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Categorical perception of familiar objects

Fiona N. Newell[a,*], Heinrich H. Bülthoff[b]

[a]Department of Psychology, Áras an Phairsaigh, University of Dublin, Trinity College, Dublin 2, Ireland
[b]Max Planck Institute for Biological Cybernetics, Spemannstrasse 38, Tübingen 72076, Germany

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Abstract

We report three experiments where the categorical perception of familiar, three-dimensional objects was investigated. A continuum of shape change between 15 pairs of objects was created and the images along the continuum were used as stimuli. In Experiment 1 participants were first required to discriminate pairs of images of objects that lay along the shape continuum. Then participants were asked to classify each morph-image into one of two pre-specified classes. We found evidence for categorical perception in some but not all of our object pairs. In Experiment 2 we varied the viewpoint of the objects in the discrimination task and found that effects of categorical perception generalized across changes in view. In Experiment 3 similarity ratings for each object pair were collected. These similarity scores correlated with the degree of perceptual categorization found for the object pairs. Our findings suggest that some familiar objects are perceived categorically and that categorical perception is closely tied to inter-object perceptual similarity. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

It is well documented that visual stimuli varying on a monotonic scale are often not perceived as gradually changing. Instead, the elements along this continuum are often perceived as belonging to discrete categories. For example, observers rarely report perceiving continuity of colour change along the colour spectrum but report "shifts" in colour categories from, say, red to orange to yellow, etc. Changes in facial identity and facial expressions are similarly perceived as categorical. These and other findings have suggested to researchers that the brain somehow categorizes perceptually similar stimuli

* Corresponding author.
E-mail address: fiona.newell@tcd.ie (F.N. Newell).

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into qualitatively different categories to allow for more efficient processing of the perceptual world (see Harnad, 1987 for a review).

The world is filled with a rich variety of shapes, both living and non-living. Remarkably, by perceiving the similarities and the dissimilarities between objects, we can create classes of objects to effectively reduce the overwhelming number of entities in the world to more manageable proportions (Rosch, 1975; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976; Tversky & Hemenway, 1984). The number of possibilities of different object shapes in the world is endless yet each shape can be effortlessly categorized, even if the shapes are unfamiliar (Murphy, 1991). These findings suggest that there exists a specialized perceptual system that can group particular objects into different object classes based on their shape.

Recent research has found that recognition performance on objects is related to the degree of perceptual similarity between the items in a task such that recognition is faster and more efficient when inter-object similarity is low and less efficient when inter-object similarity is high (Edelman, 1995a; Newell, 1998). For example, if the task involves recognizing objects from different classes then recognition is generally quick and error-free. It is argued that such efficient recognition performance can occur by building a description of the object based on its component parts (Biederman, 1987; Biederman & Gerhardstein, 1993; Marr, 1982; Marr & Nishihara, 1978). Thus, recognition could be achieved when a generic description of the object's structure is built from the image and subsequently matches a memory representation of that object's description. Part-based descriptions of objects are often sufficient to discriminate between different object classes since these descriptions are mostly unique across classes (Biederman, 1987; Rosch et al., 1976). Moreover, it is often argued that much of object recognition occurs at the most general category level of abstraction, that is, the basic or entry level (Biederman, 1987; Joilcoeur, Gluck, & Kosslyn, 1984; Rosch et al., 1976).

Yet basic-level recognition is not the only recognition task for the visual system. Many researchers argue that recognition often involves discriminating between items within the same class (Bülthoff, Edelman, & Tarr, 1995; Tarr & Bülthoff, 1995), that often share the same part-based descriptions (Rosch et al., 1976; Tversky & Hemenway, 1984). For example, such a task might be to discriminate a Ford Escort from a Volkswagen Golf. The visual recognition system therefore needs to be able to discriminate between different exemplars within a category. When items within a task are highly similar, then recognition is less efficient, with performance often dependent on changes in the image characteristics such as viewpoint (Bülthoff & Edelman, 1992) or illumination (Tarr, Kersten, & Bülthoff, 1998). Moreover, incidental changes in viewpoint produce a higher cost on recognition performance if the objects in the task are highly similar, and less pronounced if the objects are not very similar (Newell, 1998). In sum, research into object recognition suggests that the recognition system is tuned to the specific shape characteristics of categories of objects and that representational object space is structured into classes of perceptually similar objects sharing a basic set of features (Edelman, 1995b).

Given the evidence that the object recognition system can distinguish between different object classes and objects within a class the question arises as to how such a system can work. Although many methods can be proposed we will consider two, more obvious, ones. First, the perceptual system may be tuned to a particular combination of features that represent a particular class of objects. In this case we would predict a qualitative difference in the way similar objects actually look to the perceiver, if those objects belonged to separate categories. Consequently, objects with the required set of features would be classified differently than objects with less than the required set. On the other hand, small, even continuous, changes between similar objects may be perceived directly and it is only the later semantic or verbal systems that are tuned to categorize these shapes. If this were the case then we can predict no effect of category membership at the perceptual level.

In the following experiments we investigated whether objects are indeed classified at the perceptual level using a paradigm often used in psychophysics called categorical perception (CP). The hallmarks of CP are usually twofold: First, the probability of identifying an object should not vary linearly along a continuum of shape change but should change relatively abruptly at the subjective category boundary. Second, pairs of shapes differing by the same physical amount should be more discriminable if they straddle this category boundary than if they lie within one category.

In the past, CP effects within the visual domain have been demonstrated using continuous stimuli such as colours (Bornstein & Korda, 1984), facial identity (Beale & Keil, 1995), facial expressions (Calder, Young, Perrett, Etcoff, & Rowland, 1996; Etcoff & Magee, 1992) and the race of faces (Levin & Beale, 2000). In one such study on faces, Calder et al. created photo-realistic sequences of morphed images between different expressions of a face. Participants were first required to discriminate between pairs of images along each expression continuum that differed by equal physical increments between two different expressions. They were then required to label each morphed image as one of two pre-specified facial expressions. Calder et al. reported finding sharp, step-like functions categorizing images into two different facial expressions. Moreover, they found an increased sensitivity to discriminating images that lay along the category boundary. Thus, their study provided evidence that higher-order stimuli such as facial expressions are categorical at the perceptual level.

In the same way that facial expressions and facial identities are reported to promote CP, we investigated whether objects are also categorical at the perceptual level. Previously, CP effects have been demonstrated using exemplars from the same class (e.g. faces) with very little variation in shape between the exemplars. Thus, one might argue that CP effects are found only when there are subtle changes in shape. Shape differences between objects, however, can vary quite dramatically, particularly across different basic-level classes (e.g. from a bottle to a car) whereas more subtle shape changes are likely to occur *within* an object category. Consider, for example, the category of 'Bottle': in the real world, the difference between two bottles may only involve slight changes in shape and size. Consequently, it would be important for the perceptual system to differentiate, or 'tag' similar bottle shapes together for identification purposes. Tagging could occur through learning to identify the relevant dimensions on which the objects differ (Goldstone, 1994). Such a process would apply when discriminating between wine bottles and coke bottles, for example, but may be unnecessary when discriminating between a wine bottle and church bell. The intrinsic shape differences between a wine bottle and church bell may suffice for efficient identification whereas the perceptual system may need to specify qualitative shape differences between a wine bottle and coke bottle in order for these shapes to be discriminated, thus resulting in effects of CP.

