The Role of Physical Properties in Understanding the Functionality of Objects

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Abstract

We investigate the role of physical properties in determining how people select objects for use in physical activities. We propose a geometric model in which dimensions represent properties relevant to the goals of the activity and objects occur as points in this property space. An object's proximity to an ideal value on each property is additively combined across properties to produce a measure of the usefulness of the object for that activity. We report an experiment that shows that this ideal-point model successfully describes how people select an object for use in a physical activity by using physical properties as an intermediary factor. This model is derived from models of preference choice in which an individual selects objects that he or she prefers.

Properties and Functionality

If you want to pound in a nail, but have no hammer, would you rather use a pillow, a metal paperweight, or a table? Although we typically think of using an object for its intended purpose, most objects can be used in different ways, depending upon the demands of the activity. The classic studies of functional fixedness (Duncker, 1945) show that people can decide to use objects for unusual purposes, but that the intended (or most frequent or recent) use of an object strongly interferes with the person's ability to recognize unusual uses.

When people list attributes of objects, they frequently include the functional uses of an object among its characteristics (e.g., "makes music" for a piano; Rosch & Mervis, 1975; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976; B. Tversky & Hemenway, 1984). Other listed attributes include physical properties (e.g., "is made of wood") and parts (e.g., "has keys"). Richards, Goldfarb, Richards & Hassen (1989) found that affecting an object's ability to perform its main function strongly affected the classification of that object. For example, few people still called an object "that is just like a shower cap but had big holes in it" a shower cap. Thus, how people categorize an object depends upon how physical properties relate to the object's functional use. In this paper we present and empirically validate a mathematical model that describes how physical properties influence how people select objects for use in physical activities.

A Strategy for Object Choice

One strategy for deciding what to use to pound a nail is to first prioritize the physical properties required of any object to be used in the task. For example, you might identify the physical properties "hard" and "graspable" as being important aspects of the object. Next, order the set of available objects relative to an ideal value for each of these physical properties for the activity. Finally, combine this ordering information to select an object for use. Thus, in the absence of a hammer, you might prefer a metal paperweight over a pillow (which is not hard) or a table (which is not

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graspable).

To make our hypothesis more specific, we identify the following steps for selecting an object for use in an activity. First, physical properties that the goals of the activity require be true of the object are identified and weighted according to their importance for achieving the goals. Second, the object is rated on each physical property dimension. Independently, an optimal value, or "ideal point", is selected on each property dimension. The ideal point specifies the value that any object should have on the dimension to best achieve the goals of the activity. Finally, this information is combined to produce the "usefulness" of the object in the given activity.

The weightings of properties according to the goals of the activity are independent of specific objects, and hence can be used for any set of objects. Also, the ratings of an object on each of the property dimensions are independent of any activity, and hence can be used for any activity. However, because the placement of an ideal point on a property dimension is dependent on the activity, object ratings relative to the ideal point are dependent on the activity.

A Preference Choice Model

This process of determining the usefulness of objects in a physical activity is similar to that described by models of preferential choice in which an individual selects items that he or she prefers based on relevant feature dimensions. Comparing our model to the preference choice models, we replace the agent that does the selecting, i.e., the individual, with the physical activity. Thus, the physical activity "selects" the object that best satisfies its goals (i.e., that it "prefers") based on relevant physical properties. To emphasize the difference between the two scenarios, in a preferential choice situation, preferences are assumed to vary across individuals as well as across contexts, whereas in selecting an object in a physical activity, preferences are assumed to only vary across activity contexts. In particular, it is assumed that for each activity the usefulness of an object is objectively determined by the constraints of the physical universe. Differences between individuals in their assessment of an objects usefulness could arise from individual experience with the objects or in the activities.

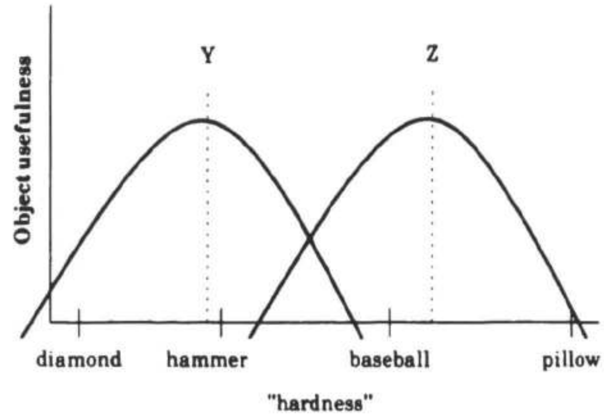

Figure 1: Illustration of the ideal-point model in one dimension. Objects "diamond" through "pillow" are ordered on the dimension of "hardness." Y and Z are ideal points for different activities. Usefulness increases upward.

