, together with the localization of an object’s center, provides the foundation for size-invariant information about an object’s speed of rotation.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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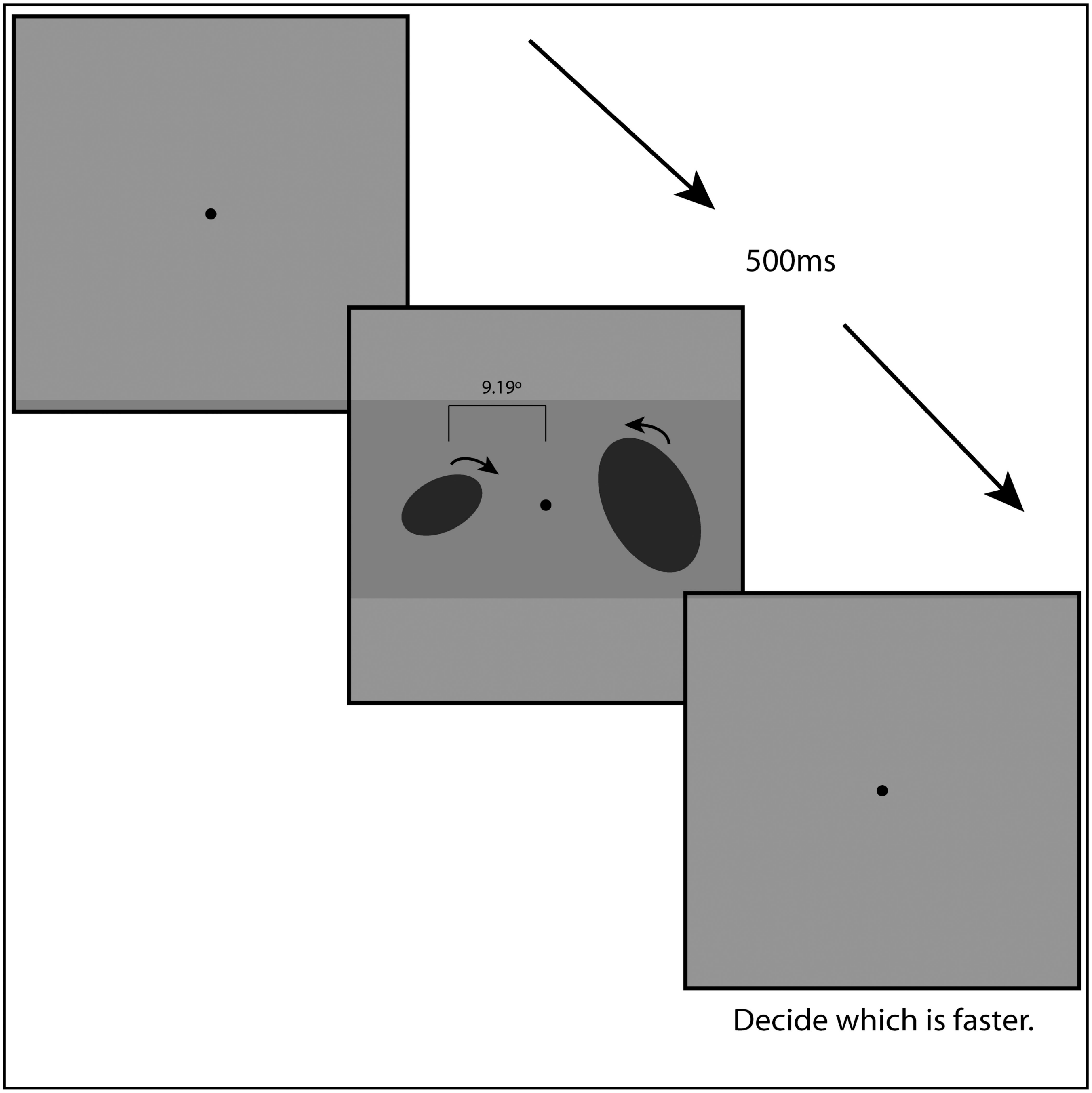

Figure 1. Trial Presentation

On each trial, participants fixated a central dot at all times. Rotating stimuli were presented on either side of fixation for 500ms before the screen returned to displaying only the fixation dot, at which point participants indicated which of the two objects was rotating faster.