In general, very little research has been conducted on the perceptual categorization of shape. However, there has been a very recent increase in the number of reported studies on effects of categorization in object recognition. In particular, Rosielle and Cooper (2001) reported finding that the relative orientation of parts of an object are perceived categorically. In their study, they found that objects differing in an angular separation between their parts of 30° were easier to discriminate if the angles were qualitatively different (e.g. perpendicular vs. oblique) than if they were relatively the same (oblique vs. oblique). Thus, Rosielle and Cooper found evidence that objects are perceived as categorical based on their intrinsic part structure.

It has also been reported that other types of local shape changes are also categorically perceived (Mamassian, Kersten, & Knill, 1996). In their study, Mamassian et al. asked participants to classify a specified local shape on an object surface as either hyperbolic or elliptical. Each local shape was a sample of a continuum of shape change along a surface of a 'croissant-like' object. They found that participants could reliably partition the local shapes into either hyperbolic or elliptical surfaces. A sharp step-like function relating the number of responses to the continuum of local shape change marked the subjective category boundary that partitioned the two surface descriptions. The authors argued that this ability to correctly locate the partition between the classes of curved surfaces may be a property of the visual system that is used to, say, partition objects into their component parts. Their study also provided evidence (albeit indirectly, since discrimination sensitivity at the category boundary was not measured) that shape changes between similar object properties, such as from elliptical to hyperbolic surfaces, can be categorically perceived.

Recent neurophysiological studies have found evidence supporting a neuronal representation of objects based on category membership (Freedman, Riesenhuber, Poggio, & Miller, 2001; Sigala & Logothetis, 2002). Freedman et al. reported that cells in cortical areas which are sensitive to shape are also sensitive to categorical distinctions between objects. They recorded from cells in the prefrontal cortex of monkeys during presentation of exemplar stimuli from two different categories: cats and dogs. The stimuli were computer generated and blended together such that some category members were more like members of another category than their own category members. They tested activation in cells while the monkey performed a delayed match-to-sample task on the different category objects. The task was to decide whether two successive stimuli were from the same category. Freedman et al. reported finding that cells in prefrontal cortex were sensitive to category boundaries, such that differential activation was observed between different categories of objects but not between members of the same category (despite large differences between the shapes of category members). In another categorization study, Sigala and Logothetis (2002) trained macaque monkeys in an object (i.e. schematic faces and fish) categorization task. Their stimuli were constructed such that half of an object's features were relevant for categorization whereas the other half were not. Sigala and Logothetis found that cells in inferotemporal cortex selectively responded to features of objects which were diagnostic of category membership. In a parallel, psychophysical study using monkeys and humans, Sigala, Gabbiani, and Logothetis (2002) reported that categorization of novel stimuli involved a similarity comparison to already familiar category members. More pertinently, Sigala et al. also found that after category learning, both humans and monkeys were sensitive to the position of the linear category boundary between categories such that classification of novel stimuli was related to their distance from the boundary. All of these studies provide evidence that categories are coded at the neuronal level, in particular in the prefrontal and inferotemporal areas. Moreover, these studies also provide further evidence on the flexibility of categorization: object categories can be learned despite high cross-category similarity between objects and low within-category similarity between objects (see also Goldstone, Lippa, & Shiffrin, 2001; Levin & Beale, 2000) and categorization can be dependent on the position of the boundary between categories.

In Experiment 1(a) we investigated whether familiar objects were perceived categorically. Two main groups of objects were used as stimuli: objects from within the same basic-level category and objects from different basic-level categories. Categorical perception was tested between all possible pairs of objects within each group. We found evidence of CP for some, but not all, of the object pairs. In Experiment 1(b) we increased the difficulty of the discrimination task used in Experiment 1(a) because of a concern that the discrimination task was not sensitive enough to show effects of CP which may be present for some object pairs. In Experiment 2 we tested whether effects of CP found could generalize across different viewpoints of the same object. Finally, in Experiment 3 we collected similarity ratings for the pairs of objects used as stimuli in our experiments and compared those to the categorization performance.

2. Experiment 1(a)

In the following experiment participants performed two tasks: a discrimination task followed by an identification task. The discrimination task was based on an XAB paradigm where participants had to discriminate between pairs of images that lay within the morphed continuum between two objects. These pairs of images were separated by equal increments along the shape continuum between two objects. At the beginning of the identification task participants were first presented with two shapes of objects and asked to memorize them. They were then shown single-image presentations of object shapes and were asked to decide which of two memorized objects each shape was more like. In the second part of the experiment, the discrimination (XAB) task assessed observers' ability to discriminate between object images that lay along a shape continuum and the identification task determined how observers classify these same object images.

2.1. Method

2.1.1. Participants

Forty-five undergraduate students from the Eberhard-Karls University of Tübingen, Germany participated in the following experiment for pay. Twenty-four of the participants were female. The participants' ages ranged from 18 to 28 years old. All participants had normal or corrected-to-normal vision.

2.1.2. Stimuli and materials

The stimuli consisted of 11 morphed images from each of 15 pairs of objects. The objects were two different exemplars from five different basic-level categories. The categories, including the two exemplars, were as follows: Bottle (Wine Bottle, Coke Bottle); Lamp (Bedside Lamp and Desk Lamp); Glass (Wine Glass and Beer Glass); Vase (Urn and Single-stem Vase); and Bell (Church Bell and Hand Bell). These objects were paired as five pairs of within-class objects and ten pairs of between-class objects. The between-class pairings constituted all combinations of category objects using one exemplar object from each class (e.g. Wine Bottle and Hand Bell).

The stimuli were generated using SoftImage|3D 3.7 software on a Silicon Graphics, Indigo 2 workstation. This software package allows modelling and rendering of 3D objects. The ten basic object shapes were designed in the following manner: the objects were drawn as solids of revolution by defining the occluding contour of each object and rotating this contour around the object's axis of elongation. All objects were designed with approximately the same aspect ratio of 2:1:1, with respect to the length of the elongated axis, the width and the depth of the object. The main elongated axis was the same length for all objects. The occluding contour was specified by a number of co-ordinates. All objects were created from the same basic number of co-ordinate points but the position (i.e. radial distance from the elongated axis and the position along the axis of elongation) of these co-ordinates was different for each object shape. The objects were designed using the same number of co-ordinates in order to allow for correspondence between the objects during shape interpolation. The interpolation routine was a SoftImage|3D, morphing algorithm applied to a pre-specified pair of 3D object shapes. This algorithm measures the distance between each of the corresponding co-ordinates on the objects and simulates an animation procedure by gradually moving each co-ordinate in the first object to the position of the corresponding co-ordinates in the second object along a linear trajectory. The number of steps taken to transform the shape of object 1 into the shape of object 2 was pre-specified. We specified 11 steps, therefore, 11 images were taken as output from the morphing procedure for each object pair. These 11 images were evenly spaced samples of the morphing routine from object 1 to object 2 along the shape continuum. See Fig. 1 for an illustration of the morphing routine.

