Chapter 12

"Center of Mass Perception": Affordances as Dispositions Determined by Dynamics

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12. 0 Introduction

Affordances are dispositional or relational properties. They consist of properties of objects in relation to properties of a perceiver/actor in the context of a task or a goal to be achieved by way of the affordance (Gibson, 1979). The basis of the relation unifying object properties into an affordance property is the task goal. Thus, understanding affordances requires some understanding of the manner in which physical properties of object and actor are invoked by tasks.

The relation between affordances and goals is problematic. On the one hand, affordances are task specific. On the other, a given goal might be achieved via various means involving different affordances respectively. The way to resolve this apparent contradiction is via the process of goal specification. Tasks can be analyzed into a sequence of alternative subgoals corresponding to the various ways that the superordinate goal might be achieved. Actual performance of the task requires the successive determination of subgoals. How might such goal specification proceed? Goal specification entails the perception of affordances corresponding to subgoals. The implication is that there are superordinate and subordinate affordances. The problem is to understand the relation between the former and the latter. For instance, a goal might be to transport an object from a table to a shelf. Suppose that one recognizes that the object affords being so transported by oneself. That is, the size and weight and surface properties are such that one could control the trajectory of the object from the table to the shelf via a variety of means, using either one hand or two or perhaps using two elbows if both hands are occupied.

The particular means need not be specified and, in certain circumstances, are unlikely to be specified until the action is actually being performed. For instance, suppose a collection of differently shaped objects, all of similar sizes and weights, is to be transported to the shelf. Possible transportation using a one handed grasp for each might be apprehended. Nevertheless, assuming that the shapes are different enough to require different types and locations of grasping, the particular form and locus of the grasp in each instance is unlikely to be determined at the time when the overall sequence of actions is initiated. What structure might underlie the progressive specification of the affordance for grasping each object? Imagine further that the objects must be replaced on the table from the shelf. The way that each object is grasped this second time may be related, but not identical to the initial grasp. What structure is the basis for this constrained variability? Finally, imagine that the objects must be placed the second time at orientations other than their initial orientations. The grasp types and locations are very likely to be different from the previous ones, yet they will remain related. What structure is the basis for both the new organization and its relation to the old?

Performers anticipate the ways in which they can combine physical properties of themselves with physical properties of objects to achieve specific outcomes, meaning trajectories and / or states[1] of self and objects. The detailed relations that can be established and employed are simultaneously constrained and indefinitely variable. The basis of this generativity is the physical dynamics of actors and objects, and it is on these dynamics that the focus of our study must be placed. As perceptible properties rooted in the dynamics of objects and actors, affordances entail KSD or Kinematic Specification of Dynamics. Informative patterns within energy distributions impinging on the sensory apparatus are kinematic in their dimensions, that is, the patterns vary in lengths and times. The problem is to describe how such spatiotemporal properties provide information about dynamically determined or mass related properties of objects and events and to discover which spatiotemporal properties provide information about affordances in given instances.

[1]Although trajectories and states are usually construed as kinematic, they need not be necessarily. We do not here intend to assign goals to a kinematic level of description.

Affordances are dynamically determined dispositions that cannot correspond to simple properties or variables taken from classical dynamics. Due to inalienable requirements for identification, scaling, and orientation of affordances, more than one classical dynamical variable is required for the determination of any given affordance property. Accordingly, an affordance exhibits continuity of structure (including dynamical variables) shared with neighboring affordances. The continuity of such structures is the coherent basis for progressive goal specification. The shared structure and/or variables provides a basis both for individuating the entire structure at a superordinate level as well as for progressing to more distinct subordinate alternatives for action.

In what follows we investigate "graspability" as one of the most oft–cited examples of an affordance (Gibson, 1979; Mark, 1987, Mark, Balliett, Craver, Douglas, & Fox, 1990; Turvey, Shaw, Reed, & Mace, 1981; Warren, 1984). First, we attempt to provide a general description of "graspability," one that is indifferent to the wide variety of tasks in which grasping is involved. We succeed only in illustrating the task specificity of affordances that are, nevertheless, related by common dynamical characteristics. Next we briefly address the problem of goal specification. We suggest that, underlying and enabling the process of goal specification, there should be a continuous perceptible structure that is rooted in the dynamics of objects and actions and that contains related alternatives for action. We advocate the search for a perceptible layout of dynamically determined alternatives. Accordingly, we describe investigations of "center of mass perception" for the visual guidance of precision grasping which reveal a very small, yet distinctly structured region within the layout of affordances for grasping.

12.1 "Graspability" and the Task Specificity of Affordances

We might describe *grasping* as "taking on and supporting an object's weight by enclosing object surfaces with hand surfaces." This accords with the object properties typically listed as determining *graspability* namely, the shape, size, and weight of the object taken with respect to corresponding properties of the hand. However, in grasping a pole on the subway or in grasping someone's hand to shake it, we do not support the object's weight. Although the former might involve supporting a portion of one's own weight, the latter involves no weight bearing whatsoever. Certainly, mere contact of hand and object surfaces together with some weight bearing is not sufficient because we do not "grasp" a wall when we "lean" on it with our hand. Nevertheless, such "leaning" is very closely related to the function performed when one "grasps" the pole on the subway. Enclosing with hand surfaces might seem to capture what we mean, but one encloses water with hand surfaces when swimming without really "grasping" the water. Also, one might enclose a cricket with one's hand surfaces to trap it without really 'grasping' it. Although it might be in contact with hand surfaces that support its weight, room would be left for it to move within the hand. We might say that one is merely "trapping" or "imprisoning" the cricket without really "grasping" it.

Perhaps, we might refine our definition by requiring that the surface contact be of a sort that prevents the object surfaces from moving relative to hand surfaces. Surface texture or compliance properties are sometimes listed as relevant to "graspability" because they determine frictional forces. We note again, however, that this is relevant as well to "leaning" on a wall with one's hand. Previously, we invoked enclosure by hand surfaces to distinguish "grasping" from "leaning," but certainly complete enclosure of an object is not necessary for "grasping." Napier (1956) distinguished a number of distinct types of grasps, depending on the amount of enclosure from "power grasps" to "precision grasps." In a *power grasp*, an object is wrapped and nearly enclosed by palmer hand surfaces. However, in a *precision grasp*, an object is merely pinched between the distal segments of the thumb and fingers, often only the index finger. This latter grasp involves relatively small areas of contact between object and hand surfaces. Nevertheless, to fix an object with respect to the hand, precision grasps require contact on opposite sides of an object so as to produce oppositely directed and mutually canceling forces yielding a stable configuration at equilibrium[2]. Thus, we might revise *enclosure* to mean pinched between such oppositely directed forces from hand contact. Still, difficulties remain.

Does one grasp an object when one supports its weight on the flat surface of an upturned palm, or does one merely support it? Is this "supportability" as opposed to "graspability?" It's similar to the case of

[2]With misgivings that we subsequently make explicit, we will use "center of mass perception" as shorthand for "perception of grasp locus on an object affording a neutrally stable precision grasp." We use the shorthand because the perception of this affordance happens to coincide more or less with "center of mass perception."

"leaning," but with a change in direction (that is, palm facing the gravitational direction) and with the difference that the object's weight is now being supported by hand surfaces. The difficulty is that a continuum can be established between a "power grasp" of an object and a "support grasp" of this sort.

Imagine grasping a soda can by wrapping the cylindrical shape with fingers, palm, and thumb as one normally would. This illustrates the essential *power grasp*. Now, imagine grasping the can by placing its end on the palm and contacting the cylindrical sides with the fingers and thumb. This is another form of power grasp. Orient the palm of the hand upright so that the weight of the can rests on the palm. Gradually, extend the fingers and thumb at the metacarpal–phalangeal (or knuckle) joints, one at a time. The result is a gradual, continuous, and benign transition from a strict power grasp to a support grasp. The transition is benign because an equilibrium state was maintained throughout the transition and the object remained on the hand, its trajectory still determined by the hand. Despite the change in the relation between the hand and object, the function was preserved, namely, the trajectory of the object with respect to the hand was fixed. Thus, the support grasp must be a proper type of grasp that does not involve enclosure or pinching between hand surfaces. Of course, a similar transition can be described between the grasp of the pole on the subway and the mere "lean." The implication is that the 'lean' is a type of grasp as well, despite the fact that this departs from what we usually mean by a grasp. Certainly, we would not refer to leaning on a table top with our hands palm downward as "grasping the table." Nevertheless, such a posture is not disjoint in character with postures normally referred to as "grasping." Consider, for instance, "palming" a ball which is a type of grasp. One could not lift a table in this way , but the table could perhaps be slid sideways.