The notion of an ideal point, relative to which preferences for items are determined, was first studied by Coombs (1950, 1964) with his unidimensional unfolding model. Coombs proposed that preference functions are single-peaked and symmetric with respect to items that lie on some ordered dimension. We follow Coombs' approach, and show in figure 1 an example of a function that specifies the usefulness of an object in an activity. Several objects are ordered along the single dimension of "hardness." The usefulness of an object is displayed in the dependent axis (increasing upward) and is assumed to peak, for a given activity, at some ideal point on the item dimension, such as Y or Z. For the activity with ideal point Y the usefulness ordering of objects is: hammer, diamond, baseball, pillow; whereas for the activity with ideal point Z the usefulness ordering of objects is: baseball, pillow, hammer, diamond.

The single peaked preference function of Coombs was extended to the multi-dimensional case by Bennett and Hay (1960) and Carroll (1972, 1980). The current model for object functionality follows the computational analysis presented by Carroll. As in Carroll's model, the current model represents the selection or choice process in a geometric model, where the property values of objects occur as points in a multi-dimensional space with physical properties as dimensions. We assume the standard Euclidean distance metric in this multi-dimensional property space. Then the distance $d(i,j)$ between a point x and an ideal point y in this space is given by:

$$d^2(i,j) = \sum_{k}^{r} w(i,k) \times (y(i,k) - x(j,k))^2 \quad (1)$$

where $d(i,j)$ is the distance of object j from the ideal point for activity i, $y(i,k)$ is the coordinate of ideal point y on dimension k for activity i, $x(j,k)$ is the coordinate of item j on dimension k, $w(i,k)$ is the importance that dimension k has in activity i, and r is the number of dimensions. We further assume that the usefulness of object i in activity j is proportional to the square of this distance, $d^2(i,j)$, and is linear. Then:

$$u(i,j) = a(i) \times d^2(i,j) + b(i) \quad (2)$$

where $u(i,j)$ is the usefulness rating of object j in activity i, and $a(i)$ and $b(i)$ are constants specific to activity i. The assumptions of a Euclidean metric in the property space and a linear relation between $u(i,j)$ and $d^2(i,j)$ implies that the usefulness function as shown in Figure 1 will be parabolic and centered at the ideal point y.

Equation 2 provides the computational form of a quantitative ideal-point model for determining the usefulness of objects in different activities. The ideal points $y(i,k)$, the weights $w(i,k)$, and the constants $a(i)$ and $b(i)$ are the unknown parameters to be estimated from the data.

An Empirical Test

We have tested the ideal-point model by collecting data for the right hand side of Eq. 2 to calculate a predicted value for $u(i,j)$. We also collected data for the left hand side of Eq. 2 to provide observed values for $u(i,j)$ to which predicted values were compared and used to evaluate the fit of the model. To reduce the number of unknown parameters in the model, we assume the weights $w(i,k)$ as given; therefore, the total number of unknown parameters is $r+2$. Thus we obtained data for three different rating tasks: rating objects on properties $(x(j,k))$, rating objects in an activity context $(u(i,j))$, and rating the importance of properties in an activity context $(w(i,k))$.

Objects: boomerang, bowl, cap, diamond, hammer, helmet, knife, needle, pillow, plate, rolling pin, screwdriver, sofa, table, tennis ball.

Properties: hardness/softness, flexibility, thickness/thinness, smoothness/roughness, fragility, size, flatness/curvedness, graspability, weight.

Activities: unscrew a 1/2-inch screw, anchor a helium-filled balloon that is attached to a string, flatten dough for baking cookies, slice a carrot, poke a hole in the side of a soda can, protect your head from harmful blows, pound a 1-inch nail into a wooden wall, sit down comfortably on an object, pry open a can of house paint.