In any study of CP it is important to ensure that the morphing procedure produces a linear continuum of shape changes for the purposes of observing the effects of CP. Although linearity is easily assumed in the perception of low level features such as colour or orientation (i.e. by measuring the wavelength of the colour or the angle of orientation, respectively), it is more difficult to assume in complex, multi-dimensional stimuli such as faces or objects. Given these issues, we took measures to avoid any non-linearities in the shape continuum which may affect the results. First, the stimuli were carefully chosen to avoid unpredictable, nonsense shapes that would result from morphing (e.g. between a face and a car). Second, the morphing sequence itself was a straightforward, simple interpolation between corresponding points and any crossings of the trajectories between the points were avoided. Finally, and most importantly, the linearity of the morphing sequence stems from the point-wise contour interpolation method we used to generate the intermediate shapes. Indeed, that method is precisely equivalent to a constant-increments linear interpolation in the 16-dimensional space formed by the x,y co-ordinates of each of the eight control points common to all the objects.[1] Even with these precautionary

[1] The authors would like to thank Shimon Edelman for this comment.

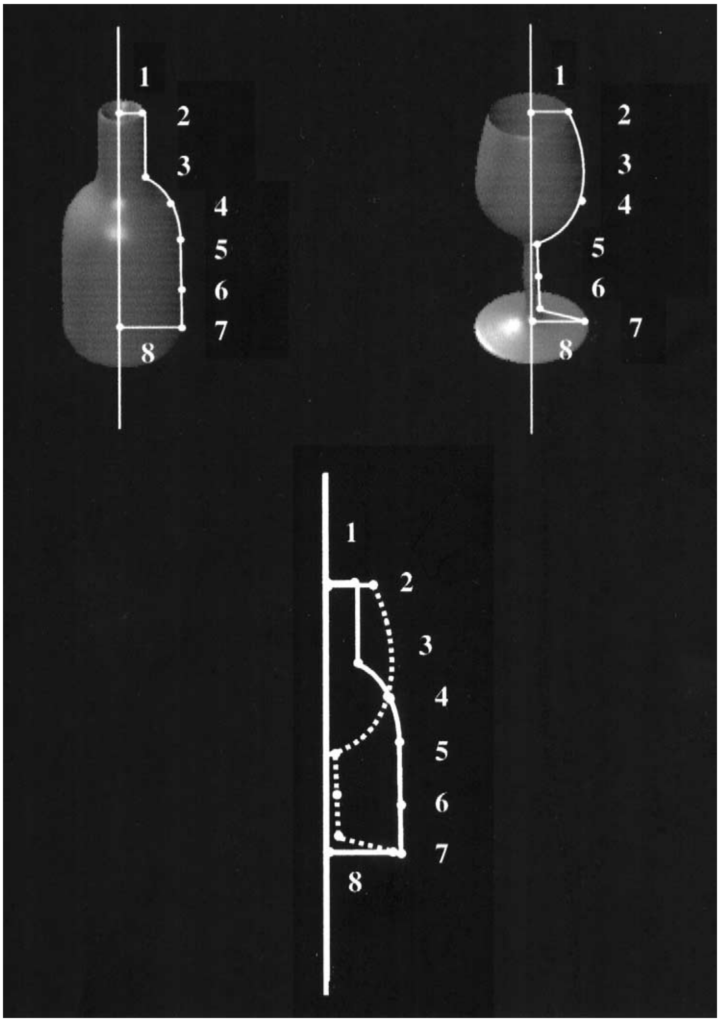

Fig. 1. A schematic illustration of the nature of the morphing routine used to create the image morphs between two original objects. An object was drawn by rotating a contour around the main axis of elongation. In the figure above, the contours of a Bottle and a Glass are shown superimposed on the object shapes. The morphing procedure can be imagined as follows: the contour of the Glass is redrawn from the contour of the Bottle by hand. Then, the distance between each of the corresponding co-ordinates between the objects is calculated. In our illustration the corresponding co-ordinates are marked by a number. Once the distance is calculated the position of each co-ordinate on the Bottle is moved, linearly, to the position of the corresponding co-ordinate of the Glass. The number of steps taken between the original positions of the two co-ordinates is pre-specified. A new 3D object shape is generated at each step (see Fig. 2).

steps, it is important to point out that it is probably an impossible task to provide a single, unequivocal measure of linearity between complex shapes, especially one which lies along a dimension we can say with certainty is the most perceptually salient. In our paper, however, we have attempted to provide evidence to show that when CP is found it is not due to non-uniformity in the images due to the morphing procedure.

The objects were rendered under a perspective projection from their 3D models using the Silicon Graphics Indigo 2 workstation with the SoftImage software. A shaded, 256 grey levels image was rendered using a Lambertian shading model by assuming a point light source at infinity, 45° up and 15° left from the line of sight and another light source (with the same intensity) at the viewpoint. The objects were presented in a canonical view[2] against a black background. All images of the objects were 256 by 256 pixels in size. See Fig. 2 for an illustration of the images from each of the object continua used in Experiment 1.

The object images were transferred to a Macintosh Quadra computer and the stimuli were presented on a 256 colour, 16-inch Macintosh monitor. The object images subtended, on average, a vertical visual angle of 5° and a horizontal visual angle of 3°. The experiment was run using the PsyScope 1.04 presentation package for the Macintosh. Participants used a button box for responding.

2.1.3. Design

The experiment was divided into two separate tasks: an XAB discrimination task and an identification task. Participants were divided into five groups of nine. Each group was tested on three pairs of objects, from the set of 15 pairs, in both tasks. Two of these pairs were of objects from across different classes (e.g. Lamp to Bottle) and one was a within-class object pair (e.g. Bedside Lamp to Desk Lamp). All participants assigned to a group saw the same three object pairings in both the discrimination and identification tasks. The images from each object pair were blocked in both tasks and the order of presentation of the object pairs was counter-balanced across the participants in each group. The order of the trials within each block was randomized across participants.

The discrimination task was based on an XAB design in which an image of the first object (stimulus X) was presented initially in a trial followed by the second and third images of objects (stimuli A and B) presented simultaneously, left and right of fixation. Stimuli A and B were always physically different from each other and stimulus X was identical to either stimulus A or B. Stimuli A and B differed by two steps (e.g. images 1 and 3) along the object pair shape continuum. The order of the stimuli was counter-balanced which resulted in four orderings of any two stimuli (AAB, ABA, BAB and BBA). In the identification task participants were presented with single images of the object pairs from along the shape continuum.

There were ($3 \times 9 \times 4$) 108 experimental trials in the discrimination task (object pairs, shape pairs and XAB counter-balancing) and (3×11) 33 experimental trials in the identification task (object pairs and morphed images).

2.1.4. Procedure

Participants were seated 57 cm away from the computer monitor. Each participant was required to perform first the discrimination task followed by the identification task with a

[2] The term canonical view refers to the best and most familiar view of the object. See Palmer, Rosch, and Chase (1981) and Blanz, Tarr, Bülthoff, and Vetter (1998) for a further description.

