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Perceived object stability depends on shape and material properties

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ABSTRACT

Humans can detect whether an unstable object will fall or right itself, suggesting that the visual system can extract an object's center of mass (COM) and relate this to its base of support. While the COM can be approximated by its shape, this assumes uniform density. We created images of computer-generated goblets made of different materials to assess whether the visual system estimates an object's COM from both shape and material properties. The images were either uniformly dense (e.g., glass, gold, etc.) or made of composite materials (e.g., glass and gold) and positioned upright or upside-down near a table ledge. We compared each goblet's critical angle (CA), the angle at which each goblet is equally likely to fall or right itself, to the perceived CA in a two-alternative-forced-choice paradigm. Participants also rank-ordered 20 materials by density on a questionnaire. The results show that observers accurately estimate the CA for all goblets and are sensitive to subtle changes of an object's COM with change in shape and composite material properties. Importantly, rated density – as measured from the questionnaire – and true material density were positively correlated, suggesting that humans might maintain a representation of relative material density with which to assess object stability. We conclude that the brain is able to assess an object's behavior in a gravitational environment by forming a reliable assessment of an object's COM from both its geometric shape and material properties.

1. Introduction

In order to determine if an object will fall off a table, the visual system must have an accurate representation of the physical laws governing object stability as well as an accurate estimate of an object's center of mass (COM). Shape of an object alone can provide information about an object's COM (Bingham & Muchisky, 1993; Davi et al., 1993; Proffitt, Thomas, & O'brien, 1983; Yakimoff, Bocheva, & Mitrani, 1990). This strategy works well for natural objects (e.g., stone) as they are generally uniformly dense. However, man-made objects can have gross differences in density. For example, an empty vase with a thick base will have a lower COM than predicted from shape alone. Further, man-made objects are often made of composite materials. In order to detect the true COM of a non-uniformly dense object, the human visual system could approximate density from visual information available from material properties (e.g., texture and color), assuming that it has an accurate representation of the relative density of materials.

When an object is unstable, the direction of its movement is governed by the relation between its center of mass (COM) and the support area (SA; Fig. 1). The COM is the point in an object where all resulting forces act upon it and the position of the distributed mass sums to zero, while the support area is the convex hull of points of contact between the object and the plane that supports it. If the net force acting on an object is zero, it remains in static equilibrium. The critical angle (CA) of an object is the angle at which the object is equally likely to fall or right itself. The perceived CA is found by measuring the angle at which an object is perceived to be equally likely to fall or right itself (Barnett-Cowan et al., 2011; Fleming & Singh, 2009).

The ability to rapidly infer an object's COM is thus integral when interacting with objects in order to correctly estimate their behavior, such as when falling in a gravitational environment. Humans are capable of reaching and grasping objects with visually guided dexterity such that the opening of our fingers and the orientation of our hand reflect the size, shape, and COM of the object as well as its orientation in egocentric space well before we make contact with it (Jeannerod, 1988; Lederman & Wing, 2003; Wing & Lederman, 1998). When judging object stability, previous research has largely focused on human sensitivity to change of the COM with object shape. Samuel and Kerzel (2010) found that observers are reasonably accurate at identifying an object's COM from shape,

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but tend to be conservative when judging whether an object will fall or right itself. In their study, observers consistently underestimated the CA, suggesting that they expect objects to be more likely to fall than they will. Barnett-Cowan et al. (2011) also found that observers are sensitive to change in the COM by varying the height of the bulge of an object placed at the edge of a table, however, their results did not confirm a conservative tendency in judging object stability. Cholewiak, Fleming, and Singh (2013) showed that observers can reliably match perceived object stability across three-dimensional objects with different shapes that vary in their degree of asymmetry, suggesting that perceived stability is likely to be represented along a single dimension. Further, observers were able to incorporate attached parts of an object (e.g., arms of a cross) but tended to down-weight the influence of the attached part on the object's stability (Cholewiak et al., 2010).

The representation of physical laws have also been shown to affect perceived object stability in addition to the shape of an object. Barnett-Cowan et al. (2011) had observers judge the stability of five objects with different COMs' positioned near a table edge and found that perceived object stability changes in accordance with shift of the COM along the long axis of the object. Participants in this study were also tested in three different body orientations (upright, lay on their left or right side) where the CA for all objects and body orientations were measured. They found that the physical laws that govern object stability are accurately represented in the brain when upright. However, estimates of object stability are biased by the direction of body orientation, suggesting that prior assumptions of the body being upright affect the representation of the physical laws of gravity.