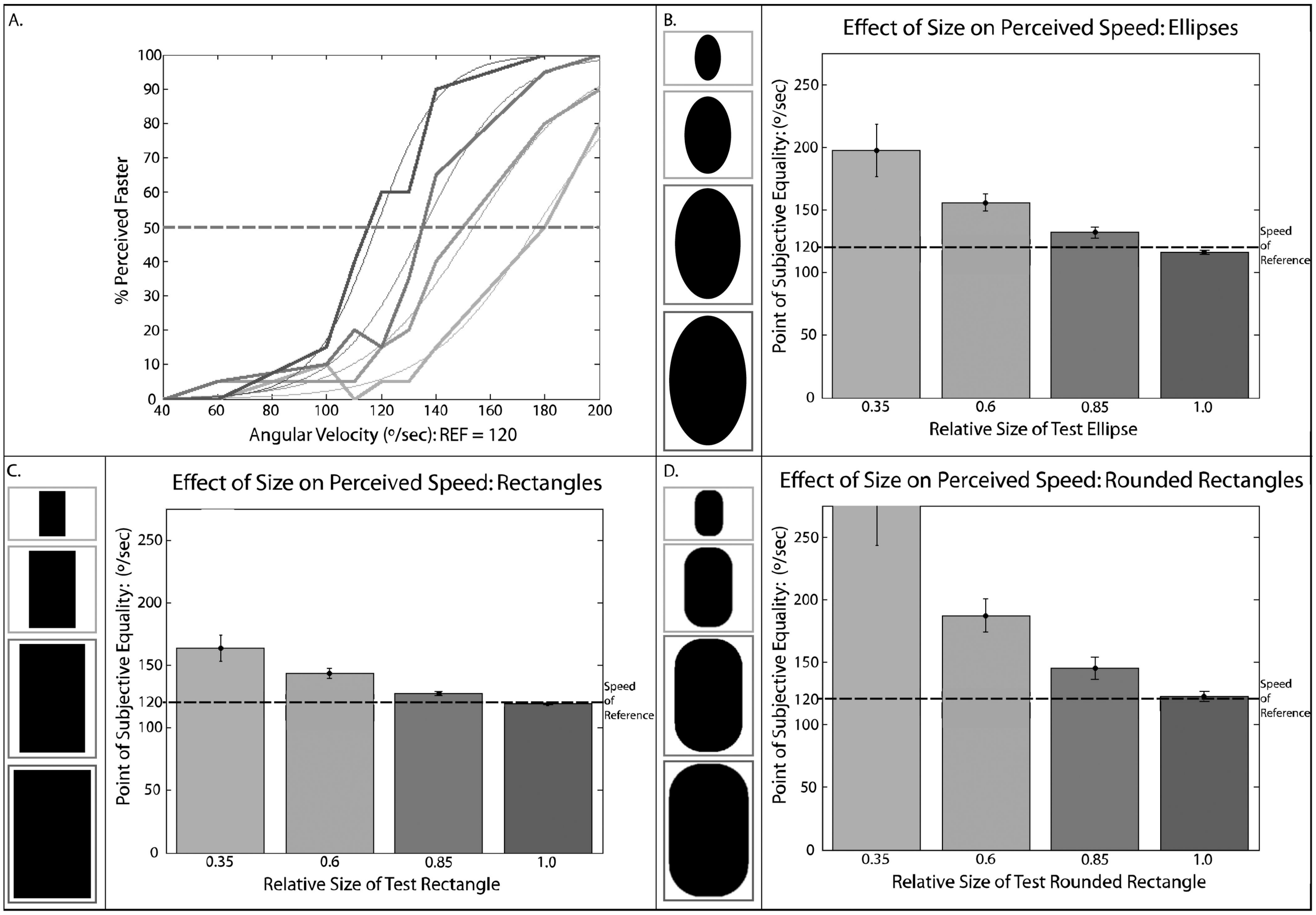

Figure 2. Results Experiment1

(A) *Ellipses*. Data from a representative subject: The psychometric function, and corresponding curve-fits for the rotating ellipses of different sizes used in experiment.