We have suggested that the essence of grasping might be the fixing of relative positions of hand and object surfaces in contact with one another. But this is not consistent with the active manipulation of objects within a grasp. Ultimately, stable grasping involves dynamic equilibrium (Raibert, 1986) as much as (or more than) static equilibrium. A ball or a pencil might be manipulated within a stable grasp by momentarily fixing and rolling it between two digits, free of other hand surfaces. Alternatively, one might simply allow the ball or pencil to roll along the palmer hand surface from wrist to finger segments. An excellent example that illustrates the difficulties and complexities of dynamic grasping is that seen in the movie *Blow Up* in which the protagonist fidgets with a coin by flipping it end over end across the back sides of the proximal-most segments of his fingers. One might protest that this was not grasping because the coin was situated on the back of the hand. But during each flip, the end of the coin was lodged between two fingers. Does one not grasp a cigar when one holds it between two fingers? Actions like this seriously challenge and defy any straightforward scheme for defining an affordance property like graspability in a categorical fashion distinct from given tasks.

There is a tremendous amount of functional variability underneath the categorical terms, *grasping* or *graspability*, and to the contrary, there is functional similarity despite variation in terms appropriately or preferentially applied, as in *leaning, supporting, trapping, grasping* , and so on. What determines the variability, on the one hand, or the similarity, on the other, is the physical properties that are marshaled in achieving specific goals and the manner in which they are marshaled, including the geometries according to which they are configured and the values associated with the particular properties.

12.2 The Problem of Goal Specification

Even if we focus on what would seem to be an indisputable and relatively uncomplicated grasping task, for instance, passing a soda can from one person to another, the relation between the goal and affordances for grasping is one to many. For instance, various types of precision grasps, power grasps, or support grasps all might satisfy and be admitted by the relevant constraints in the task.

The proliferation of means to an end is a familiar problem in the study of human action. For instance, within the trajectory-formation tradition, goals have been described as kinematic entities, that is, particular end positions or trajectories to be achieved via the appropriately organized dynamics of the motor system (e.g., Hollerbach, 1982). The problem has been that a good deal of kinematic variability can occur in goal directed limb movements without significant functional repercussions. A desired end point can be reached without hesitation in reaching movements despite significant mechanical perturbation of the hand on its way to that end point. In recognition of this and other related stabilities commonly exhibited in human limb movements, Saltzman and Kelso (1987) formulated an approach in which tasks were described explicitly in terms of dynamics. This general approach, called *task dynamics*, has been adopted widely (Beek,

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Nevertheless, even at the dynamical level of description, there may be many ways to achieve a given goal. For instance, in passing the soda, one might specify the palmer side of the recipient's hand as the equilibrium point or "point attractor" of a critically damped mass-spring task dynamic defined with respect to the center of mass of the soda can as the mobile. This abstract organization for the multilink arm, hand, and can system would leave unspecified, however, the use of either a power grasp, a variety of precision grasp, or even a support grasp to achieve control over the center of mass of the can. Fortunately, as the performer approaches and begins to move through the actual performance of the task, additional constraints may come to bear on the possible subgoals. For instance, transfer to the recipient's grasp might be facilitated by use of either a support or precision grasp which would leave greater can surface exposed for contact by the recipient. On the other hand, desire for stability in the face of significant lateral accelerations might rule out the use of a support grasp.

The remaining subgoal would be to establish a stable precision grasp. The problem is that this subgoal remains ill specified. A precision grasp can be established at a continuous variety of locations on the can. The locations are not equivalent in their effect on the stability of the resulting precision grasp. Formulating the subgoal requires that a coherent and connected subset of affordance properties be specified so that an appropriate member of the set might be selected.

12.3 The Center of Mass in Precision Grasping

We consider the types of equilibrium postures in precision grasps in which the stability of the equilibrium configuration is determined by the location, relative to the center of mass, of an axis running between the two pinching hand surfaces. For an equilibrium posture, the forces applied to opposite and (approximately) parallel object surfaces by the index finger and thumb pads must be oppositely directed, co-linear, and equal.[3] We call the line along which they are directed the *opposition axis*

[3] This also is not precisely true. Fearing (1983) has shown that strict opposition of contact forces is not required. The angle between the force vectors from opposing segments of the hand can vary within a tolerance determined by the frictional characteristics of the object and hand surfaces. Thus, a grasp can be less than enclosing in this sense as well, that is, the hand surfaces would surround an arc of less than 180°.

(Iberall, Bingham, & Arbib, 1986). Such equilibrium configurations can vary in their stability from stable, to neutrally stable, to unstable configurations as the opposition axis is varied in its position with respect to the center of mass.

When this axis passes above the object center of mass, the equilibrium configuration is stable. If perturbed, the object will return to its original orientation when the perturbing force is removed. Such a configuration is optimal when trying to keep a hot cup of coffee upright in one's grasp.

When the opposition axis passes directly below the object center of mass, the configuration is unstable. When displaced by perturbation, the object will continue to rotate away from the original orientation. This configuration is useful for passively reorienting an object in one-handed manipulation, for instance, picking up a rod lying on a surface so that the end nearest the grasper is finally oriented upward within a grasp placed just below the top end.

When the opposition axis passes directly through the center of mass, a neutral stability is achieved. The object exhibits no preferred orientation around the opposition axis. The object will remain at any given orientation and can be reoriented to arbitrary orientation with a minimum of effort. This configuration might be preferred in a "peg-in-a-hole" task in which fine manipulation of orientation is required. This posture would also be desirable in situations in which the final desired orientation is not apparent at the moment of initial grasping.

As a generator, the center of mass produces a continuous set of related although distinct dispositions. The transition from strongly stable, to weakly stable, to neutrally stable, to weakly unstable, and finally to strongly unstable can be affected by continuously varying the position of the opposition axis with respect to the center of mass. Although the center of mass is a property found in all objects, the dispositions are not. For instance, one cannot grasp a banana in a precision grasp so as to pass the opposition axis through the center of mass, because the center of mass lies outside the banana's skin. Nevertheless, if the banana's weight is to be supported in a precision grasp at equilibrium, then the opposition axis must lie along a vertical through the center of mass.

Because affordances are perceptible properties, these dynamical dispositions only remain as possible affordances until we establish that they are perceptible. The focal question becomes whether and how observers can apprehend dynamically determined properties of objects and events. Over a decade ago, Runeson introduced and discussed the notion of "dynamic event perception" and the perception of "dynamic properties" (Runeson, 1977). Runeson suggested that many perceptible properties might be understood or modeled as built from, and therefore continuous with, properties of standard mechanics. They need not be identical to any familiar or named properties in mechanics, although they might happenstantially be close in specific circumstances.

One prerequisite for dynamic properties to be construed as affordance properties is that the dynamic property be a dispositional property of objects. Some standard mechanical properties can indeed be construed as dispositionals. For instance, moments of inertia are dispositions to turn with specific rotational accelerations given certain torques applied about axes corresponding to those inertial moments. Another example, pursued in the research to be reported in this chapter, is the center of mass. The center of mass can be construed as a disposition for an object to accelerate along a straight line in proportion to the amount of force applied along a line passing through the center of mass. Whether these dispositions are perceptually salient is as much to be doubted as is the possibility that torques or forces are explicit control variables in human action (Bingham, 1988; Feldman, 1986; Hogan, et al., 1987; Stein, 1982). Nevertheless, the center of mass is usefully approached as the generator of a family of dispositions that are of relevance to human activity.

12.4 Perception of the Center of Mass

Dynamic properties are physical properties and, as such, are described in units of mass as well as length and time. On the other hand, patterns detectable by the perceptual systems are described only in length and time units. Thus, in the context of events, information about dynamics must be found in motions described, using kinematics, in length and time units. Information about dynamics involves a series of relations, first between dynamics and kinematics and then, between kinematics and optics (Bingham, 1987a, 1987b, 1988, In Press; Bingham, Rosenblum, & Schmidt, In Press). Kinematics or trajectories as information are properties of events as are the dynamics that generate them. The event trajectories must next map into spatiotemporal patterns in distributed energy fields that can be detected by the perceptual apparatus.

The trajectories of an object held in a grasp might provide information about the dynamical disposition for stable, neutrally stable, or unstable equilibrium. The trajectories would map either into the transforming distributed structure of the tissues of the haptic array (Bingham, et al. 1989; Solomon, Turvey, & Burton, 1989a; b) or into flow patterns in the optic array (Bingham, 1987a, 1987b, In Press; Bingham et al., 1989, In Press; Gibson, 1979; Todd, 1981). People performing assembly tasks while blindfolded have been seen to test an object by lifting it briefly on first encounter with the hand and then to go for a grasp established about the center of mass (Iberall, et al. 1986).

However, only visual information about the object would be available before an object has been contacted by the hand and, most typically, before coming into contact with the hand, an object lies immobile on a supporting surface. Would visual information about the center of mass be available in such situations? If so, then information would have to be found in geometric properties of the object. Thus, when the perception of dynamics in events has been called a KSD problem (Kinematic Specification of Dynamics), the perception of dynamical properties in static situations might be called a GSD problem, that is, Geometric Specification of Dynamics (Muchisky & Bingham, 1991). On the other hand, geometric properties are a subset of those studied in kinematics, so we might dispense with the extra terminology. Furthermore, to be apprehended visually, object properties must map to informative properties of the optic array which would be spatiotemporal properties generated by observer motion, even if the object itself was unmoving. We studied center of mass perception as a KSD problem in which we addressed the question of information in object geometry but did not attempt to reveal or describe the corresponding optical information.