Table 1: The objects, properties, and activities used in the experiment.

Method

Fifteen commonly known objects were chosen so as to provide a variety of similar and dissimilar object pairs, as well as to have physical properties that are highly associated with the object's main function. In addition, 10 physical activities were chosen. All objects and activities were represented by line drawings. Finally, nine properties were obtained in a preliminary session where eight subjects were instructed to list those physical properties that the activity suggested should be true of objects. Table 1 gives the objects, properties, and activities. Using these stimuli, 29 subjects gave three different types of ratings: (1) object-on-property ratings, in which subjects rated objects on the given properties, (2) property-on-activity ratings, in which subjects rated how much the property mattered for an object that was to be used for the given activity, and (3) object-on-activity ratings, in which subjects rated the usefulness of objects in the different activities. Objects (other than these stimuli objects) were given as endpoint references for the object-on-property rating task in order to make the scale endpoints more determinate.

Results

To test that subjects sufficiently discriminated in their ratings of the selected items (objects, properties) on their respective scales (property, activity), we calculated all pairwise T-tests for ratings between items on a scale. The percentage of item pairs whose ratings on a scale were significantly different at the $\alpha = 0.05$ level averaged 59% across properties for object-on-property ratings, 57% across activities for object-on-activity ratings, and 43% across activities for property-on-activity ratings. The averages above 50% for the object-on-property and object-on-activity ratings were taken to imply that subjects sufficiently discriminated between items on these scales, and that the data could be used in the model. (The only exception was the object-on-activity ratings for the activity "to protect your hand while holding a hot pan", which was eliminated from further analyses due to a small percentage of significant T-tests.) The below-50% average for the property-on-activity scales indicates that, at least in this rating task, properties do not vary much in their relative importance in a given activity, or equivalently that many property weights are about equal. For this reason we report results in which the $w(i,k)$ property weights in Eq. 2 are assumed to be equal.

We fitted the ideal point model given in Eq. 2 to the data for each of the activities. Observed data were used for the known parameters in the model, the $u(i,j)$ and $x(i,k)$. Averaged values (over the 29 subjects) were used for these parameters. The $w(i,k)$ or property-on-activity ratings were set equal to 1 (without loss of generality). We used an iterative weighted non-linear regression method to estimate the unknown parameters, the $y(i,k)$ or ideal points, and the constants $a(i)$ and $b(i)$. Although Carroll (1972, 1980) showed that Eq. 2 reduces to a standard linear regression equation from which the unknown parameters (the $y(i,k)$, $a(i)$ and $b(i)$) can be analytically determined from an exact least-squares solution, we could not use this approach because we wanted to restrict the ideal point estimates to the range of the object-on-property ($x(i,k)$) scales. Also, the reduced linear regression equation is too sensitive to collinearities between the property dimensions that do not exist in the original non-linear regression equation (Eq. 2). The non-linear regression procedure minimized the weighted sum of squared errors between the predicted and average observed $u(i,j)$ values with each error term in this sum divided by the variance (across subjects) of the observed $u(i,j)$ value. We used a chi-square test to determine the goodness-of-fit of the model to the data. The chi-square term was equal to the sum, over objects, of squared Z-scores, where Z-scores were calculated by dividing the difference between the predicted and averaged observed $u(i,j)$ values by the standard error of the mean of the observed $u(i,j)$ values.

We performed this analysis for each of the nine activities using from one to all nine properties in the ideal point model (i.e., in Eq. 2 the index r ranged from 1 to 9). We used the average observed property-on-activity ratings ($w(i,k)$) to determine the order in which properties were added to the model for a given activity. Properties rated as more important for that activity were added to the model first. (Other methods may also be used to determine an ordering.) For each activity, Table 2 gives the estimated ideal point values for the minimum number of properties needed to achieve chi-square significance using the ideal point model in Eq. 2. For example, for the activity "to unscrew a screw," six properties were needed before the model achieved significance with the data. The average minimum number of properties needed to achieve significance was 6.22, which is greater than 1 ($t(8) = 6.56, p < .01$) and less than 9 ($t(8) = -3.48, p < .01$).