(B) *Ellipses*. Mean points of subjective equality for rotating ellipses across all subjects in Experiment 1 (Shades of grey used here and in (A) correspond to the bounding boxes in the inset to match data with specific stimuli). Higher PSE values on the left of the graph indicate that the smaller ellipses had to rotate faster in order to be perceived as rotating at the same speed as the larger reference ellipse. All error bars represent the standard error of the mean.

(C) *Rectangles*. As was the case with ellipses, the smaller rectangles had to rotate faster in order to be perceived as fast as the larger reference rectangle.

(D) *Rounded Rectangles*. As was the case with ellipses and rectangles, the smaller rounded rectangles had to rotate faster in order to be perceived as fast as the larger reference rounded rectangle. As can be seen by comparing the data shown in B–D, the degree to which size influenced perceived rotational speed was different for each shape-category.

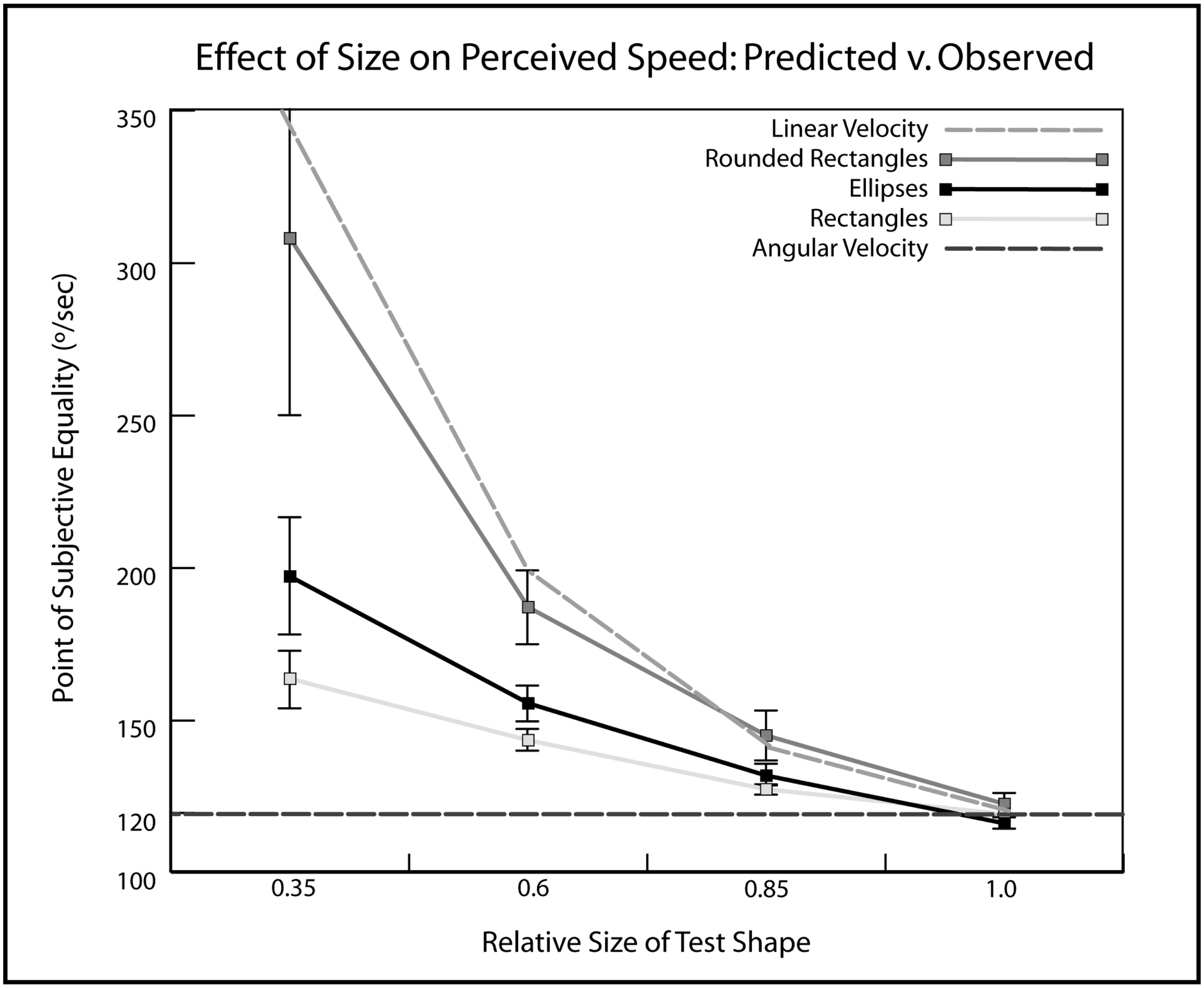

Figure 3. Comparison to linear and angular velocity: Experiment 1

The data shown in Figure 2(B–D) are re-graphed along with the values one would expect if either the angular velocity or the linear velocity of a rotating shape were perceived (dashed lines). The shallower slope