We studied the simplest of object manipulation tasks, that is, to grasp an object using a precision grasp yielding neutral stability. Essentially, we asked observers to locate the center of mass (henceforth, CM). We asked if only visual information were available before contact, would it be sufficient for observers to locate the CM of an unmoving object? If so, then what would the information be? Consideration of the potentially relevant informational factors is instructive because this task provides an indication of the minimum complexity that we should expect to encounter in describing affordances as dynamically determined dispositions.

Three general factors are relevant, namely, form, scale, and orientation. These are fundamental to the description of any affordance property as follows. Form is entailed by the need to recognize an affordance, that is, for a solution to the identification problem (Bingham, 1987b, In Press, Bingham et al. In Press). Such form might be either geometric or kinematic. Scale is important for two related reasons: First, it contributes to a determination of identity (Bingham, 1987bBingham, Rosenblum, & Schmidt, In Press), because objects and events are scale specific; they occur within definite scale ranges. More precisely, as studied in allometry (e.g., Hildebrand, Bramble, Liem, & Wake, 1985), in scale engineering (e.g., Baker, Westine, & Dodge, 1973), and in similarity theory (e.g., Szücs, 1980), scale and form are co-determinate (Bingham, 1993a, 1993b; Bingham & Muchisky, 1992; Shaw, Mark, Jenkins, & Mingolla, 1982). Second and relatedly, the functional value and/or repercussions of an object or event is determined by its scale relative to the scale of the observer or actor (Warren, 1984; Warren & Whang, 1987). Finally, orientation is important because gravity is a dynamical component that contributes significantly to the form of every terrestrial event at the scale of human activity, including human activity itself. Bingham, Rosenblum, and Schimdt (In Press) have shown that orientation must be specified to determine identity when using kinematics as visual information about events. To the extent that functional repercussions are intrinsic to affordances as perceptible properties, orientation also must be relevant to the identification of any affordance. The implication of this last factor is that the recognition of affordances is an inherently multimodal affair, because kinesthetic or haptic information about the gravitational direction would be an inalienable component of visual recognition.

Accordingly, in studying CM perception, we manipulated three geometric object properties: shape, size, and orientation. The shape of an object is relevant because the CM is a symmetry property (Becker, 1954; Sears, Zemansky, & Young, 1987). The CM falls on any axes of reflective symmetry or at the center of a radial or rotational symmetry in an object with a homogeneous mass distribution, because the CM is the point around which the mass is balanced. Three noncoplanar axes of reflective symmetry or a center of radial symmetry about two axes uniquely specify the location of the CM.

The detection of symmetry properties would locate the CM. Might greater amounts of symmetry increase the accuracy in locating the CM? If so, we should expect random error in locating the CM to decrease with increasing symmetry. (Note that we have assumed a homogeneous mass distribution. This assumption is valid for a large class of objects which are made of a single material such as wood, plastic, metal, ceramic, stone, glass, or organic fibers.)

The size of an object of a given shape determines, for any given error distance, the repercussions of missing the CM. Ignoring torques around the opposition axis created by frictional forces, a miss of a given distance will produce less rotational acceleration of a larger object than of a smaller object. The greater the rotational acceleration, then for a given amount of rotation, the smaller the time in which to respond, or alternatively, within a given response time, the greater the amount of undesired rotation. However, shape, in addition to size, affects rotational acceleration. Both shape and size determine an object's moment of inertia or resistance to rotation. Might shape and size interact in determining the accuracy of judgments of the center of mass? We should expect random errors in locating the CM to increase both as objects increase in size and as shapes become more elongated and less compact.

Finally, orientation is potentially relevant for two reasons. First, the consequences of inaccurately locating the CM are a function of orientation with respect to gravity. The repercussions of missing the CM are potentially less severe for misses along the vertical direction than for those along the horizontal. If the pattern of errors reflects this, we should expect more errors along the vertical than along the horizontal direction from the CM. Second, orientation is purported to affect the recognition of symmetry in an object. According to Rock (1973), predominant axes and especially reflective symmetry axes are more easily recognized when parallel to gravity. The further away from a vertical orientation a symmetry axis was, the less often it was recognized as such. When reflective symmetry axes are parallel to gravity, might accuracy in locating the CM increase?

We have run a number of experiments investigating these and related questions (see, e.g., Bingham & Muchisky, 1993a, 1993b). We describe two of them at length. In the first, we investigated the use of object symmetry properties as visual information about the location of the CM in an object. In the second, we investigated the use of approximations to symmetry as visual information about CM location.

12.5 Symmetry, Size, and Orientation in Center of Mass Perception

A set of 7 planar objects was designed to vary the number of axes of reflective symmetry from 0 to 4. We used planar shapes cut from 1 cm thick plywood to simplify the problem while retaining much of the variation in object shape relevant to precision grasps. Rotational symmetry (or periods of rotation in the plane of the object required for self congruence) also varied. Furthermore, some of the shapes possessed radial symmetry, that is, reflective symmetry through a point in contrast to a line as in axial reflective symmetry. The shapes and symmetries of the objects are shown in Figure 12.1. Each of the planar shapes was created in three sizes of 100 sq. cm., 200 sq. cm., and 300 sq. cm. The largest set allowed a pair of tongs to reach far past the centers

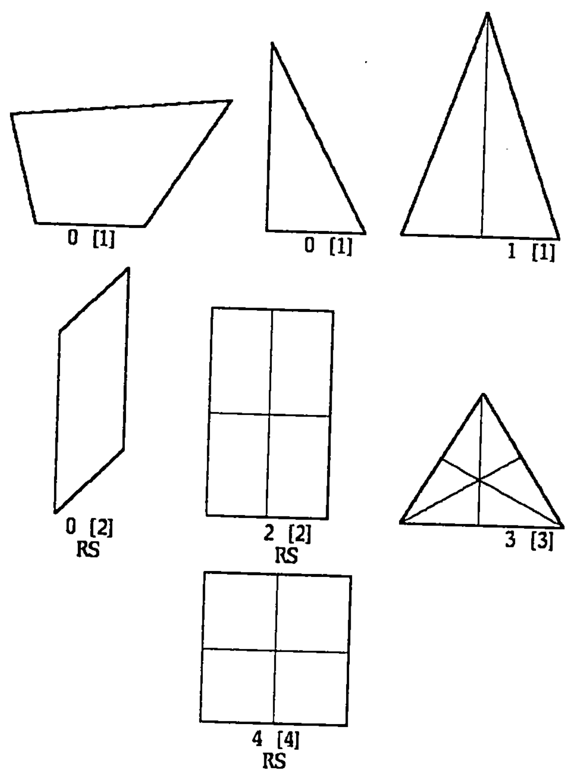

Figure 12.1. *The planar shapes used in the experiment included a right triangle [0 reflective axes, period=360°], a quadrilateral [0 reflective axes, period=360°], a parallelogram [0 reflective axes, period =180°, radial symmetry], an isosceles triangle [1 reflective axis, period=360°], a rectangle [2 reflective axes, period=180°, radial symmetry], an equilateral triangle [3 reflective axes, period=120°], and a square [4 reflective axes, period=90°, radial symmetry].*

of the figures from almost any direction in the plane of the objects.

Fifteen undergraduates at Indiana University participated in the experiment for pay. The objects were presented to observers with the plane of the figure parallel to gravity. Objects were held upright in a transparent spring loaded clamp affixed to a wooden base as shown in Figure 12.2. The side of the figure facing observers was an unfinished smooth-wood surface. The side facing the experimenter had polar coordinate paper attached to it with the origin of the coordinates fixed at the CM. The Archimedean method was used to determine the location of the CM in each object and to place the polar graph paper accordingly. This was accomplished by suspending each object from two different points along its perimeter. A plumb line was hung from each point in turn and marked on the object. The intersection of the two lines marked the location of the CM.

Observers used a set of tongs to express their judgments of the CM. The tongs were held and manipulated in one hand like a large pair of scissors. The point of the tongs that contacted the surface of the object viewed by participants was padded to prevent indentation of the surface. A sharp point contacted the side observed by the experimenter to allow precise determination of contact coordinates.

Observers were asked to judge where they felt the "stable point" was. We explained that the stable point referred to the point at which an object would remain stable without rotating about the point of contact when held upright with the thumb and index finger. Furthermore, if the object were to be rotated to another orientation, it would remain in the orientation in which it had been placed. This was demonstrated using an object other than those used in the judgment trials. The phrase *stable point* was used for two reasons: First, to avoid using the word *center* in the task description; second, stability was the disposition that we wished our observers to achieve. During each trial observers were asked to close their eyes while the object in the clamp was changed. In this way, they were prevented from obtaining information about the CM by witnessing the experimenter's handling of the objects.