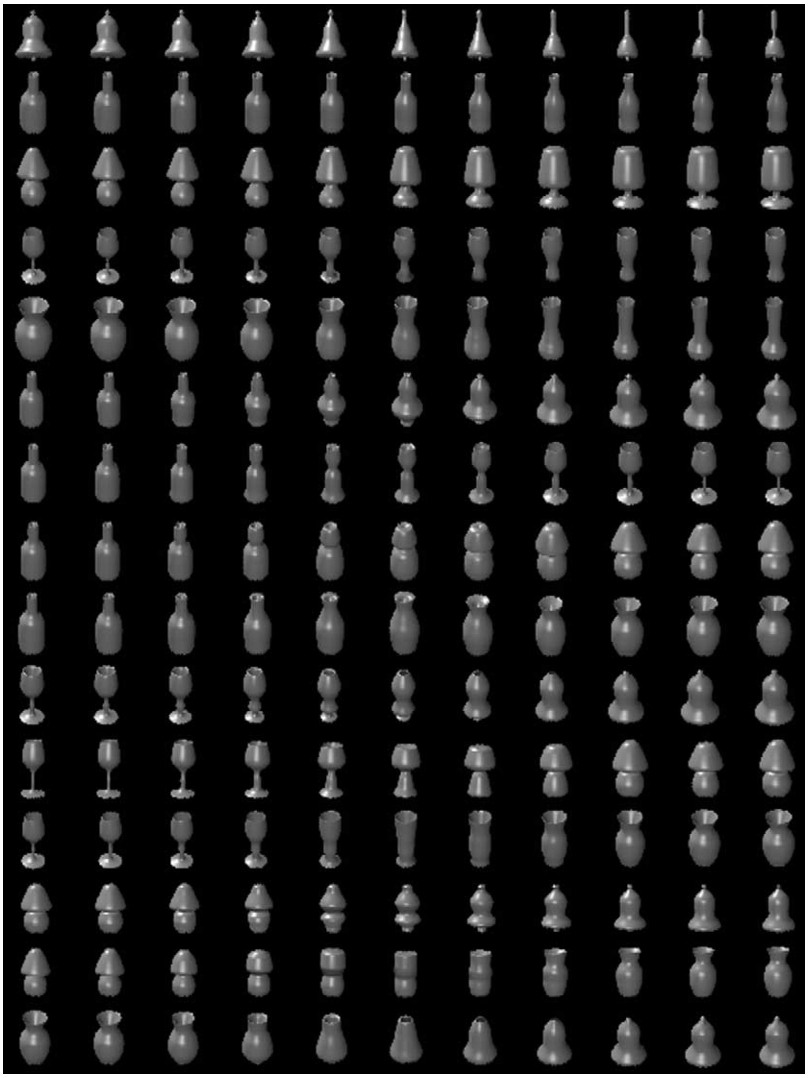

Fig. 2. An illustration of all of the shape continua used in Experiment 1. All of the objects were rendered in the canonical view with a fixed light source. The object morphs are listed in rows in the following (top to bottom) order: Church–Hand Bell, Wine–Coke Bottle, Bedside–Desk Lamp, Wine–Beer Glass, Urn–Single-stem Vase, Bottle–Bell, Bottle–Glass, Bottle–Lamp, Bottle–Vase, Glass–Bell, Glass–Lamp, Glass–Vase, Lamp–Bell, Lamp–Vase, Vase–Bell.

self-timed break between the two tasks. The identification task determined the subjective category boundary for each object pair, hence it was conducted after the discrimination task in order to avoid any biasing during the discrimination task.

A fixation cross preceded the object stimuli in all tasks for 250 ms. In the discrimination task, there were three object stimuli shown in any one trial. The first object image (X) was shown for 100 ms in the centre of the screen, followed by a mask for 1 s. The next pair of stimuli (A and B) remained on the screen until the participant made a response. Each of the A and B stimuli were displayed 3 cm to the left and right of the centre point of the screen. An inter-trial interval of 500 ms followed the participant's response. In order to acquaint participants with the XAB procedure in the discrimination task, the experiment began with a random selection of 20 practice trials. There were three blocks to the discrimination task and participants received a self-timed break between blocks.

In the identification task each trial began with a 250 ms fixation cross. An object image then appeared and remained on the screen until the participant responded. An inter-trial interval of 500 ms followed each participant's response. In the identification task the images from each object pair were presented in different blocks with a self-timed break between blocks. At the beginning of each block participants saw two shapes of objects (which corresponded to the object shapes at the extreme end of each object pair continuum). The participants were instructed that each shape was associated with either the left or right button on the button box. (For example, the Coke Bottle shape belonged to the left button and the Wine Bottle shape to the right button.) Participants were then instructed to decide as fast and as accurately as possible which of two object shapes each of the presented images looked more like. This procedure was repeated for each object pair. For each participant, the object images in the identification task were always the same as those shown in the discrimination task. Participants took approximately 1 h to complete the experiment.

2.2. Results

The mean number of correct responses made to the identification tasks and the XAB tasks are shown in Fig. 3. The subjective category boundary was determined by the identification performance. We determined the category boundary as the point at which the identification function crosses the 50% correct response level. We then conducted a two-way, mixed design ANOVA using category position and object pairs as factors. The category position factor refers to the discrimination performance to pairs of images that lay at either end of the shape continua (e.g. the average performance to image pairs 1–3 and 9–11) and the discrimination performance at image pairs that straddle the category boundary. A main effect of category position was found ($F(1, 120) = 252.8$, $P < 0.001$). An effect of object pairs was also found ($F(14, 120) = 3.912$, $P < 0.001$). There was no interaction between the factors. Post-hoc, paired *t*-tests revealed that the effect of category position was significant for all object pairs at the $P < 0.05$ level of significance. The position of the category boundary and the *t*-test results are shown for each object pair in Table 1.

Finding a significant difference between the number of correct responses made to the images on the end of each object pair continuum and those that straddle the category boundary is not, in itself, sufficient evidence that the object pairs are categorically perceived. For example, the discrimination may not just be best at the point of the subjective category boundary but may be equally good for other image pairs along the continuum (see objects Lamp–Bell in Fig. 3 for an illustration of this point). In a second test for CP, the discrimination performance of the participants can be predicted from the identification data. The method of deriving the predicted performance from the identification perfor-