created by the observed rectangle values more closely matches the predicted angular velocity line, while the steeper rounded rectangle curve more closely matches the predicted linear velocity line.

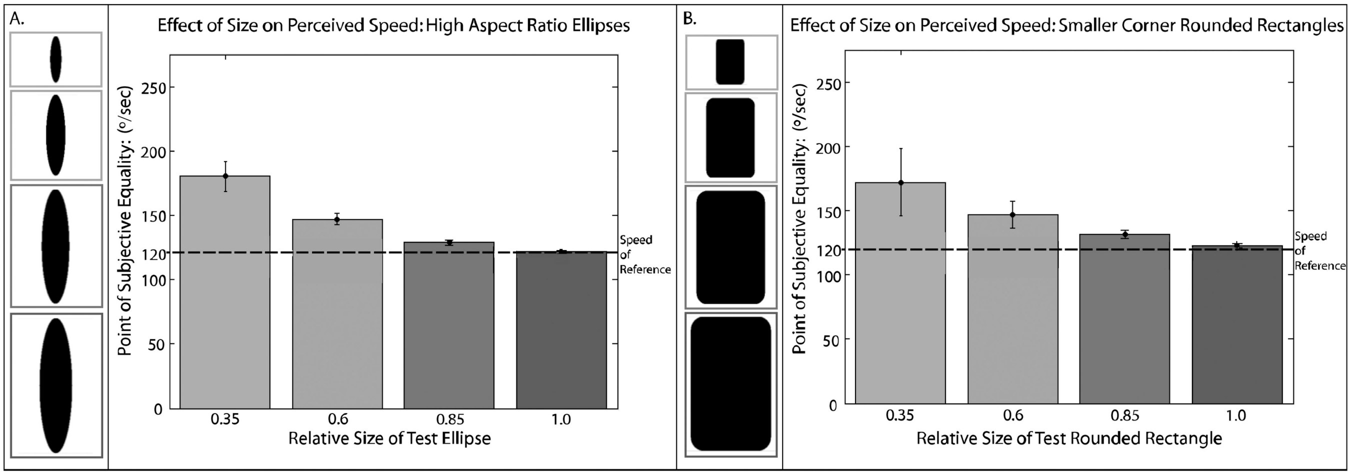

Figure 4. Results Experiment 2

(A) *High Aspect Ratio Ellipses:* Mean points of subjective equality for the higher aspect ratio ellipses. Higher PSE values on the left of the graph indicate that the smaller ellipses had to rotate faster in order to be perceived as rotating at the same speed as the larger reference ellipse. Although the PSE of the smallest ellipse was reduced from ~200°/sec in Experiment 1 to ~180°/sec in Experiment 2, the overall effect of size on perceived speed was not significantly different between the two experiments.

(B) *Smaller Corner Rounded Rectangles:* Mean points of subjective equality for the smaller-cornered rounded rectangles. As in all other instances, higher PSE values on the left of the graph indicate that the smaller rounded rectangles had to rotate faster in order to be perceived as rotating at the same speed as the reference rounded rectangle. Here, changing the curvature significantly reduced the effect of size on perceived rotational speed compared to the results obtained in Experiment 1 (Compare with Figure 2D).