Participants indicated their judgments of the stable point by lightly grasping the object with the tongs at the appropriate location. Participants never actually picked up the objects. The experimenter measured the error in estimation by noting the angle and the radial distance of the point of contact (in millimeters) in the polar coordinates on the back of the object. Observer's viewed all 6 of the objects at 4 different orientations at 0°, 90°, 180°, and 270°, from initial orientations similar to that shown in Figure 12.2. Each participant saw each of the 7

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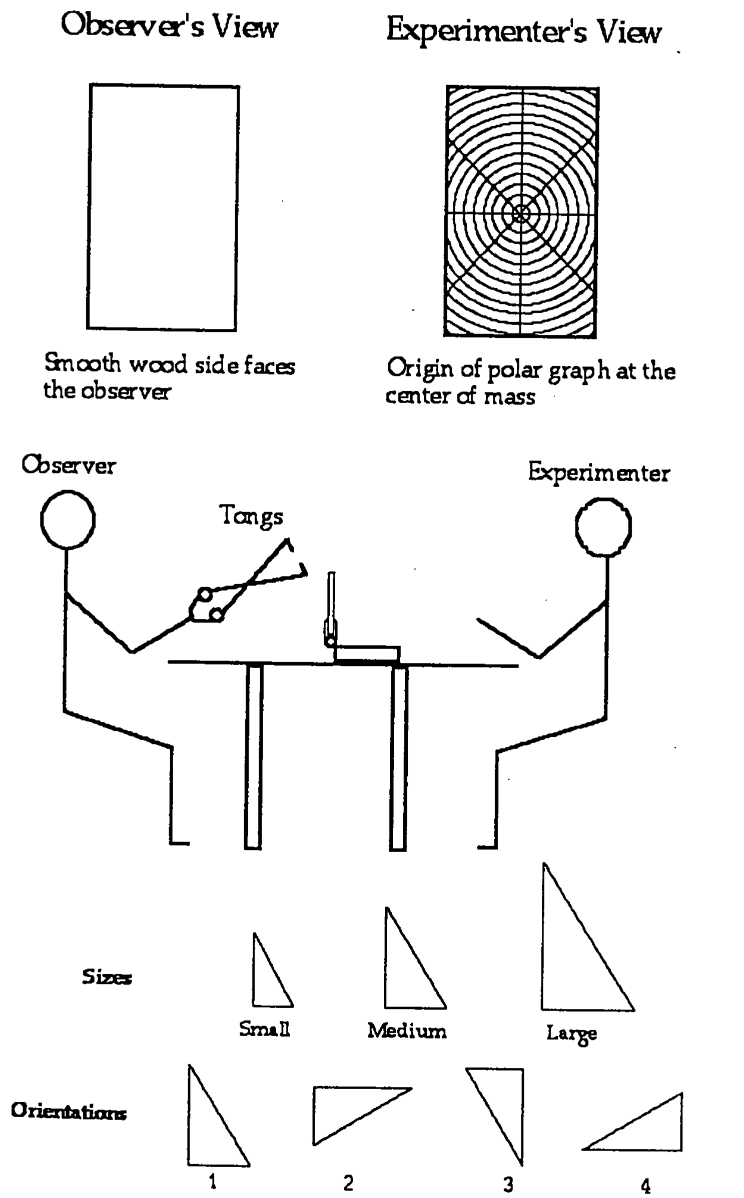

Figure 12. 2. *The organization of the experiments. In addition to variation in shape, objects were varied in size and presented in 4 different orientations.*

shapes in 3 sizes at each of the 4 orientations 3 times each for a total of 252 presentations in 3 blocks of trials. Presentation order within each block was randomized. An experimental session lasted approximately 75 min. Two sessions were required for each participant. All factors were within-subjects.

12.5.1 Results

Measurements in polar coordinates were converted to Cartesian coordinates with the origin at the CM. Zero degrees of polar angle was designated as the positive X direction. The spatial distribution of the data for each object exhibited an elliptical shape including distinct major and minor axes as illustrated in Figure 12.3a. Major axes in the distributions generally aligned with X axes. The X axis had been aligned with distributions exhibited in previous experiments. As shown in Figure 12.3b, for analysis of the systematic error along both the X and Y axes, we used the means of the X and Y data points across trials. Standard deviations calculated for each participant across trials (as well as across participants and trials) were used to analyze the random error along the X and Y axes.

Systematic error was analyzed by performing repeated measures analyses of variance (ANOVA) on the X or Y data with shape, orientation, and size as factors. For the X data, the size and shape factors were not significant, but the orientation factor was, $F(3, 27) = 11.5$, $p < .001$, as was the size by orientation interaction, $F(12, 108) = 3.8$, $p < .001$. In a simple effects test, size levels were significantly different, $p < .04$, at orientations 1 and 4 whereas orientation was significant, $p < .001$, at all levels of size. Other interactions were significant, but the means in each case varied only by +/-1mm and the patterns seemed random.

On the Y axis, the shape factor was significant, $F(6, 54) = 5.5$, $p < .001$, but all means were within +/-1mm except for the quadrilateral which was at 1.8 mm. Both orientation, $F(3, 27) = 9.3$, $p < .001$, and size, $F(2, 18) = 28.8$, $p < .001$, were significant. The interaction was not.

X and Y means were affected primarily by orientation. The overall trend was for the centroids of the distributions to be located below and to the left of the CM by about 2–3 mm. Given the fact that fingerpads are on the order of 15 mm in width, this variability should have minimal functional consequence, that is, all of the mean judgments can be counted as accurate.

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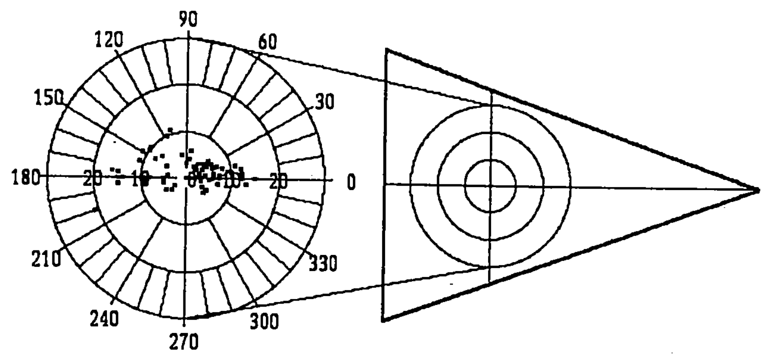

Figure 12.3a. *The elliptical distribution of the data is illustrated. The polar coordinate paper used in the experiment had a larger number of coordinate lines for precise measurement.*

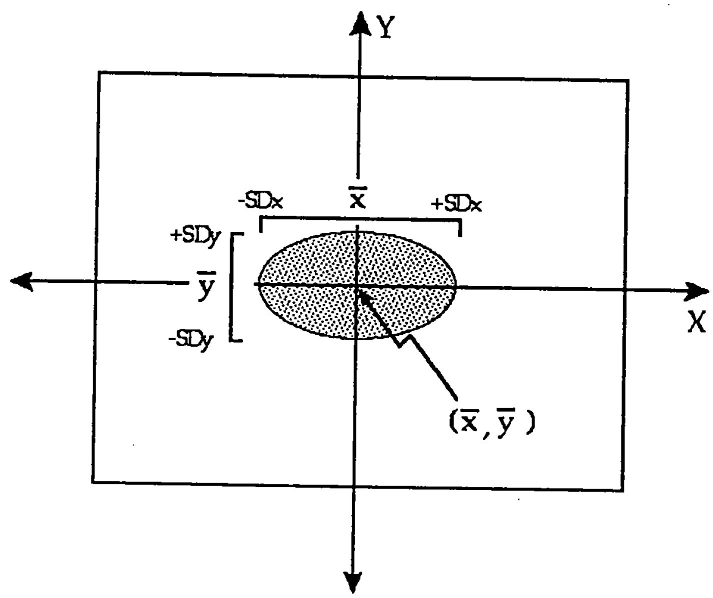

Figure 12.3b. *Modeling the elliptical distributions simply in Cartesian coordinates for statistical analysis. X and Y means represented systematic errors while X and Y standard deviations represented random errors.*

Random errors were analyzed by computing *X* and *Y* standard deviations across trials within shapes, sizes, and orientations. A repeated measures ANOVA was performed on *X* SDs with size, orientation, and shape as factors. There were only main effects of size, $F(2, 18) = 37.9$, $p < .001$, and shape, $F(6, 54) = 33.2$, $p < .001$. As shown in Figure 12.4, the *X* SDs increased as size increased in most objects. The exceptions were the square and the rectangle in which size changes produced no difference. The size by shape interaction was significant, $F(12, 108) = 2.61$, $p < .004$. In simple effects tests, size was significant, $p < .01$, for all shapes except the square and rectangle, $p > .1$, while shape was significant, $p < .05$, at all size levels. The main effect for shape reflects the decrease in the *X* SDs as symmetry increased. The equilateral triangle was an exception to this trend, exhibiting random errors comparable to the parallelogram.

