Visual perception of the physical stability of asymmetric three-dimensional objects

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Visual estimation of object stability is an ecologically important judgment that allows observers to predict the physical behavior of objects. A natural method that has been used in previous work to measure perceived object stability is the estimation of perceived “critical angle”—the angle at which an object appears equally likely to fall over versus return to its upright stable position. For an asymmetric object, however, the critical angle is not a single value, but varies with the direction in which the object is tilted. The current study addressed two questions: (a) Can observers reliably track the change in critical angle as a function of tilt direction? (b) How do they visually estimate the overall stability of an object, given the different critical angles in various directions? To address these questions, we employed two experimental tasks using simple asymmetric 3D objects (skewed conical frustums): settings of critical angle in different directions relative to the intrinsic skew of the 3D object (Experiment 1), and stability matching across 3D objects with different shapes (Experiments 2 and 3). Our results showed that (a) observers can perceptually track the varying critical angle in different directions quite well; and (b) their estimates of overall object stability are strongly biased toward the minimum critical angle (i.e., the critical angle in the least stable direction). Moreover, the fact that observers can reliably match perceived object stability across 3D objects with different shapes suggests that perceived stability is likely to be represented along a single dimension.

Introduction

In addition to estimating the current properties of objects and surfaces based on visual inputs, human observers are very good at predicting how objects are likely to behave in the near future. For example, observers can visually extrapolate the trajectory of a moving object (Becker & Fuchs, 1985; Pavel, Cunningham, & Stone, 1992; Verghese & McKee, 2002), and predict where an object that disappears behind an occluder is likely to re-emerge (Graf, Warren, & Maloney, 1995; Scholl & Pylyshyn, 1999; Shah, Fulvio, & Singh, 2013). Even more impressive are cases where observers can make visual predictions about object behavior based on the inference of unseen forces, such as momentum (Kim, Feldman, & Singh, 2013; Newman, Choi, Wynn, & Scholl, 2008; Todd & Warren, 1982), gravity, and support relations (Barnett-Cowan, Fleming, Singh, & Bülthoff, 2011; Hamrick, Battaglia, & Tenenbaum, 2011; Samuel & Kerzel, 2011). Indeed, infants as young as 8 months of age have been shown to be visually sensitive to support relations and gravity, and are surprised when shown a scene in which an inadequately supported object appears to maintain its position in space (Baillargeon & Hanko-Summers, 1990; Baillargeon, Needham, & DeVos, 1992). Predictions such as these rely on a “causal understanding” of the scene based on visual information (Cooper, Birnbaum, & Brand, 1995).

Traditional work on naïve physics has documented various ways in which people’s intuitions are often inconsistent with Newtonian mechanics (e.g., McCloskey, Caramazza, & Green, 1980). However, when shown dynamic “real-time” displays simulating physical behavior, observers can be quite accurate at detecting deviations from Newtonian mechanics (Kaiser, Proffitt, & Anderson, 1985; Kaiser, Proffitt, Whelan, & Hecht, 1992; Proffitt & Gilden, 1989). More recent work has also demonstrated that observers...
correctly take into account acceleration due to gravity—consistent with Newton’s laws of motion—when timing their hand movements in order to catch a falling ball (McIntyre, Zago, Berthoz, & Lacquaniti, 2001; Zago & Lacquaniti, 2005). These results are also consistent with our day-to-day experiences of manipulating and interacting with objects, where we are generally quite good at predicting the physical behavior of objects and using these predictions to guide our motor actions.

In a recent study on the perception of object stability, Samuel and Kerzel (2011) used planar polygonal objects, shown sitting on a supporting edge/base, with varying degrees of “imbalance”—measured in terms of where the COM of the object lies relative to the center of the supporting edge (including the possibility of being outside this supporting base—in which case the object would not physically stay upright). Subjects indicated whether a given object (shown resting on its supporting edge) would stay upright or fall over. Their responses exhibited a conservative (or anticipatory) bias—i.e., in the direction of perceiving an object to be unstable, even though physically it would maintain its upright posture. These results were interpreted in terms of a conservative tendency to keep judgments of object stability “on the safe side.”