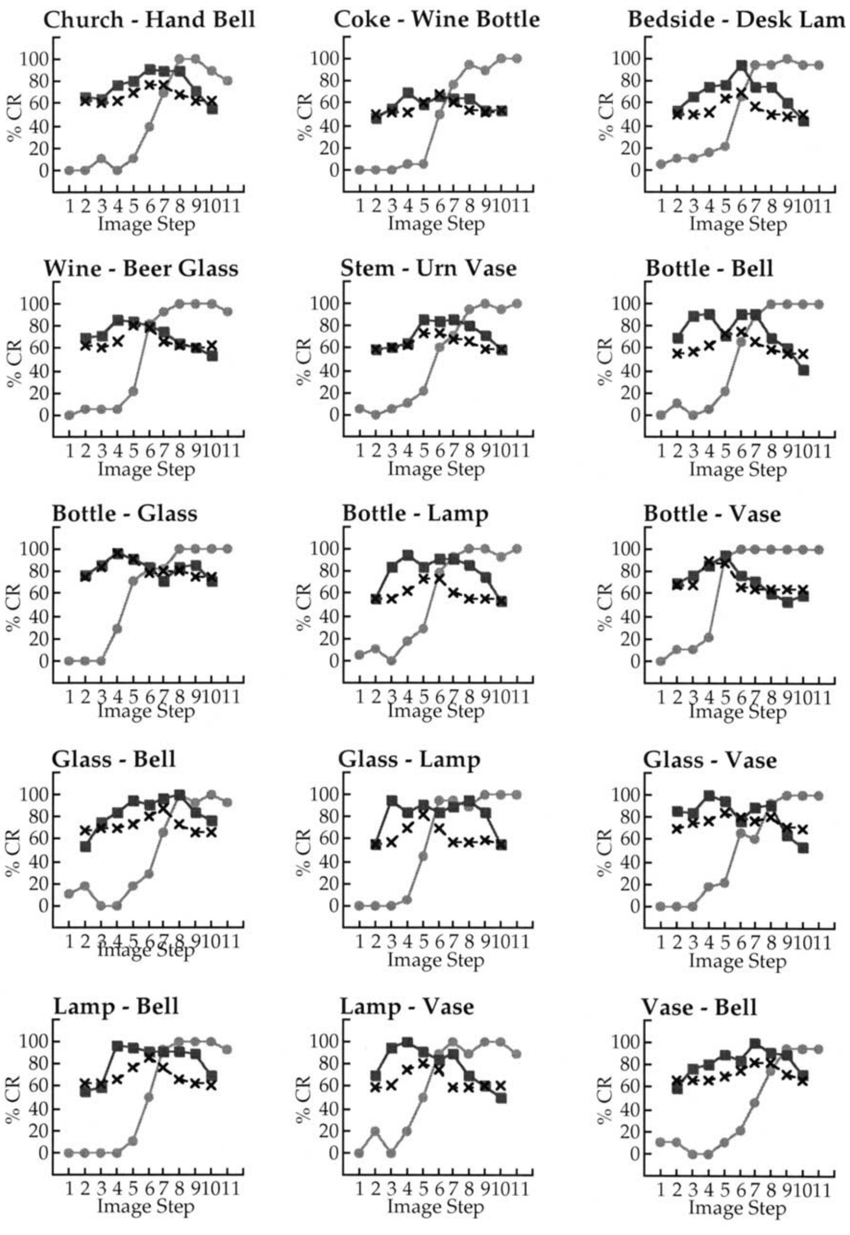

Fig. 3. Plots showing identification and discrimination data for each of the 15 object pairs shown in Experiment 1. An explanation of the functions in each plot is as follows: ●, the identification data show the mean percentage with which the first object image of the morph pair was correctly identified (e.g. Church Bell, Coke Bottle, Bedside Lamp, etc.); ■, the discrimination data show the mean percent correct (%CR) at discriminating the two object images at either side of each data point; ×, the predicted discrimination data for each object pair. See Appendix A for a description of how the predicted curve is derived.

Table 1
Results of the one-way ANOVAs and correlations to each of the object pairs used in Experiment 1(a)[a]

Class	Object pairs	ANOVA		Correlation (r)
		Boundary	t-tests ($t(8)$)	
Within	Church Bell–Hand Bell	6–8	5.149**	0.817**
Within	Coke Bottle–Wine Bottle	5–7	2.529*	0.770*
Within	Bedside Lamp–Desk Lamp	5–7	7.333**	0.766*
Within	Wine Glass–Beer Glass	5–7	3.795**	0.739*
Within	Single-stem Vase–Urn	5–7	3.207*	0.858**
Between	Bottle–Bell	5–7	2.138	0.501
Between	Bottle–Glass	4–6	4.000**	0.791*
Between	Bottle–Lamp	5–7	5.292**	0.533
Between	Bottle–Vase	4–6	7.234**	0.802**
Between	Glass–Bell	6–8	6.782**	0.575
Between	Glass–Lamp	4–6	6.353**	0.358
Between	Glass–Vase	4–6	1.154	0.601
Between	Lamp–Bell	5–7	3.395**	0.560
Between	Lamp–Vase	4–6	5.079**	0.540
Between	Vase–Bell	6–8	5.976**	0.765*

[a] Objects pairs from the same class (Within) and object pairs from different classes (Between) are indicated in the first column (Class). The names of the object pairs are presented under Object pairs. The paired t-test results per object pair are the results of comparing the mean number of correct responses made to the object images at the extreme ends of each shape continuum to the number of correct responses made to the image pairs that straddle the category boundary. The image numbers which straddle the category boundary are indicated for each object pair (boundary) and can also be seen in Fig. 3. This table also shows the correlation between the observed discrimination performance and predicted discrimination performance for each object pair (Correlation). $*P < 0.05$, $**P < 0.01$.

mance is widely used in the CP literature (Calder et al., 1996; Liberman, Harris, Hoffman, & Griffith, 1957). The performance predicts the likely outcome in the discrimination task provided the objects were categorically perceived. This predicted performance can then be correlated with participants' actual observed performance on the discrimination task. If the two are correlated for an object pair then we can say that those objects were perceived categorically.

For each object pair, participants' predicted performance for the discrimination task was derived from the formula outlined in Appendix A (see Calder et al., 1996). The predicted performance and the observed performance are shown for each object pair in Fig. 3. These predicted data were then correlated with the observed discrimination data. The results of these correlations are shown in Table 1. The results indicate that some, but not all, of the object pairs showed significant correlations between the predicted and observed discrimination performances. A significant correlation was taken as evidence for CP of the object pair. The object pairs that showed correlations between the observed and predicted functions included the following: Bells, Bottles, Lamps, Glasses, Vases, Bottle–Glass, Bottle–Vase and Vase–Bell. There was no correlation found between the following pairs of objects: Bottle–Bell, Bottle–Lamp, Glass–Bell, Glass–Lamp, Glass–Vase, Lamp–Bell and Lamp–Vase.

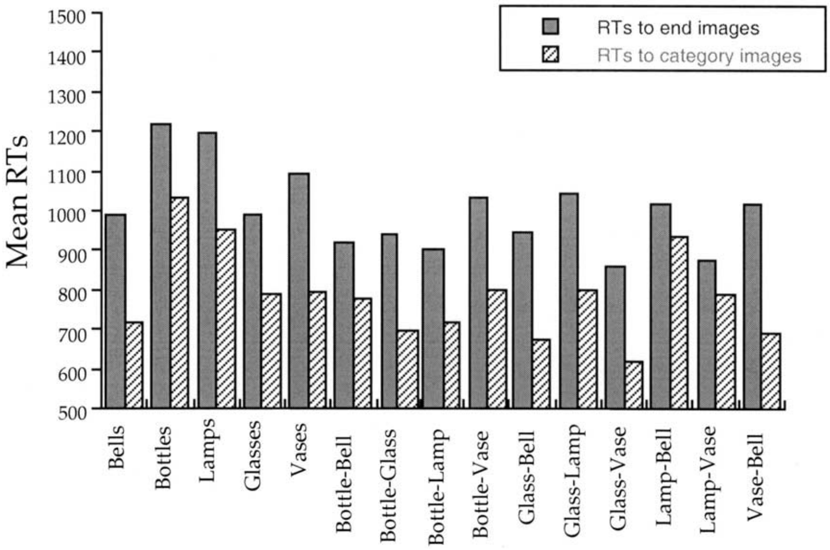

Fig. 4. Plot showing the mean RT taken to discriminate images at the end of each object continuum and images that straddled each category boundary, for all of the object pairs in Experiment 1. For all objects, the mean discrimination time to images at the ends of the continua (within-category images) were slower than the discrimination times to images on either side of the category boundary (across-category images).