All three main effects were significant for the *Y* SDs, including size, $F(2, 18) = 14.74$, $p < .003$; orientation, $F(3, 27) = 5.90$, $p < .004$, and shape, $F(6, 54) = 7.94$, $p < .001$. As the symmetry of the objects increased, the random error on the *Y* axis decreased. The *Y* SDs increased for the less symmetric objects as the size of the objects increased. The size by shape interaction was marginal, $p < .08$. The reason that this interaction was only marginally significant in this case was that random errors in the three most symmetric shapes were affected by orientation. The *Y* SDs for these objects were higher when the *Y* axis was parallel to gravity. The same trend occurred in the *X* SDs although there it failed to reach statistical significance. The effect can be seen in Figure 12.4 in which mean SDs for *X* or *Y* vertical versus horizontal were plotted separately for each size. Means for the most symmetric objects (rectangle, equilateral triangle, and square) at vertical orientations of both *X* and *Y* axes were greater than those at horizontal orientations. The orientation by shape interaction was significant, $F(18, 162) = 1.66$, $p < .05$. There was a trend in this direction for other shapes as well, but it was clearest in the most symmetric shapes. This effect was especially curious in the case of the square, because nothing specific to the shape changed with changes in orientation of the square. Thus, to account for this effect we must go beyond consideration of shape.

The random errors for the equilateral triangle consistently deviated from a trend of decreasing random error with an increase in the number of axes of reflective symmetry. The equilateral triangle, which has three axes of reflective symmetry, exhibited more random error than the rectangle, which has only two axes of reflective symmetry. Furthermore, the parallelogram, which has no axes of reflective

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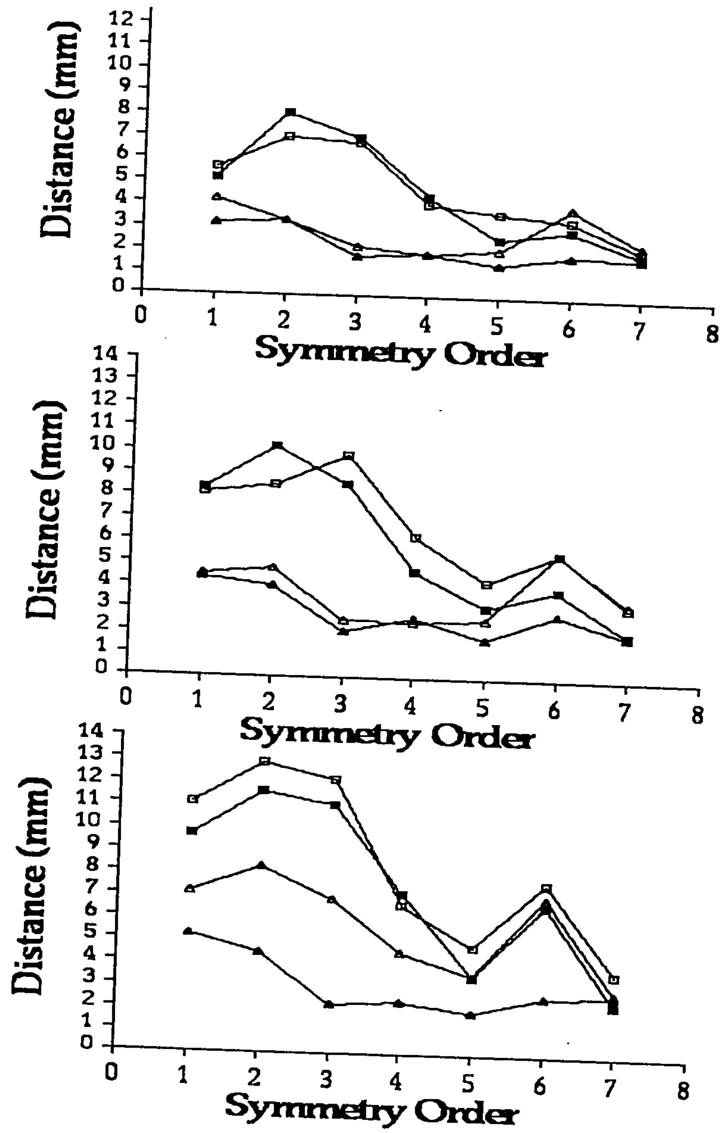


Figure 12.4. *Mean random X and Y errors for 3 object sizes, 7 shapes, and 2 axis orientations either horizontal or vertical. X axis vertical (open squares); X axis horizontal (filled squares); Y axis vertical (open triangles); Y axis horizontal (filled triangles). The object shapes were in order of total symmetry: 1) quadrilateral; 2) right triangle; 3) isosceles triangle; 4) parallelogram; 5) rectangle; 6) equilateral triangle; and 7) square. Top: 100 sq cm. Middle: 200 sq cm. Bottom: 300 sq cm.*

symmetry, exhibited less random error than the isosceles triangle, which has a single axis of reflective symmetry. Clearly, the amount of reflective symmetry can not be the only determinant of random errors.

The inclusion of other types of symmetry, however, may account for the results. The objects used in Experiment 1 varied in the presence or absence of radial symmetry and in amounts of rotational symmetry as well as in amounts of axial reflective symmetry. The triangles, in particular, possessed no radial symmetry, whereas the parallelogram as well as the rectangle and square did (see Figure 12.1). A multiple regression regressing the number of reflective axes, the presence or absence of radial symmetry, and size on *X* SDs accounted for 80% of the variance with beta weights of –.49 for axial reflective symmetry, –.47 for radial symmetry, and .43 for size. A multiple regression on *Y* SDs including the number of reflective axes (β =–.20), whether the orientation of the *Y* axis was horizontal or vertical (B=.36), whether the object possessed any symmetry or not (β =–.44), and size (β =.55) accounted for 72% of the variance. Similar but slightly weaker results were obtained using rotational symmetry in place of axial reflective symmetry. A number representing the total amount of symmetry (number of axes of reflective symmetry plus number of self-congruences in 360° of rotation plus 1 for radial symmetry) accounted for 67% of the variance in *X* SDs, but only 26% of the variance in *Y* SDs in simple linear regressions.

12.6 Reflective Versus Rotational Symmetry

In an attempt to parse out the effects of axial reflective symmetry versus rotational symmetry, we performed additional experiments with two new sets of objects. The first set contained both types of symmetry, and a second comparable set contained only rotational symmetry. The addition of semicircular protrusions along the edges of circles restricted the infinite symmetry of a circle down to the amounts of reflective symmetry exhibited by objects in the initial experiment. In the second set of shapes, the reflective symmetries were eliminated and the rotational symmetries preserved by the addition of small half-oval protrusions just to the side of each larger semicircular bump.

Overall, the results were similar for the two sets, although superior for the set with both types of symmetry. The implication was that observers could use either type of symmetry or both.

In all of the objects except the first and least symmetric of each set, the CM of the object happened to fall very close to the center of the underlying circle upon which all of the objects were based. The CM in the first asymmetric objects in each set fell to the negative side on both the *X* and *Y* axes due to the grouping of the protrusions added to eliminate symmetry. In the absence of the symmetry exhibited by the other objects, observers overestimated the amount to which the CM was moved away from the center of the underlying circle. This result leads to our next question.

What do observers do in the absence of symmetry? Do they use an approximation to symmetry? The results with the perturbed circles would indicate that this was not the case. Approximation to symmetry would have been reflected in a tendency to err in the direction of the center of the underlying circle. Participants erred in exactly the opposite direction. The result suggests, nevertheless, that the underlying approximate symmetry structured the estimates. Did participants use the approximate symmetry to base estimates of CMs? We investigated this question in the next experiment.

12.7 Center of Mass Perception and Approximation to Symmetry

The location of the CM in a planar object that has two axes of reflective symmetry is determined readily because the CM must lie on both axes. An object with only one reflective symmetry axis leaves the location of the CM along that axis undetermined. If a rectangular planar object (with two axes of reflective symmetry) were perturbed by attaching another small rectangular piece to one side, the piece might be added so as to preserve reflective symmetry about one axis while leaving the near symmetry about the remaining axis apparent. If observers used an approximation to symmetry in judging the location of the center of mass, then we would predict that the judgments would tend toward the location specified by the symmetries of the original perturbed rectangular shape. If the size of the added rectangle were to be gradually increased, a new larger rectangle with two symmetry axes would be approached accordingly. As the shape approached the larger symmetric figure, the perturbation would become effectively a perturbation away from the larger rectangle by the removal of pieces. In such circumstances, judgments based on approximation to symmetry should err in the direction of the location determined by the symmetry of the larger rectangle as shown in Figure 12.5a.

As is also shown in Figure 12.5a, we created a continuum along which the location of the CM changed linearly across objects. We added successively larger square figures to one side of an initial square-shaped object. The CM moved 1.25 cm along the X axis in each successively larger object. The series consisted of 9 objects beginning with a square (100 cm^2) and finishing with a rectangle (300 cm^2). We predicted that the occurrence of a second symmetry in the square (object 1) and in the rectangles (objects 5 and 9) would structure the pattern of errors as shown in Figure 12.5a. We predicted that the symmetries would attract

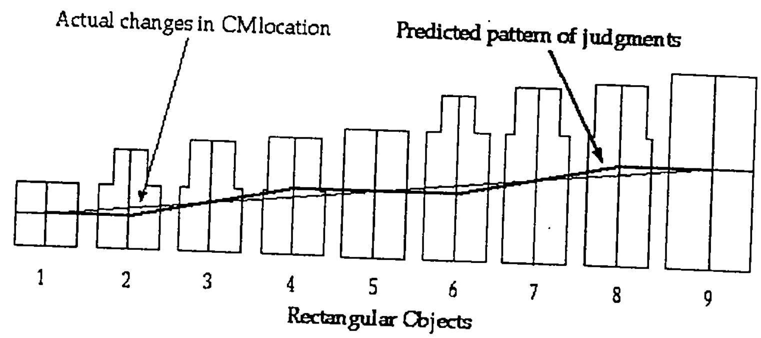


Figure 12.5a. *The rectangular objects used to move the CM along a line along with predictions of how judgments might vary about the line.*

judgments, depending inversely on the deviation from approximate symmetries.