1.1. Material properties

The size, weight, and texture of an object affect how it is perceived and acted upon. Classic examples of this are the Size–Weight Illusion (SWI) and the Material-Weight Illusion (MWI). The SWI occurs when equally weighted objects of different sizes are incorrectly perceived as having different weights when lifted (Charpentier, 1891). Larger objects are perceived as lighter and smaller objects perceived heavier due to the anticipation of the size of the object. Similarly, in the MWI objects which appear to be made from lighter materials feel heavier than equally-weighted objects which appear to be made from heavy materials (Seashore, 1899).

What makes these illusions so compelling is that they persist with repeated experience, suggesting that they are deeply grounded by prior expectations of the relationship between weight and size or material. For example, in a study conducted by Buckingham, Cant, and Goodale (2009), the MWI was induced using three equally weighted blocks that appeared to be made of different materials. Participants were instructed to lift each object using two fingers on a handle which measured their grip and lift forces. Results indicated that the MWI was present during initial trials, but in subsequent trials, participants readily adapted to the actual weight of the object regardless of its material. In other words, materials influence grip and lift forces in the short-term, but the perceptual illusion persists in the form of biased weight estimates. Furthermore, Buckingham, Ranger, and Goodale (2011) later found that continuous feedback of material properties was not necessary to experience the MWI, merely priming participants' expectations of heaviness will induce a robust illusion. Additionally, these expectations continued to influence participants' lifting forces after multiple trials.

One well known example of how humans can misattribute an object's behavior based on material properties comes from Galileo's falling bodies experiment. Objects of different weight fall at the same rate in a gravitational field with minimal air resistance (Galilei, 1638). However, since Aristotle (Stillman, 1978), humans tend to believe that the speed of an object's fall is dependent on its weight. That is, heavier objects should fall faster since they are more affected by gravity, but in reality, lighter objects reach their terminal velocity quicker, where the speed at which the force of gravity equals the force due to air resistance, so heavier objects can reach a higher speed. However, it is uncertain as to whether participants inaccurately believe that heavier objects are more affected by gravity than lighter objects, or whether they lack the necessary knowledge of air resistance to help influence their judgments (Oberle et al., 2005).

An erroneous belief of heavier objects being more affected by gravity is consistent with the literature on naïve physics, which generally suggests that erroneous beliefs about the fundamental laws of physics are held by many (Halloun & Hestenes, 1985; Kozhevnikov & Hegarty, 2001). For example, when participants are asked whether a 5-lb ball or a 50-lb ball will hit the ground first when dropped at the same height, some would say the 50-lb ball because "the mass is greater, therefore it will accelerate faster" (Whitaker, 1983). The fact that participants choose the 50-lb ball illustrates the notion that an object's weight commonly influences a person's judgment. Thus, if individuals are administered an object stability task, they may perceive heavier looking objects to be more likely to fall, as the apparent material would influence their judgments of a material's perceived weight.

Whether people believe that heavier objects are less stable, has been partially addressed by Battaglia, Hamrick, and Tenenbaum (2013) who proposed that humans use a cognitive mechanism underlined through intuitive physics that allows them to make probabilistic and fast inferences to react to unobserved stimuli in naturally complex environments. To assess this hypothesis, they measured human sensitivity to object stability using random configurations of a 10-block tower and asked whether the tower

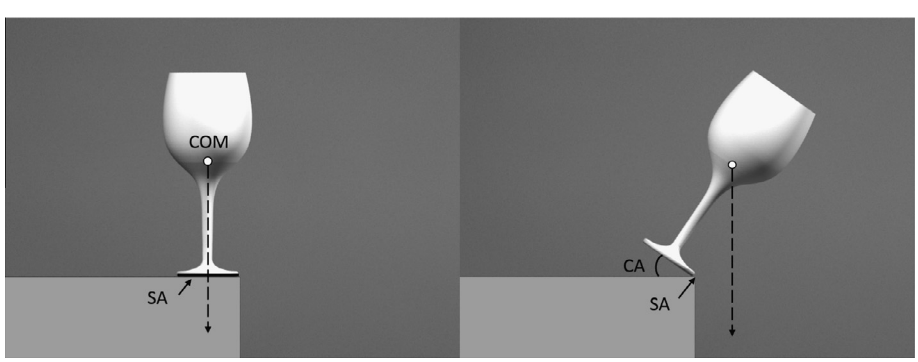

Fig. 1. Depiction of the relationship between the center of mass (COM) and the support area (SA) for object stability. An upright object remains stable when the COM is directly above the SA (left). A tilted object is equally likely to fall or right itself when the COM is directly above the point of support. An object will fall when the gravity projected vector (dashed line) from COM lies beyond the SA (right).