2.2.1. Reaction times

The mean reaction times (RTs) to image pairs which lay on the ends of the continua and those image pairs which straddled the category boundary are plotted in Fig. 4. For all the objects, the mean RT to discriminate image pairs at the end of the continua was slower than the RT taken to discriminate image pairs which straddled the category boundary. A two-factor mixed design ANOVA was conducted on the participants' RTs with category position (image pairs at the end points and straddling the category boundary) as the within-subjects factor and object pair (15 object pairs) as the between-subjects factor. A significant effect of category position was found ($F(1, 119) = 99.220$, $P < 0.01$). A significant effect of object was also found ($F(14, 119) = 3.202$, $P < 0.01$). Post-hoc Newman–Keuls analysis revealed that RTs to the Bottles were significantly slower than RTs to all objects except the Lamps, Vases, Lamp–Bell and Vase–Bell ($P < 0.05$) and RTs to the Lamps were slower than to the Glass–Vase ($P < 0.01$). There was no interaction between the factors ($F(14, 119) < 1$).

2.3. Discussion

We found evidence that familiar objects can be perceived categorically. However, not all of our object pairings were categorically perceived by the participants. First, all of the object pairs that belonged within the same semantic categories were perceived as categorical. Second, three out of ten of the between-class object pairs were perceived as categorical.

We originally argued that CP may only arise to stimuli that are continuous in the real world. For example, the entire spectrum of colour in a rainbow is experienced as distinct colour bands. Similarly, changes in facial expression can be witnessed in any dynamic face. Moreover, it might even be plausible to consider that facial identity may be continuous, e.g. within families, etc. Consequently we hypothesized that only images from object pairs that are possibly found in the real world would be perceived as categorical. In fact our results did not conform to this idea. Some object pairs from different classes were also perceived as categorical, therefore, same basic-level class membership was not a necessary condition for CP.

3. Experiment 1(b)

In the following experiment participants were presented with a subset of the object pairs seen in Experiment 1. These object pairs included the pairs of objects where little or no evidence for CP was found in Experiment 1(a). One of the possible reasons for this could be because the discrimination task was not equivalent across all object pairs. The task, therefore, may have been sufficiently easy for some object pairs to effectively obscure any effects of CP which may be present.

The mean discrimination performance for the nine object pairs that were perceived categorically was 74.2% as opposed to a mean discrimination performance of 80.1% for the object pairs that were not perceived categorically. The difference between these discrimination performances almost reached significance (unpaired, two-tailed t-test, $t(13) = -1.728$, $P < 0.10$). Although an error rate of approximately 20% is not generally considered ceiling performance we felt it was necessary to attempt to rule out such possible effects. The plot of the Glass–Lamp pair of objects in Fig. 3 illustrates the point: although discrimination of pairs of images that lay at either extreme end of the continuum was low (mean 57%) the discrimination of pairs of images that lay between the extreme points was much better. In fact, the discrimination function is almost a straight line between the end pairs of images. We reasoned that an increase in the difficulty of the discrimination task may allow for effects of CP to emerge because for some object pairs the discrimination task was not sensitive enough to show any effects of CP.

The object pairs included in the following experiment were, therefore: Bottle–Bell, Bottle–Lamp, Glass–Bell, Glass–Lamp, Lamp–Bell and Lamp–Vase. As already argued, one of the reasons why CP might not have been observed for such object pairs was because the step size between the images along the shape continuum was sufficiently large to allow for easy discrimination. This possibility needed to be investigated. In the following experiment we decreased the step size between the images to one in the discrimination task (in Experiment 1(a) participants had to discriminate between images that lay two steps away on the shape continuum). See Fig. 2 for an example of the stimuli used. We predicted that increasing the difficulty of the discrimination task would promote CP.

3.1. Method

3.1.1. Participants

Sixteen students from the Eberhard-Karls University of Tübingen participated in the following experiment for pay. Eleven of the participants were female. The participants' ages ranged from 21 to 30 years old. All participants had normal or corrected-to-normal vision.

3.1.2. Design and procedure

The discrimination task in this experiment was rendered more difficult than in Experiment 1 by using pairs of images that were closer together along the morph sequence (e.g. participants discriminated between images 1–2 rather than 1–3 as in Experiment 1(a)). In all other ways the experiment was similar to that in Experiment 1(a). As in Experiment 1 there were two parts to the following experiment: the discrimination task followed by the identification task. The discrimination task was based on a two-way, mixed design with object pairs and image step as factors. Each participant was tested on three of the six object pairs. The three object pairs were randomly chosen for each participant. Images of the object pairs were blocked in each task. The order of the object pairs was counter-balanced and the order of the trials in each block was randomized across participants. In all other aspects the general procedure was the same as that outlined in Experiment 1. The experiment took approximately 1 h for each participant to complete.

3.2. Results

The mean number of correct responses to the discrimination task for the object pairs seen in this experiment was decreased from 80.1% in Experiment 1 to 66.9% in the present experiment. This decrease was significant (unpaired t-test, $t(10) = 5.894$, $P < 0.001$). We also found that the overall discrimination performance to the six object pairs in this experiment was not significantly different to the overall performance shown to the nine object pairs which yielded effects of CP in Experiment 1 (unpaired t-test, $t(13) = 2.038$, n.s.). We were, therefore, assured that we had achieved the same level of difficulty in the discrimination task in this experiment as in Experiment 1(a).

As in Experiment 1(a), the subjective category boundary was determined by the identification performance (i.e. the point at which the identification function crosses the 50% correct response level). We then conducted a two-way, mixed design ANOVA between the average discrimination performance to the image pairs at the extreme ends of each shape continua and the performance to images straddling the category boundary. A main effect of category position was found ($F(1,42) = 51.161$, $P < 0.001$). An effect of object pairs was also found ($F(5,42) = 2.67$, $P < 0.05$). There was no interaction between the factors.

We again employed the formula used in Experiment 1(a) (see Appendix A) to predict the observers' performance on the discrimination task from their performance on the identification task for each object pair. For each object pair the predicted performance was then correlated with the participants' observed performance. We found that two of the six object pairs showed significant correlations between the observed and predicted data. These object pairs were Lamp–Bell and Lamp–Vase ($r = 0.632$ and $r = 0.895$, respectively). There was no significant correlation between the predicted and observed functions for the following object pairs: Bottle–Bell, Bottle–Lamp, Glass–Bell and Lamp–Glass.

3.2.1. RTs

A two-way, mixed design ANOVA was conducted on the participants' RTs with category position (image pairs at the end point of the images and those straddling the category boundary) and object pairs (six pairs) as factors. An effect of category position was found ($F(1,42) = 5.349$, $P < 0.05$). There was no effect of object ($F(5,42) < 1$) and no interaction between the factors.

3.3. Discussion

Although the difficulty of the discrimination task was increased in Experiment 1(b) we did not achieve perceptual categorization for all object pairs. Here we found that only two of the six object pairs were perceived categorically: Lamp–Bell and Lamp–Vase. The other object pairs (Bottle–Bell, Bottle–Lamp, Glass–Bell and Glass–Lamp) were not found to be perceived categorically with an increase in difficulty in the discrimination task. It is noted that for these particular object pairs the overall discrimination performance was slightly lower than the performance to these same pairs in Experiment 1(a) which indicates that the lack of CP found is not due to ceiling effects. However, the question remains as to why some object pairs were not found to be categorically perceived.