Ten undergraduates at Indiana University participated in the experiment for credit in an introductory psychology course. Participants were required to perform the same grasping task as before. All participants viewed each of the 9 objects at 3 orientations (0°, 135°, and 270°), 3 times each in a session that lasted 1 hour. The main reflective symmetry axis was vertical in the 0° orientation just as shown in Figure 12.5a. All factors were within-subjects.

12.7.1 Results

Systematic errors were analyzed in terms of mean errors along X and Y axes. Repeated measures ANOVAs were performed on the X and Y distances with shape and orientation as factors. Along the X axis, orientation and shape were both significant, $F(2, 24) = 11.34$, $p < .004$, and

$F(8, 96) = 7.55$, $p < .001$, respectively. Along the Y axis only shape was significant, $F(8, 96) = 3.29$, $p < .002$. We will focus on the X means for the 0° orientation in which the symmetry axis common to all of the objects was vertical. As shown in Figure12.5b, the results exhibited exactly the inverse of the pattern predicted by direct approximation to symmetry. Instead, the X means followed a pattern consistent with overestimation of the perturbations as was found with the circular figures of the previous experiment. (The mean errors on the Y axis, though significant across shapes, showed too little range -.75 mm to .75 mm to be of any real significance. Observers stayed very close to the single common symmetry axis.)

Random errors were analyzed via ANOVAs performed on the SDs along the X and Y axes with orientation and number of symmetry axes as within-subject factors. Rather than analyzing each object separately, we grouped the objects into those that had a second reflective symmetry axis and those that did not. For the X SDs, the amount of symmetry was significant, $F(1, 12) = 53.63$, $p < .001$. Judgments were much less variable with both reflective symmetries than with only one. The amount of random error also increased linearly with increases in the size of the objects as can be seen clearly for objects 1, 5, and 9.

The combined pattern in Figure 12.5b and 12.5c demonstrates that symmetries, whether exact or approximate, strongly influence judgments of CM location in objects. The crossing and recrossing of the 0 distance axis in Figure 12.5b exhibits a pattern clearly defined in terms of the points at which the second axis of reflective symmetry appears. In addition to being on the 0 distance axis at the symmetry points, the data cross at points midway between the symmetry points, that is, the crossing locations are symmetrically distributed with respect to the underlying points of symmetry in the set of objects. Rather than staying close to the CM location of the nearest symmetric shape, observers seem to overestimate the strength of the perturbation, whether it be material added to a symmetric form or material subtracted from a symmetric form. Halfway in between the two balance.

12.8 The Role of Dynamics in the Patterning of Estimations

We have described this task in terms of the perception of a dynamic property—the center of mass. One might argue, however, that this is inappropriate and that to interpret these results in terms of perceiving

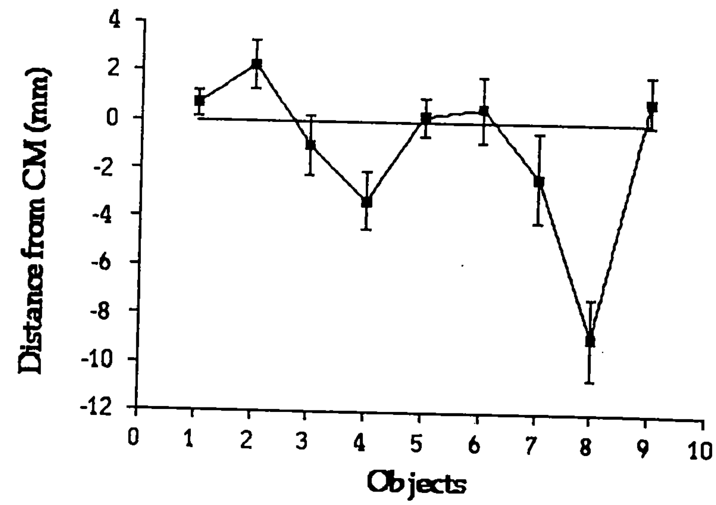


Figure 12.5b. *Mean judgments (with standard error bars) for the upright orientation. Object numbers correspond to those shown in Figure 5a.*

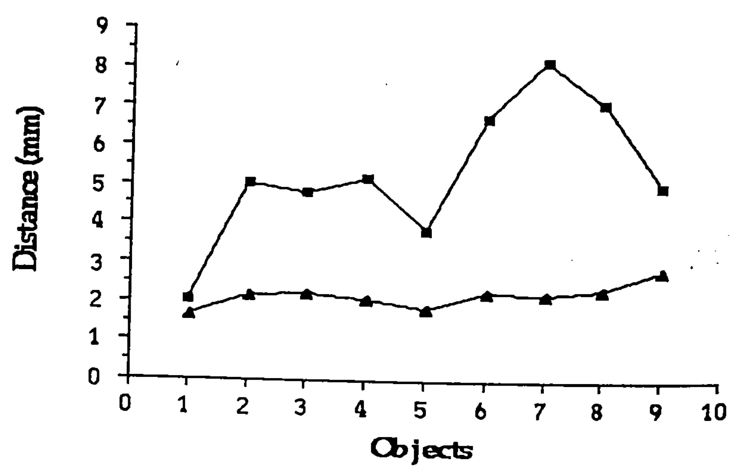


Figure 12.5c. *Mean standard deviations along the X (squares) and Y (triangles) axes.*

dynamic properties or affordances is to read into the data what is not properly there. We reduced our object variations to variations in planar shapes. This suggests that the participants might only have been judging centroids of areas as such, that is, a strictly geometric property with no dynamic content whatsoever.

The difficulty for such an account is in handling variations in judgments produced by variations in object orientation. The judgments reflected the gravitational direction. This certainly implied dynamic content. Systematic errors tended to fall below and to the left of the CM. Rather than undershooting, we might have expected to see overshooting so as to produce a stable equilibrium. However, because the grasps were established from the right side of the object, contact below and to the left of the CM would allow the object to rotate to the right coming to rest against the hand. The result would be an especially stable configuration.

We also found an orientation effect in random error patterns in the first experiment. In the most symmetric objects, random errors were greater along an axis aligned with gravity. The interesting aspect of this effect was that it occurred when no shape related changes accompanied changes in orientation, that is, with the square. In fact, the whole effect seems to have emerged as the objects became more symmetric and shape variations became less of a factor. How might we account for this pattern?

The nature of the pattern is shown in Figure 12.6a and 12.6b, in which contour plots of judgment frequencies are shown as distributed about the CM on object surfaces. Plots for an equilateral triangle appear in Figure 12.6a and for a square in Figure 12.6b. For each object, the results for each of the 4 orientations are shown with the gravitational direction indicated. As previously noted, the distributions tended to be elliptical with the long axis of the ellipses aligned with the gravitational direction. Why should this have been so?

What are the functional repercussions of missing the CM by various distances in various directions? In particular, what is the difference between missing above or below the CM as opposed to missing off to the side? The analysis is shown in Figure 12.7. The object acts as a physical pendulum, so the relevant equation of motion is that for the pendulum. We used the parallel axis theorem to compute the moment of inertia around the contact point. The inertia was computed as the inertia around the CM plus the object mass times the square of the distance from the CM. The inertia about the CM was computed, in turn, as a function of two shape specific constants and the squares of object