In the current paper, our interest is in the visual estimation of the degree of physical stability of 3D objects which are in stable equilibrium (in the sense that, if left unperturbed, they would maintain their current position). For example, the two objects in Figure 1 are both in stable equilibrium (in each case, the COM of each object is directly above the center of a circular base). However, it is visually apparent that the object in Figure 1a is physically more stable than the one in Figure 1b. In other words, based on vision alone, one would naturally expect that the object in Figure 1a is more resistant to the actions of perturbing forces than is the object in Figure 1b.

One natural way of capturing object stability, therefore, is in terms of the maximal extent to which an object can be tilted away from its “upright” stable position and still return to that upright position when released. We refer to this angle of tilt as the critical angle (see Figure 2). At this angle of tilt, the center of mass (COM) of the object is directly vertically above the point of contact on the base, around which the object is being rotated (see Figure 2c). By definition, any tilt greater in magnitude than this critical angle will result in the object toppling over, rather than returning to its upright position. With this definition in mind, it is easy to appreciate that the object in Figure 1a is physically more stable because it has a larger critical angle than the one in Figure 1b.

In previous work, we have used the visual estimation of critical angle to measure the perception of stability for three-dimensional objects that were rotationally symmetric (Barnett-Cowan et al., 2011; Cholewiak, Singh, Fleming, & Pastakia, 2010). While critical angle provides a natural measure of overall physical stability for such objects, the situation is more complicated for asymmetric 3D objects. Specifically, for an asymmetric object, the critical angle is not a single value, but depends on the direction in which the object is tilted. Since the object can be tilted in any radial direction varying from 0° to 360°, the critical angle is really a function defined on [0°, 360°). However, as we will see, observers can reliably judge the overall stability of such

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**Figure 1.** Two objects sitting near the edge of a table, one that is very perceptually stable (a) and one that is very perceptually unstable (b).
an asymmetric 3D object. This ability raises the question of how people combine the information about different critical angles in different possible tilt directions into a single overall estimate of the physical stability of an object. To address this question, we use two experimental methods: visual estimation of critical angle in different directions (Experiment 1) and perceptual matching of overall stability across objects with different shapes (Experiment 2 and Experiment 3).

In Experiment 1, we explicitly test how well people can estimate the critical angle of an object as a function of the direction in which the object is tilted relative to its direction of intrinsic skew. In Experiments 2 and 3, we ask how these different critical angles in different tilt directions are combined into a single estimate of overall stability. Specifically, we compare two natural combination rules: (a) that the overall perceived stability is determined by the average critical angle across all possible tilt directions; and (b) overall perceived stability is determined by the minimum critical angle (i.e., the critical angle in the least stable direction).

**Experiment 1: Measuring critical angle in different directions**

In the first experiment, we investigated whether observers could accurately track the critical angle of asymmetric 3D objects as a function of the direction in which they are tilted. The objects used in these experiments were skewed conical frustums (see Figure 3). In what follows, it will be important to distinguish between (a) the direction in which the object is tilted (the magnitude of tilt is adjusted interactively by the observer); and (b) the intrinsic direction of skew of the conical frustum objects. The angle of relevance to us is the direction in which the object was tilted measured relative to the intrinsic direction of skew of the object. We refer to this angle as \( \alpha \). In the experiments, the object was always tilted directly over the precipitous edge of a table, but the direction of intrinsic skew of the object was varied from trial to trial, thereby manipulating \( \alpha \) (see Figure 4).

**Methods**

**Observers**

Fourteen Rutgers University undergraduate students participated for course credit. All reported normal or corrected-to-normal vision.

**Apparatus**

The stimuli were generated in MATLAB 2012a using Psychotoolbox-3 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) running on an HP desktop computer—with an Intel Core i7 870 processor (8MB cache, 4-cores running at 2.93 GHz) and 4 GB of RAM—and presented on a Sony Trinitron 20 inch CRT with a 1024 × 768 pixel resolution at a refresh rate of 140 Hz. Within Psychotoolbox-3, experimental scenes were rendered using the Matlab OpenGL (MOGL) toolbox and were presented stereoscopically using an NVIDIA Quadro 4000 graphics card and 3D Vision 2 LCD shutter glasses. Observers were comfortably seated with a chin-rest supporting their head 80 cm from the screen.