Discussion

In all activities the ideal-point model fit the data, and in general more than one physical property was needed to determine an object's usefulness. In addition, the set of properties needed is determined by the context of the activity. For example, only one property, weight, is important for determining how useful an object is for anchoring a balloon; however, this property is not important for determining how useful an object is for unscrewing a screw, although six other properties are important.

The ideal point values given in Table 2 vary widely across activities, as expected, and are intuitively reasonable.[1] For example, the ideal point values for the property "thickness" imply that a thick object is most useful for protecting your head from harmful blows, but that a thin

[1] Only ideal point values for the property "hardness" appear to be counter-intuitive, a result for which we currently do not have a good explanation.

Activity	Minimum Number of Dimensions (χ^2)	*Flatness*	*Fragility*	*Grasp-ability*	*Hardness*	*Weight*	*Rigidity*	*Size*	*Smooth-ness*	*Thick-ness*
		child's ball	light bulb	police pistol	human hair	kitchen stove	wine glass	auto-mobile	nail file	bedroom dresser
Anchor a helium bal-loon	1 (3.234)					2.3				
Flatten cookie dough	7 (6.928)	2.4	5.8	1.0	2.5	1.2	1.0		9.0	
Protect your head from blows	8 (6.170)	6.2	6.0	7.1	9.0	9.0	6.7	3.3		1.2
Pound a nail into a wall	9 (7.047)	6.2	7.5	4.6	1.6	3.4	1.0	9.0	3.7	6.3
Pry open a paint can	7 (7.411)	7.4	9.0	1.7	1.9		1.1	3.9		6.8
Poke a hole in a soda can	5 (7.557)		2.1~	4.8~	8.3~		9.0~			1.9~
Unscrew a screw	6 (11.119)	7.5	8.9	2.5	1.7		1.4			6.9
Sit comfortably	5 (4.157)		5.9~		7.6~		4.5~	9.0~	5.6~	
Slice a carrot	8 (9.940)[a]	9.0	9.0	1.5	2.0	1.2	1.5	9.0		7.4
		ironing board top	tanker anchor	rain barrel	diamond	maple leaf	bow (ribbon)	shirt button	glass bottle	razor blade

1 ↑ physical property scale ↓ 9

Table 2: Ideal points occur on the rating scale from 1 to 9 shown at the right. For each property, the objects used as scale endpoints are shown at the top (for "1") and bottom (for "9") of each column.

a. For all reported chi-squares, the null hypothesis that the predicted and observed $u(i, j)$ values are equal could not be rejected at the $\alpha = .05$ level (i.e., $p > .05$), except for the last item, marked by "a", for which $p > .01$.

~ Values indicated by tilde (~) are anti-ideal points (see Carroll, 1980), i.e., values that are the *least* useful rather than the *most* useful. Comparing to Figure 1, the usefulness curve for an anti-ideal point is inverted and concave upward. Hence objects become *more* useful the farther they are from an anti-ideal point in either direction along the dimension.

object is most useful for prying the lid off a paint can. Our ideal point values suggest design strategies for "ideal objects" as well as an account of the affordance characteristics of objects in particular activities (Gibson, 1977; Norman, 1988). For example, Table 2 suggests that the ideal object for protecting your head from harmful blows should be light but rigid. In fact, manufacturers of helmets are constantly searching for new materials to satisfy these constraints; the problem being, of course, that lighter materials tend to be flexible.

This phenomenon can also be viewed from the standpoint of ad hoc categories (Barsalou, 1983). Selecting objects for an activity such as "to pound a nail" can be viewed as rating objects in the ad hoc category "things to use to pound a nail." From this standpoint, our research describes how a set of objects leads to a particular graded structure for particular activities. Also, this work can be viewed as a study of the effect of activtyi context on properties and concept definition. Previous results have shown that context affects the salience of properties (Barsalou, 1982; A. Tversky, 1977) as well as concept definition (Roth & Shoben, 1983).

In summary, the ideal-point model used to describe preferential choice data for individuals was successful in describing how people use physical properties to determine the usefulness of objects in different activities. Properties relevant to the goals of the activity are identified and an ideal value for each property is selected. An object's proximity to the ideal value on each property is additively combined across properties to produce a measure of the usefulness of the object for that activity. This characterization provides us with a better understanding of how people come to use objects in different activities, as well as how they perceive functionality in general.

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