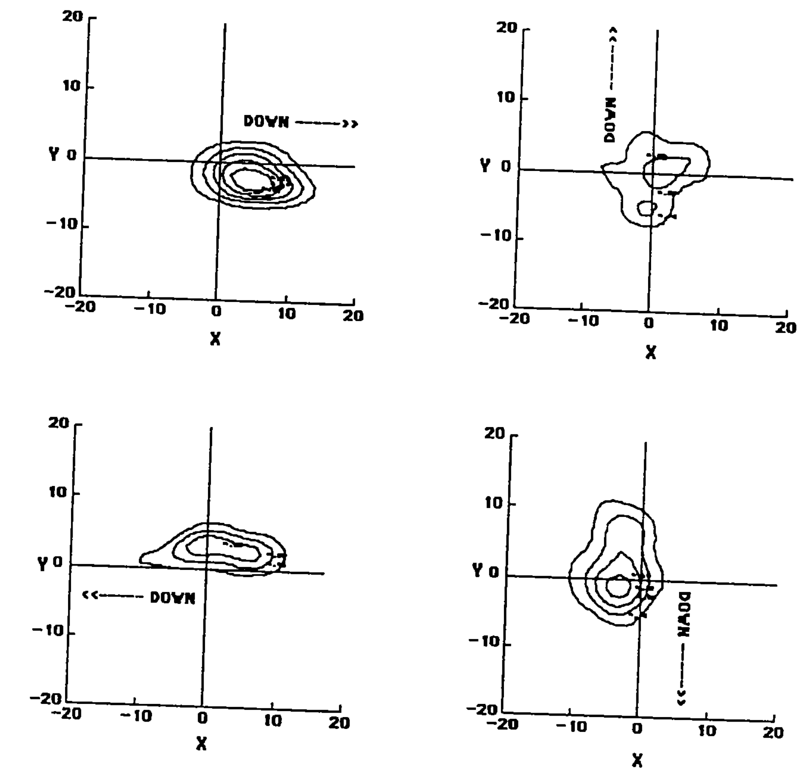
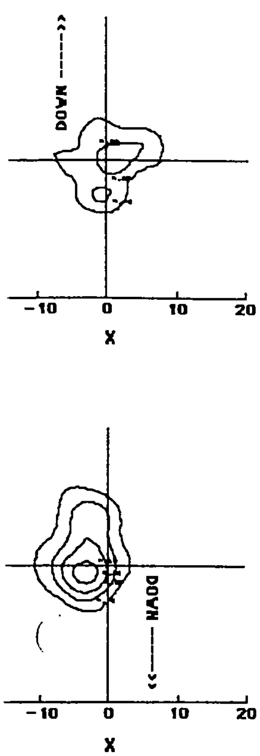


Figure 12.6a. *Contour plots of judgment frequencies for the smallest equilateral triangle plotted separately for each orientation. The direction of gravity is indicated as "down." The X–Y origin is at the CM.*

dimensions. When these were substituted into the original expression, the masses canceled meaning that the rotational acceleration is a function only of the geometry of the object and gravity; q and r can be thought of as polar coordinates on the object surface with the origin at the CM. Thus, for each object of a given shape, the rotational acceleration can be computed for each potential contact point on the object surface using the derived function as a single valued function (yielding rotational acceleration) in two variables (q and r). All of the objects produced acceleration surfaces of the same basic shape shown in Figure 12.8. Only the relative height of the hills and the steepness of their slopes forming the valley varied. The valley always aligned with gravity. We suggest that the elliptical distributions in the data were



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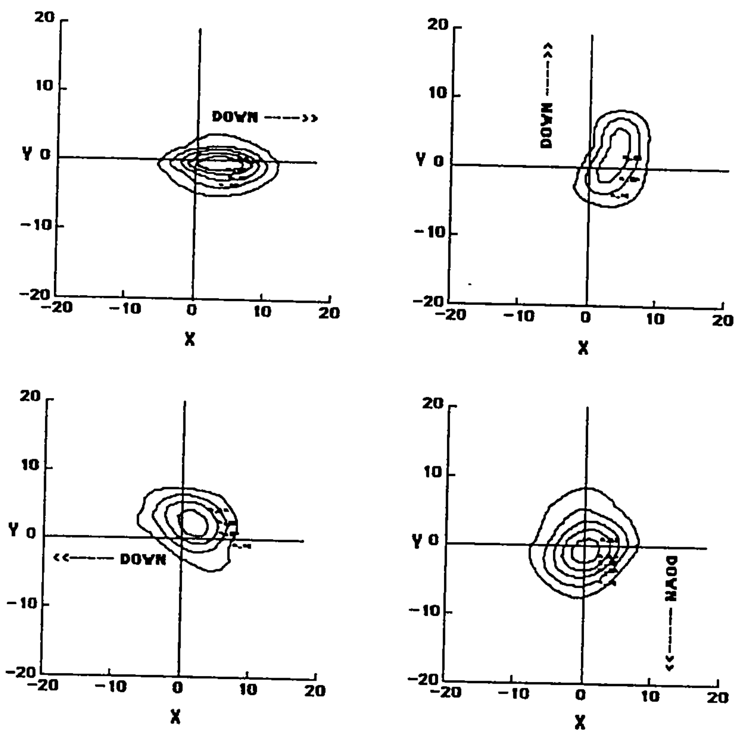


Figure 12.6b. *Same as 12.6a for the medium-sized square.*

constrained to lie along the valley in this plot. Greater errors occurred along the vertical direction where the repercussions were less strong.

Note that this plot is the product of a very local analysis in time, which does not reflect the asymmetry in the stability of points located above versus below the CM. These are the accelerations generated instantaneously at the given location. The graph is relevant when a complete lack of rotation is desired (as opposed to rotations that take one into desirable configurations) and when corrections or responses to rotations can only be provided in some finite time.

The implication of our analysis was that yet another dynamical property—the moment of inertia—contributed to the dispositional property perceived by our observers. This possibly was lent further support when we addressed a remaining aspect of the orientations of

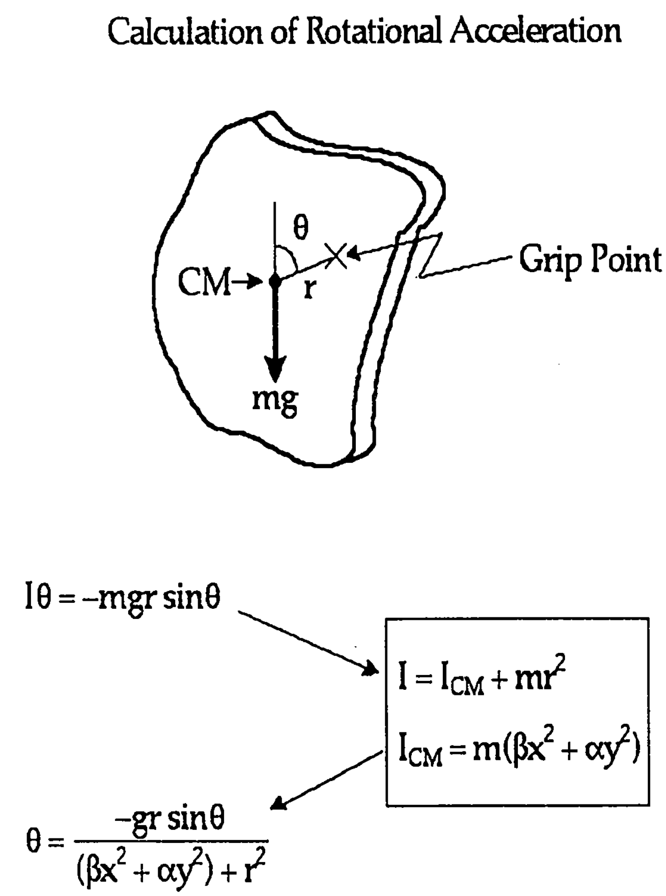


Figure 12.7. *Dynamics generating rotational acceleration around contact points displaced from the CM. I is the moment of inertia; m is object mass; g is gravity; r is the distance from the CM to the contact point or axis of rotation. Remaining variables are described in the text.*

judgment patterns. We have noted that in objects with maximum symmetry, the elliptical data distributions tended to align with gravity. Most often, however, and especially for asymmetric objects, elliptical data distributions tended to align regularly within the object geometry, whatever its orientation. However, the major or minor axes of the distributions did not align with the longest axes that one might find in

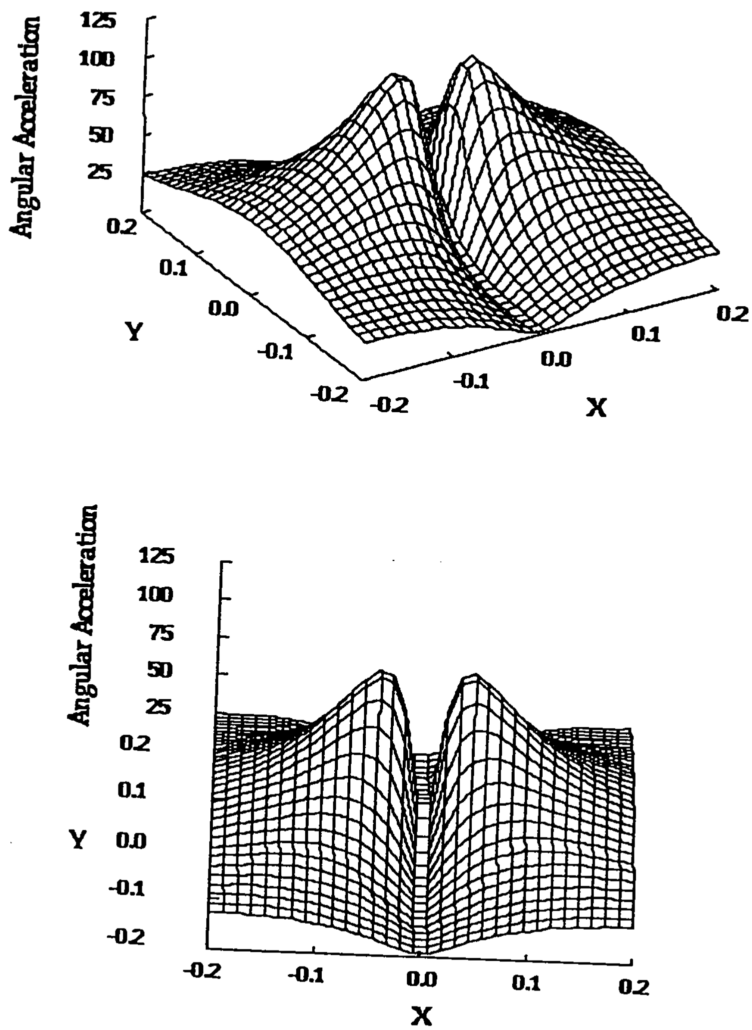


Figure 12.8. *Two perspectives on an angular acceleration surface plotted over X and Y object coordinates centered with the origin at the CM. The Y axis is parallel to gravity.*