The individual object meshes and all relevant quantities (volumes, COM locations, critical angles, etc.) were calculated using Mathematica 8. The experimental scenes were illuminated with OpenGL’s per-vertex lighting model using a fixed function pipeline.
with specular highlights applied to textured objects, and with the specular reflection angles calculated assuming a constant view direction parallel to the z axis. There were two light sources, both with white ambient, diffuse, and specular components and the objects’ surfaces had ambient, diffuse, and specular reflectances. Objects were textured with 2D planar textures mapped to their surfaces.

**Stimuli and design**

The experiment used the method of adjustment to measure the perceived critical angle for objects in a 3 (aspect ratios) × 6 (skew directions) factorial design. The objects were conical frustums that were placed close to the edge of a rendered table. The objects had three possible aspect ratios (height: base diameter; 2:2, 3:2, 4:2) and subtended approximately 6.4-10.7 DVA (see Figure 3). The frustums were skewed by 25° from the vertical in one of six directions relative to the edge of the table (x = 0°, 60°, 120°, 180°, 240°, 300°) (see Figure 4). At 0° the object’s skew was directed towards the precipice, in the range 0°–180° the object was facing away from the observer, at 180° the object was skewed in the opposite direction of the precipice, and in the range 180°–360° the object was skewed toward the observer.

![Figure 3. Cropped examples for Experiment 1, showing the three aspect ratios of the asymmetric conical frustums (2:2, 3:2, 4:2) with a constant skew. Note that 3D volumes were equated and all of the objects were skewed by 25° from the vertical.](image)

![Figure 4. Examples for Experiment 1 of the six possible skew stimuli (x = 0°, 60°, 120°, 180°, 240°, 300°) for a frustum with a constant aspect ratio (4:2). Note that the aspect ratio or skew angle may appear to change in these illustrative figures; however, the stimuli were presented stereoscopically, so a skew direction of x = 120° was facing into the screen/scene and x = 300° was facing out toward the observer.](image)
Objects were always tilted directly toward the edge of the table, so the skew direction determines the tilt direction relative to the object’s intrinsic skew. The observers’ viewpoint in the scene was fixed. The objects had a wood grain texture to reinforce the percept of solid, uniform density objects. These objects were described to observers as solid blocks of wood (as if cut out from the trunk of a tree). Visual cues—including shading and a metallic reflection of the objects on the table—were added to aid in the realism of the scene and, in addition, scenes were presented stereoscopically. The volumes of objects were equated across shape manipulations.

Procedure

The observers’ task was to adjust the tilt of the object until it was perceived to be equally likely to fall off the table versus return to its upright position on the table (the perceived critical angle). As noted previously, the object’s motion was constrained to move orthogonal to the edge of the table, and rotating about the point on the base of the object closest to the table’s edge.

On each trial, the conical frustum was shown with an initial tilt angle of either 0° (upright with base fully on the table) or 90° (tilted so that the entire object was over the precipice). The initial tilt angle was counterbalanced to later analyze for possible hysteresis (which would manifest itself as a reliable difference in settings between trials with an initial angle of 0° vs. 90°).

Each observer performed a total of 144 adjustments: eight adjustments for each of the 3 × 6 combinations of aspect ratio and skew directions. Half of these had an initial tilt angle of 0°, and the other half had an initial tilt angle of 90°.

Results

Observer performance was evaluated by examining their critical angle settings as a function of the skew direction (α) and aspect ratio. A repeated measures ANOVA was conducted on the pooled observer data, showing highly significant effects for aspect ratio, $F(2, 26) = 86.57, p < 0.01$; α, $F(5, 65) = 280.31, p < 0.01$; and initial tilt angle, $F(1, 13) = 11.95, p < 0.01$. There was a small but significant effect of initial tilt angle on the observers’ responses.