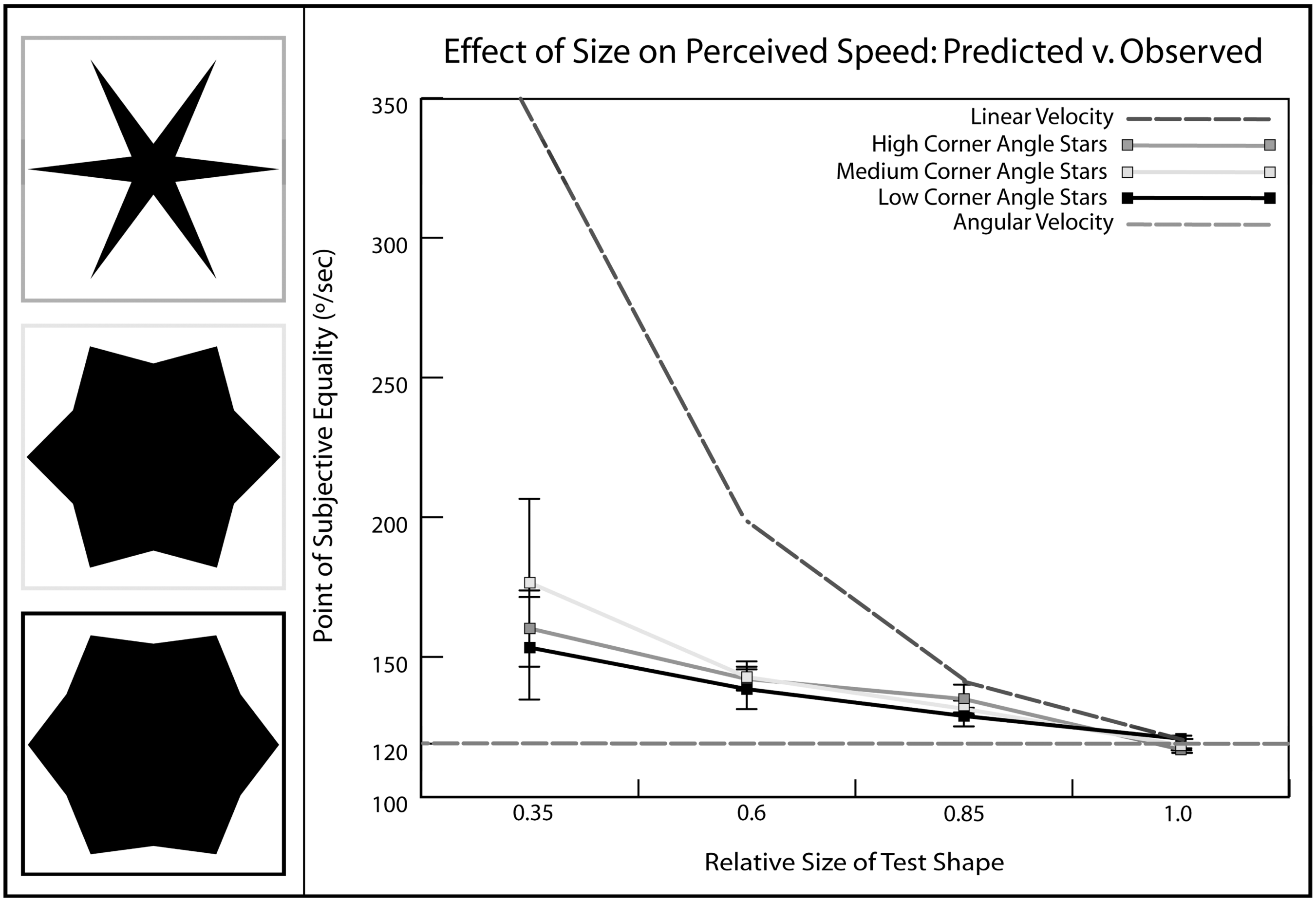

Figure 5. Results of Experiment 3 with comparison to linear and angular velocity

The observed points of subjective equality for each star type used in Experiment 3 are graphed with the values one would expect if either the angular velocity or the linear velocity of a rotating shape were perceived. The close proximity of all three lines to each other indicates that corner angle has little effect on the influence of size on perceived rotational speed in each case. The shallow slope of all three lines closely matches that of the rectangles used in Experiment 1 highlighting a perception close to that of angular velocity.