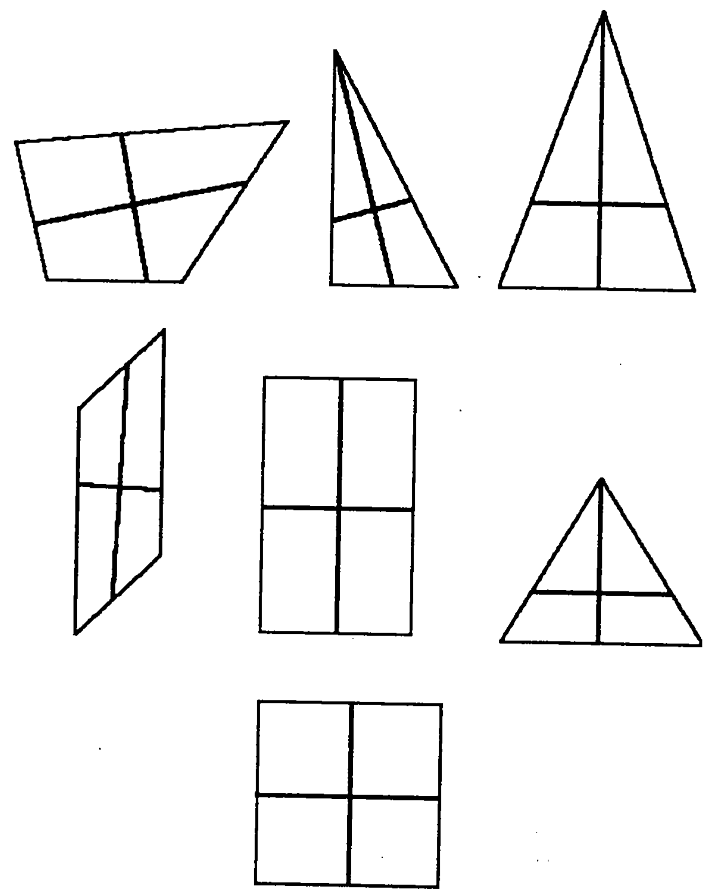
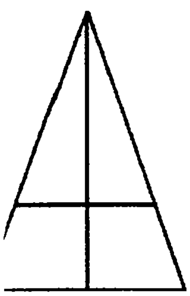
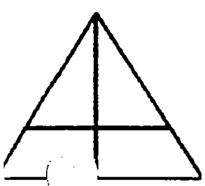


Figure 12.9. *The axes of the principle moments of inertia for the objects used in the first experiment shown together with the major and minor axes of the elliptical data distributions.*

the objects. (In the triangles, such a strategy would place one at an edge of the object.) Rather, in objects with axes of reflective symmetry, the axes of the distributions tended to align with the symmetry axes. (Symmetry axes in the squares and rectangles, for instance, did not correspond to the longest axes which run diagonally from corner to





corner.) But what of the asymmetric objects? A possibility would be to use the longest axes through the CM, but the axes of elliptical judgment distributions did not correspond to these[4]. How were axes determined in judgments? Did their means of determination relate to the use of symmetry axes where possible?

In search of an account, we turned to the moment of inertia as a dynamic property related directly to the CM. Without elaborating on the dynamical role of the moment of inertia (see Solomon, Turvey, & Burton, 1989a, 1989b), we simply note that the principle moments of inertia form a Cartesian coordinate system, intrinsic to an object and its inertial dynamics, a coordinate system with an origin at the CM. We computed the locations of the principle moments of inertia for the objects used in the CM perception experiments. As shown in Figure 12.9, the axes of the elliptical data distributions conformed very well to the axes of the principle moments. This was true in symmetric and asymmetric objects alike because the axes of the principle moments of inertia correspond to axes of reflective symmetry when they are present. The regular coincidence of judgment axes and inertial axes could not be mere coincidence. We inferred that the principle moments were determining perceptible dispositions of use in grasping, but these dispositions remain to be fully understood.

12.9 Understanding KSD: "CM Perception" Versus Dynamically Determined Dispositions

Our results provide conclusive evidence that people can perceive the location of contact points for precision grasps that yield a neutrally stable equilibrium about the opposition axis. Our observers performed with impressive accuracy, certainly sufficient to any act of grasping or object manipulation. Within a tolerance, this locus coincided with the location of the center of mass in an object and so, for convenience, we

[4] A suggestion that has appeared in the robotics literature is to use symmetry axes where possible and the longest axis through the CM otherwise. The problem is that as a rectangle is slightly perturbed into a parallelogram, the perceived axis would have to jump discontinuously from an axis running between the midpoints of the sides to an axis running diagonally corner to corner. The scheme is fundamentally unstable. Given the inevitable noise and stochastic fluctuations in any measurement system coupled with the fact that perfect Platonic rectangles are nonexistent, such instability could well yield indeterminacy in perception, that is, robots paralyzed by indecision.

have referred to this as the "center of mass perception." However, this reference is strictly incorrect for two very important reasons. Understanding these reasons will help to resolve confusions concerning KSD that have arisen in recent discussions.

First, as demonstrated by the complex patterning of judgments in our studies, *observers perceive* not the center of mass, but a *dispositional property of objects that is determined by a collection of dynamical factors* including, in addition to the center of mass, gravity, moments of inertia, frictional and compliance properties of the hand and object surfaces, and response times of the grasping system in response to perturbations of the object. That perceptible dispositions or affordances must always be determined by such a collection of dynamical factors is ensured by the character of the three attributes essential to any affordance, namely, form, scale, and orientation. Regarding form, we investigated geometric symmetries as form properties essential to the identification of a stable grasp locus because the CM is a symmetry property. But we found that symmetries of kinematic form also might play a role as shown in Figure 12.8. Furthermore, we found that the latter kinematic form was orientation-specific while the use of the former geometric forms was also conditioned by orientation. (Note once more that the orientations were determined by gravity which entailed the use of multimodal perception in performing the task.) Regarding scale, we were led to discover the relevance of moments of inertia by the necessary consideration of object size in relation to the size, speed, and perceptual skill of the performer.

Second, *the center of mass* in an object *contributes* as a dynamic factor to the determination of *a continuously related family of dispositions*. The locus of the center of mass is equally relevant to dispositions for stable, neutrally stable, and unstable equilibria in precision grasps. Furthermore, although these types would appear to be categorically distinct, they are in fact all part of a single continuous structure. Unstable equilibria surround and continuously grade into any point of stable equilibrium in which the graded magnitude of instability might be indexed by the distance to the nearest attracting stable equilibrium. The significance is that apprehension of a neutrally stable grasp locus entails the apprehension of a coherent set of alternative affordances for precision grasping. Which affordance is actually used can be determined as additional constraints are brought to bear in the process of progressive goal specification. For instance, returning to the task of transporting a set of objects from table to shelf, suppose that the actor notices upon approaching the third object that it is inverted. Instead of a stable grasp, an unstable precision grasp below the object center of

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the object center of

mass might then be used to place the object upright on the shelf. The specification of this subgoal in the task could only be based on the apprehension of the entire structure comprising the set of alternatives. Additional research on the role of the moments of inertia in grasping and manipulation of objects might reveal the more extensive nature of this structure.

We note that the use of these dispositions was conditioned by the availability of perceptual information as shown by the results of our having perturbed object symmetry. The fact that estimates were affected by the perturbation of symmetry showed both that symmetry is indeed used as information about the locus of neutrally stable contact points and that the use of the disposition depends on the availability of that information, at least before contact. When symmetry was perturbed, the use of approximate symmetry (or neighboring symmetries) as visual information allowed the performer to contact an object within a ballpark which could then be improved via haptic information that would become immediately available upon contact. An affordance is as much conditioned by the availability of perceptual information as by other dynamical factors, but that information will evolve over time and the course of an act and will involve a number of different modalities.

So, we close with the emphatic warning that the "D" in KSD should be understood as a reference to dispositional properties determined by the interplay of dynamical factors. The exact nature of those properties is an empirical problem. We must not confuse our hard won analytical apparatus, namely, dynamics, with the phenomena incidentally under study, namely, perceptible events and affordances. Classical mechanics was not developed in a week as it would have been had the dynamics underlying everyday events been immediately accessible through perception. Nevertheless, those dynamics generate the regularities that comprise and are detectable as affordances.

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