Figure 5 shows the average data plotted as a function of α along with the predicted critical angles for all three aspect ratios. Observers were, on average, quite good at estimating the critical angles when α was changed. The only notable exception was for α = 0° (especially at aspect ratios of 3:2 and 4:2), where observers overestimated the critical angle (and hence the stability) of the object—which would have caused the object to fall off the table in the real world. Observers’ settings showed that they tracked the critical angle as a function of the skew remarkably well.

Discussion

In the first experiment, we found that not only were observers able to perform the task, they were also very good at tracking the critical angle as a function of the skew direction. For all three aspect ratios, observers’ adjustments followed the physical prediction as a function of α.

Interestingly, on average, observers’ perceptual judgments were very close to the physical predictions, indicating that there was no systematic conservative bias for judgments “on the safe side” (Samuel & Kerzel, 2011).
And for $\alpha = 0^\circ$, observers actually made liberal critical angle estimates, suggesting that there may be a more complex interaction between shape and the observers’ biases to over or underestimate the critical angle.

**Experiment 2: Matching overall stability**

**Motivation**

The results of the first experiment showed that observers tracked the critical angle as a function of the tilt direction relative to the intrinsic skew of the object ($\alpha$). However, in addition to judging the critical angle in any given direction, observers can also estimate overall object stability. For example, in Figure 6a it is visually apparent that the cylindrical object on the right is more stable than the skewed frustum; whereas in Figure 6b the cylindrical object is less stable.

These observations raise the question of how observers combine information about the various critical angles into a unitary percept of object stability. Because the critical angle task inherently measures the perceived stability in a single direction of tilt, we can only answer this question by using a different task that assesses the perception of overall stability of an object, not just stability in a given direction. To do this, we use an overall stability matching task.

Observers were asked to compare the overall stabilities of two objects—a standard object (corresponding to one of the skewed conical frustums from the previous experiment) and a simple cylindrical comparison object—and to adjust the aspect ratio of the comparison object until it was perceived to be equally stable as the standard. When the stabilities of the two objects were perceptually matched, the two shapes could be considered stability metamers.

It was not obvious a priori whether observers would be able to perform such matches. A pilot study revealed, however, that observers find this a natural task, and their settings are quite precise. This finding is consistent with the idea that physical stability is a natural perceptual dimension.

How do observers combine the various critical angles into a single stability judgment? Two natural combination rules that could be used are (a) to take the average of all the critical angles; and (b) to simply use the minimal critical angle. If observers assume that an object could have a force impulse applied from any direction (uniformly sampled from every radial direction around the object), then it would make sense to integrate across all possible tilt directions, which would result in the average critical angle strategy (Hamrick et al., 2011). This average critical angle model incorporates information from every potential force vector direction, so it takes into account the minimum and maximum critical angle, as well as every critical angle in-between, when judging the overall stability.

Alternatively, observers could use the object’s minimum critical angle as a proxy for the perceived overall stability, which may be a more salient feature if individuals are looking for the critical angle that is most informative about a potential change in the

![Figure 6. Example scenes illustrating situations where a cylinder is perceptually more stable than a skewed conical frustum (a) and where a cylinder is perceptually less stable than the skewed frustum (b).](http://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932809/)
object’s state of equilibrium. A natural way to think of physical stability is in terms of the minimum force required to change the equilibrium state of the object, so if we consider the minimum of the forces in all directions, then the absolute minimum would be in the least stable direction. That is, when a force is applied in the direction of the minimum critical angle, it has the highest likelihood of changing the equilibrium state.

The fits of the average and minimum critical angle models were compared to see which model better described the observers’ settings.

Methods

Observers

Thirteen Rutgers University undergraduate students, with normal or corrected-to-normal visual acuity, participated in the experiment.

Stimuli and Design

The scene was composed of two objects, a standard and a comparison object, sitting next to each other on a virtual table. The standard objects—skewed conical frustums as in the first experiment—had three possible aspect ratios (2:2, 3:2, 4:2) and subtended approximately 4.3–6.8 DVA (see Figure 7). The frustums were skewed by 25° from the vertical and were skewed towards the left or right (see left panes in Figure 8). In addition, the standard objects were placed on either the left or the right of the comparison object (see center panes in Figure 8). The comparison object—cylinders—had one of two initial aspect ratios (1:2 or 16:2), the two opposite ends of the aspect ratio spectrum, short-and-wide and narrow-and-tall, that subtended approximately 3.0 and 12.3 DVA, respectively (see right panes in Figure 8). They had the same wood grain texture and material properties as the conical frustums and had a variable aspect ratio, to be adjusted by the observers.