In the following experiments we explore possible reasons why we found that some object pairs were perceived categorically whereas others were not. One possibility why CP effects emerged for some object pairs may be due to image artefacts which enhanced discrimination performance along some positions in the continuum but not others (see Fig. 2 for an illustration of all object continua). Some object continua showed an increase in object parts near the mid-point. Take, for example, the Bottle–Bell continuum in Fig. 2: here we can see an increase in the number of parts from three (the Bottle) to five at the mid-point.[3] In order to avoid possible artefact effects participants in Experiment 2 were tested across different viewpoints of the objects. Finally, in Experiment 3 we investigated whether CP was related to the visual similarity between the objects.

4. Experiment 2

In the following experiment we repeated Experiment 1 but across different viewpoints of the images of the objects. The effects of CP found for some object pairs in Experiment 1 may possibly be a result of an artefact in the images due to the morphing procedure itself, or due to incidental image characteristics such as the effect of lighting on the object surface. Such artefacts could lead to perceived non-linearities in the object continua which would make some image pairs more easily discriminable than other image pairs. We decided to test for this possibility in this experiment by using images of the same objects rendered from a different viewpoint. We chose a new viewpoint which was not simply a rotation in the image plane, but a view where the information about the object was changed. With the new viewpoint, for example, one could no longer see into the wine Glass but could see the bottom of the Glass which was not available in the canonical view.

[3] We note that those object continua with an increased number of parts at the mid-point were not generally perceived as categorical in Experiment 1, suggesting that part number is not solely used for discrimination.

Furthermore, the images were rendered in the new viewpoint whilst the position of the main source of light remained fixed, thus effectively changing the pattern of lighting and shading on the surface of the objects. Our reasoning for changing the viewpoint of the object images was as follows: it might be argued that perceptual discrimination performance may be based solely on image information such as local feature or illumination differences. Discriminating between objects across changes in viewpoint, however, relies on decisions that are based on object characteristics, and not on low-level image-based characteristics. Therefore, if the CP effects found in Experiment 1 were due to local image differences then effects of CP should disappear with a change in viewpoint since image information is disrupted with both changes in viewpoint (Newell & Findlay, 1997) and image illumination (Tarr et al., 1998). If, on the other hand, CP effects found in Experiment 1 were due to the object categories themselves, then these effects should generalize across changes in viewpoint. If objects are perceived as belonging to different categories then the category boundary should separate all instances of the objects' images, including differences in size, orientation, viewpoint and illumination.

The following experiment, therefore, was an attempt to control for possible image artefacts causing effects of CP in Experiment 1. We predicted that if effects of CP were based on the objects themselves, then these effects should generalize across viewpoint. In the discrimination task, participants had to discriminate between different images from an object continuum that were shown from different views.

4.1. Method

4.1.1. Participants

Twenty-four students from the Eberhard-Karls University of Tübingen and from Trinity College Dublin participated in the following experiment for pay. Eleven of the participants were female. The participants' ages ranged from 18 to 26 years old. All participants had normal or corrected-to-normal vision.

4.1.2. Stimuli and materials

The objects used were the same as those used in Experiment 1. However, for the purposes of this experiment new viewpoints of the objects were rendered using the Soft-Image rendering software. The object continua were first created as described in Experiment 1. This ensured that the same shapes were used in both experiments. The images from the continua were created in a more foreshortened viewpoint than the canonical view used in Experiment 1. We refer to this new viewpoint as 'View 2'. We chose View 2 because it has a maximum image difference from the canonical view, but without any part occlusion or accretion. Therefore, all parts of the objects were visible from View 2, but the overall image information was different. Finally, the images were rendered using the same light source intensity and position relative to the environment, therefore, different patterns of lighting and shading emerged along the surface of the objects. Fig. 5 gives an illustration of object images from two different object pairs, projected from View 2.

4.1.3. Design

The experiment was conducted on a within-subjects design with object pair (Bottles,

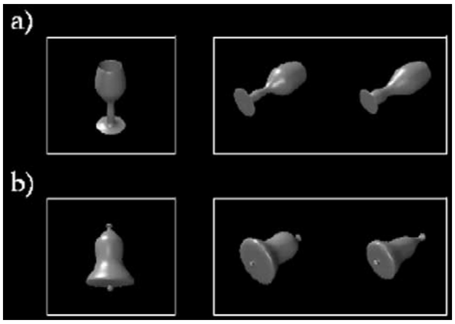

Fig. 5. Illustration of object images used in two randomly chosen XAB trials in Experiment 2. Here the images of objects were rendered from two different viewpoints: the canonical viewpoint (images on the left) and a more foreshortened viewpoint, View 2 (images shown on the right). The light source remained in the same position with respect to the environment across all views of the objects. In this illustration an example of a trial with (a) Glasses and (b) Bells is shown. The object on the left is the initial stimulus shown in a trial (stimulus X), and the objects shown on the right are examples of the two stimuli images to be matched to the first stimulus (stimuli A and B).

Bells, Glasses, Lamps, Vases, Bottle–Bell, Bottle–Glass, Bottle–Lamp, Bottle–Vase, Glass–Bell, Glass–Lamp, Glass–Vase, Lamp–Bell, Lamp–Vase and Vase–Bell) and image continua (11 images) as factors. All participants performed two tasks, an XAB discrimination task followed by an identification task. The images from each object pair were blocked in both tasks and the order of presentation of the object pairs was counter-balanced across participants. The trials were randomly presented within each block.

The XAB task was based on four combinations of the order of the stimuli per trial: AAB, ABA, BAB and BBA. In this experiment, the trial structure was counter-balanced across participants such that any participant was presented with either the AAB, ABA version or the BAB, BBA version. See Experiment 1 for further details of the XAB and identification tasks.

There were $(15 \times 9 \times 2)$ 270 experimental trials in the discrimination task (object pairs, shape pairs and XAB counter-balancing) and $(15 \times 11 \times 2)$ 330 experimental trials in the identification task (object pairs, morphed images, repeated twice).

4.1.4. Procedure

Participants were seated 57 cm away from the computer monitor. Each participant was required to perform first the discrimination task followed by the identification task with a self-timed break between the two tasks. The object pairs were blocked during both tasks and participants could take a self-timed break between blocks as required. The procedural details followed those described in Experiment 1 with the exception that the participants were informed that the discrimination task involved discriminating between objects across different viewpoints. Therefore, the XAB task involved discriminating images which were separated by two morph steps in the continuum. The first stimulus shown in an XAB trial was always shown from the canonical view, and the following two stimuli were shown from View 2 (see Fig. 5 for an example of the stimuli shown in a trial). Participants took approximately 1 h 30 mins to complete the experiment.

4.2. Results

The mean number of correct responses made to the identification tasks and the XAB tasks are shown in Fig. 6.

The subjective category boundary was determined by the identification performance. As in Experiment 1, we calculated the category boundary as the point at which the identification function crosses the 50% correct response level. We then conducted a two-way, within subjects ANOVA using object pairs and category position as factors. The category position factor was the average discrimination performance between the image pairs at the extreme ends of each shape continua and the performance to images straddling the category boundary. A main effect of category position was found ($F1(1,23) = 296.04$, $P < 0.001$; $F2(1,14) = 425.35$, $P < 0.001$). An effect of object pairs was found ($F(14,322) = 3.582$, $P < 0.001$). There was no interaction between the factors ($F(14,322) = 0.6608$, n.s.). Post-hoc Newman–Keuls analysis on the object effect revealed that the average discrimination performance to the Glass–Vase pair was significantly lower than to the Bottle and the Glass pairs ($P < 0.05$). For all object pairs, discrimination performance was better for the images straddling the category boundary than images at the end point of the continuum. The position of the category boundary and the results of post-hoc *t*-tests are shown for each object pair in Table 2.