The experiment used the method of adjustment for stability matching using a 3 (standard aspect ratios) · 2 (skew directions) · 2 (presentation locations) · 2 (initial comparison object aspect ratios) factorial design.

Procedure

On each trial, a standard conical frustum was shown alongside a comparison cylinder. The observers’ task was to adjust the aspect ratio of the comparison object until it was perceived to have the same overall stability as the standard object. The comparison object’s volume was held constant across changes in aspect ratio; hence, the observer’s adjustments affected both height and radius. Since the two objects had the same surface properties and there were no stability cues other than the visual ones, observers had to rely on shape alone in making their judgments.

When the observer finished their aspect ratio adjustment (i.e., when the perceived stabilities of the comparison and standard were subjectively the same), the two objects could be considered stability metomers (similar to color metomers, where two colors are perceived to be the same even though they have differing wavelength compositions).

Each observer performed a total of 192 adjustments: eight adjustments for each of the 3 · 2 · 2 · 2 combinations of aspect ratio, skew direction, presentation location, and initial comparison aspect ratio.
Results

A repeated measures ANOVA was conducted on the pooled observer data (see Figure 9), showing significant effects for the standard aspect ratio, $F(2, 24) = 50.80, p < 0.01$ and initial comparison aspect ratio, $F(1, 12) = 21.12, p < 0.01$. There was no effect of skew direction, $F(1, 12) = 3.67, p > 0.05$, or presentation location, $F(1,12) = 1.23, p > 0.05$. There was a small but significant effect of initial aspect ratio on the observers’ responses.

Observers’ settings were compared against predictions derived from (a) the average critical angle model and (b) the minimum critical angle model. If observers used the lowest critical angle to make their judgments, then we would expect their data to be close to the minimum critical angle prediction (blue dashed curve in Figure 9). Conversely, if observers used an estimate that uniformly took into account the object’s critical angle in all possible directions, then their judgments should be closer to the average critical angle prediction (red dashed curve in Figure 9). On average, the observers’ settings were closer to the minimum critical angle model’s predictions than to the average critical angle model.

In order to evaluate which model (average critical angle or minimum critical angle) better described observers’ performance, we calculated the likelihood ratios for each observer’s data. The likelihood ratio test allows us to compare the two stability estimation

![Figure 8. Examples of the two standard skew directions ($\alpha = 0^\circ$ and $180^\circ$), the two standard object locations (left and right), and the two initial comparison aspect ratios (1:2 and 16:2).](http://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932809/ on 06/16/2017)

![Figure 9. Average group performance for the three object aspect ratios (2:2, 3:2, 4:2) collapsed across skew direction and presentation location. The green lines represent the observers’ responses, separated by initial comparison aspect ratio (solid = 16:2, dashed = 1:2). The blue line represents the predicted comparison aspect ratio if observers used the minimum critical angle, and the red line represents the average critical angle prediction. Error bars represent 95% confidence intervals.](http://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932809/ on 06/16/2017)
models and judge which model better explains the observed data.

Normally, we would compare performance using the Bayes factor \((K)\), which is the ratio of the probability of the data given the first model \([Pr(D|M_{avg})]\) over the probability of the data given the second model \([Pr(D|M_{min})]\) (see Equation 1).

\[
K = \frac{Pr(D|M_{avg})}{Pr(D|M_{min})}
\]  

However, in this case the two models we are comparing have no free parameters, which means the Bayes Factor simply reduces to the ratio of the two model likelihoods. This likelihood ratio can now be used to judge which model better explains the data, with likelihood ratio values greater than 1 supporting \(M_{avg}\) and values less than 1 supporting \(M_{min}\). The ratios of the average and minimum likelihoods were calculated for each observer (see Equation 2).

\[
\Lambda_{observer} = \frac{\prod_{i=1}^{n} Pr(D_{i}|M_{avg})}{\prod_{i=1}^{n} Pr(D_{i}|M_{min})}
\]  

Log likelihoods were calculated for the individual models and for the likelihood ratios—positive log likelihoods supporting \(M_{avg}\) and negative log likelihoods supporting \(M_{min}\). For 10 of the 13 observers, the log likelihood ratios favored the minimum model over the average model (see Table 1), indicating that the minimum critical angle provides a better model of the observers’ stability matches than the average critical angle.

### Discussion

Observers’ judgments were better explained by the minimum critical angle, rather than the mean critical angle. Thus, the least-stable direction has a disproportionately large influence in visually estimating the overall stability of an object. As noted earlier, the direction of least stability is the most informative one about a potential change in the object’s state of equilibrium. And, indeed, it tends to dominate observers’ judgments.

### Experiment 3: Matching overall stability in different directions

#### Motivation

The results of the stability matching task in Experiment 2 indicated that observers’ overall stability judgments were informed by the minimum critical angle of the asymmetric objects. The idea behind the stability matching task presented in Experiment 2 was that, unlike the critical angle task, the stability matches for a given object should be constant as the direction of tilt varies relative to the intrinsic skew of the object. Here we test if this is indeed the case.

Dependencies on the viewing direction are common in 3D shape perception—and are particularly acute when the axis of elongation of an object is foreshortened (Biederman, 1987; Humphrey & Jolicoeur, 1993; Lawson & Humphreys, 1998; Marr & Nishihara, 1978). One may therefore expect to find some effect of viewing direction on visual judgments of object stability (if the 3D shape appears different, its perceived stability will, of course, also be affected). However, we would expect that any such effects are much smaller than the large influence of skew direction on perceived critical angles, observed in Experiment 1.

<table>
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Table 1. Log likelihoods for each model and the log likelihood ratios, \(\log(Likelihood_{avg}/Likelihood_{min})\), for each observer. Note that for 10 of the 13 observers, the log likelihood ratio favored the minimum model—that is, the likelihood ratio was negative.
In this experiment, observers compared the overall stabilities of two objects—a standard and a comparison—and adjusted the comparison object until it was perceived to be the same stability as the standard, just as in Experiment 2. However, this experiment differed from Experiment 2 in that the direction of skew was also manipulated (analogous to the manipulation of $\alpha$ in the first experiment).

**Methods**

**Observers**

Thirteen Rutgers University undergraduate students, with normal or corrected-to-normal visual acuity, participated in the experiment.

**Stimuli and design**

The experiment used the same stability matching task as Experiment 2. It used a 3 (standard aspect ratios) × 6 (skew directions) × 2 (presentation locations) × 2 (initial comparison object aspect ratios) factorial design.

As in the second experiment, the rendered scene contained two objects, a standard and a comparison object, sitting next to each other on top of a table. The standard objects had three possible aspect ratios (2:2, 3:2, 4:2), were skewed by 25° from the vertical, and were skewed in one of six skew directions (0°, 60°, 120°, 180°, 240°, 300°). In addition, the standard objects were placed on either the left or the right of the comparison object and the comparison objects had one of two initial aspect ratios (1:2 or 16:2). See Figure 8 for examples of the scene layout.

**Procedure**

The testing procedure was identical to Experiment 2. Each observer performed a total of 216 adjustments: six adjustments for each of the $3 \times 6 \times 2$ combinations of aspect ratio, skew direction, and presentation location. Half of these adjustments used an initial aspect ratio of 1:2 for the comparison object; the other half used an initial aspect ratio of 16:2.

**Results**

Observers’ performance was evaluated by examining their stability matches (aspect-ratio settings for the comparison object) as a function of the skew direction. A repeated measures ANOVA was conducted on the pooled data, showing a highly significant effect of aspect ratio, $F(2, 24) = 153.21$, $p < 0.01$, and a significant effect of initial comparison aspect ratio, $F(1, 12) = 7.53$, $p < 0.05$. There was also a significant effect of skew direction, $F(5, 60) = 39.94$, $p < 0.01$, but a Post-Hoc Tukey Test confirmed that the skew direction effect was due to the dip at 60° and 120° and that there were no other significant differences for any other slant directions.

As shown in Figure 10, on average, judgments were affected by the change in the standard aspect ratio and the direction of the skew, which had a much smaller effect. There was a slight dip in the comparison aspect ratios at 60° and 120°. It is likely this dip may have been due to perceived foreshortening when the skew was directed away from the observer.

**Discussion**

The results from the third experiment support the hypothesis that observers are able to match the overall stabilities of objects in a consistent manner, even when the asymmetric objects are rotated relative to the observer’s viewpoint.

Although the effect of skew direction was statistically reliable, it was quite small when compared to the influence of skew direction on the perceived critical angle observed in Experiment 1. Given the well-known effects of foreshortening of the axis on shape perception, it seems likely that the observed influence of skew direction on perceived stability is most likely due to the misperception of 3D shape from those viewpoints (Biederman, 1987; Humphrey & Jolicoeur, 1993; Lawson & Humphreys, 1998; Marr & Nishihara, 1978). Nevertheless, the stability matches are surprisingly flat, especially when compared with the large influence of skew direction observed in Experiment 1.

**Conclusion**

The critical angle is a good measure of stability for three-dimensional objects, incorporating information about mass distribution and shape to define an ecologically important property of real-world objects. We have previously found that people are good at visually estimating the critical angles of symmetric objects (Barnett-Cowan et al., 2011; Cholewiak et al., 2010); however, it was not clear how these results would extend to more general, asymmetric objects. Since the critical angle is not a single value for asymmetric objects, but depends on the direction in which the object is tilted, we investigated how well observers could visually estimate the critical angles in different tilt directions for asymmetric objects.

Observers were clearly able to track the critical angle as asymmetric conical frustums were tilted in different
directions relative to their intrinsic skews in Experiment 1, indicating that their judgments were appropriately informed by the shape’s asymmetry. These results extend our previous results for rotationally symmetric objects to asymmetric objects. These findings are reassuring because we have few issues making guided actions that are informed by our percepts of real-world object stability in our daily lives. In contrast to the findings of Samuel and Kerzel (2011) with 2D polygonal objects, our results show no systematic conservative bias—i.e., for stability settings to be judged “on the safe side.”

Surprisingly, observers were able to reliably match the perceived stability of two objects with different shapes in Experiments 2 and 3. These results suggest that stability may be represented along a unitary dimension. The observers were able to infer the force of gravity acting upon the shapes and compare their overall stabilities even though the shapes were quite different. Observers’ stability matches were better explained by the minimum model than the average model, suggesting that observers’ estimates were disproportionately influenced by the direction of least stability. Since physical stability is defined in terms of the minimum force required to change the equilibrium state of the object, the direction with the smallest critical angle defines where the object has the highest likelihood of changing its equilibrium state. Although the average critical angle is a measure of the central tendency of the stability for the object—taking into account the maximum and minimum stability, and all of the critical angles in-between—on average, people appeared to use the minimum critical angle as a proxy for the perceived overall stability.

Finally, Experiment 3 demonstrated that the matches were a function of the aspect ratio of the 3D shapes—with observed data exhibiting only a slight dependence on viewpoint (likely due to foreshortening).

As a whole, these results provide evidence that visual estimates of overall object stability are strongly influenced by the minimum critical angle and that perceived shape plays an important role to inform the people of the objects’ physical properties.

Keywords: 3D shape, perceived object stability, critical angle, stability matching, naive physics, intuitive physics

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Footnotes

1 The binocular views were rendered using a fixed camera separation of 6 cm.
2 A conical frustum is a cone with the pointed tip removed. The conical frustums were then skewed to produce asymmetric shapes. The magnitude of skew
was such that their central axis was oriented at 25° from the vertical.

3 This is analogous to color metamerism, where two colors with different spectral compositions are perceived to be the same. In the current context, two 3D objects that are physically very different are perceived to be the same in their stability.

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**References**