Again we used the formula described in Experiment 1 (see Appendix A) to derive the observers' predicted performance based on their categorical decisions. The plots showing both the predicted and the observed performance for each object pair are shown in Fig. 6. For each object pair the predicted performance was correlated with the participants' observed performance. The results of these correlations are shown in Table 2. We found that eight of the 15 object pairs showed significant correlations between the observed and predicted data on the discrimination task.

We used the coincidental presence of both a significant *t*-test value and a significant correlation between the observed and predicted data as evidence for CP in an object pair. Thus, here we found evidence for CP in the following object pairs: Church–Hand Bell, Coke–Wine Bottle, Bedside–Desk Lamp, Wine–Beer Glass,[4] Stem–Urn Vase, Bottle–Bell, Bottle–Vase and Vase–Bell. There was no evidence for CP in the following object pairs: Bottle–Glass, Bottle–Lamp, Glass–Bell, Glass–Lamp, Glass–Vase, Lamp–Bell and Lamp–Vase.

Since the same object pairs were used with the same level of discrimination, the results from the object pairs shown from the canonical viewpoint in Experiment 1(a) and the results from the same objects shown here from a non-canonical viewpoint (i.e. View 2) can be compared. At first glance, we noted that CP was found for seven of the object pairs from both the canonical viewpoint and View 2 tested here: Bells, Bottles, Glasses, Lamps, Vases, Bottle–Vase and Vase–Bell. We also noted that two object pairs showed CP from one viewpoint but not the other: CP was evident for the Bottle–Glass pair from

[4] It is interesting to note that CP effects were found for this object pair for both Irish and German participants, given that the Beer Glass is highly familiar to the German participants (known as a Weizenbier glass) but unfamiliar to the Irish participants.

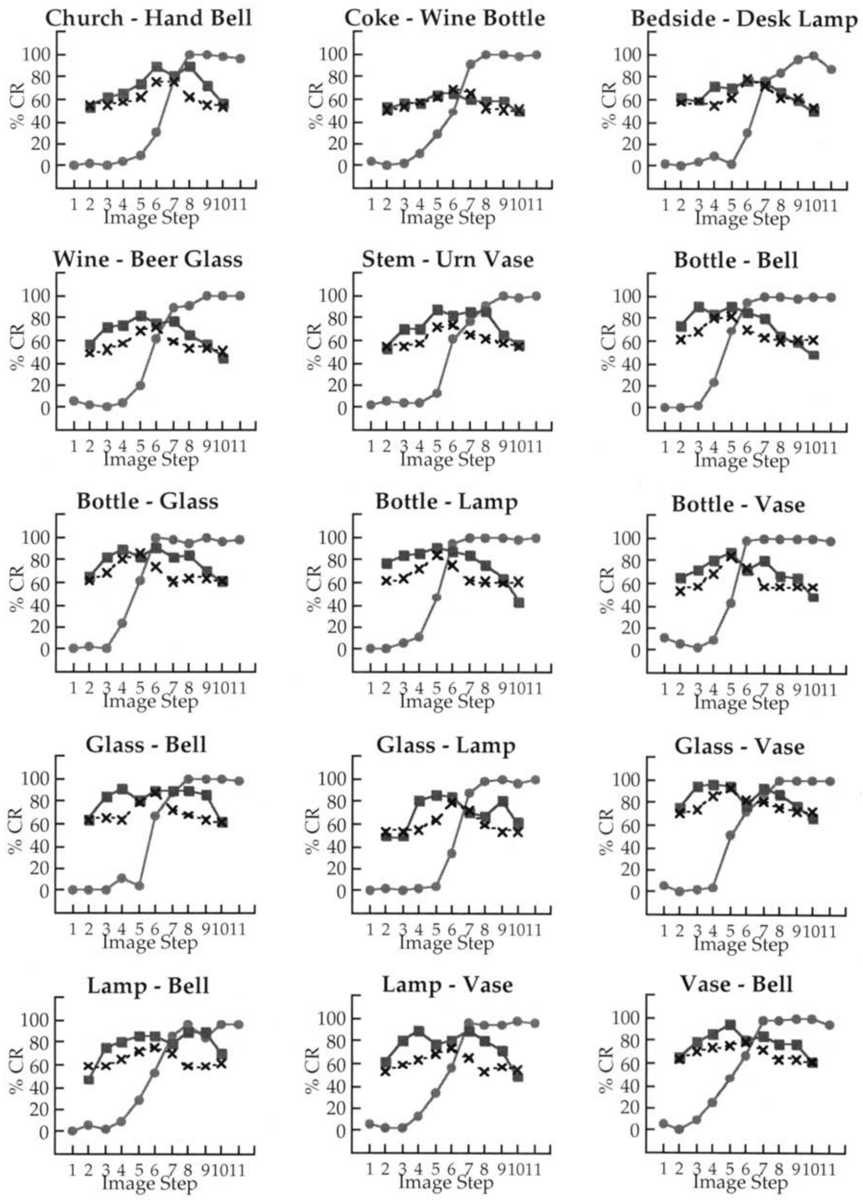

Fig. 6. Plots showing identification and discrimination data for each of the 15 object pairs shown in Experiment 2. An explanation of the functions in each plot is as follows: ●, the identification data show the mean percentage with which the second object image of the morph pair was correctly identified (e.g. Church Bell, Coke Bottle, Bedside Lamp, etc.); ■, the discrimination data show the mean percent correct (%CR) at discriminating the two object images at either side of each data point; ×, the predicted discrimination data for each object pair (see Appendix A for formula).

Table 2
Results of the paired *t*-tests and correlations to each of the object pairs used in Experiment 2[a]

Class	Object pairs	ANOVA		Correlation (*r*)
		Boundary	*F*-ratio (*t*(23))	
Within	Church Bell–Hand Bell	5–7	5.495**	0.755*
Within	Coke Bottle–Wine Bottle	5–7	2.398*	0.759*
Within	Bedside Lamp–Desk Lamp	6–8	3.286**	0.723*
Within	Wine Glass–Beer Glass	5–7	3.930**	0.709*
Within	Single-stem Vase–Urn	5–7	4.851**	0.769*
Between	Bottle–Bell	4–6	4.956**	0.676*
Between	Bottle–Glass	4–6	3.022**	0.570
Between	Bottle–Lamp	4–6	3.961**	0.621
Between	Bottle–Vase	4–6	5.752**	0.670*
Between	Glass–Bell	5–7	3.978**	0.414
Between	Glass–Lamp	5–7	5.902**	0.471
Between	Glass–Vase	5–7	8.421**	0.611
Between	Lamp–Bell	5–7	4.155**	0.305
Between	Lamp–Vase	5–7	3.652**	0.543
Between	Vase–Bell	5–7	6.235**	0.752*

[a] The *t*-test result per object pair is the result of comparing the mean number of correct responses made to the object images at the extreme ends of each shape continuum to the number of correct responses made to the image pairs that straddle the category boundary. The category boundary is indicated for each object pair and can also be seen in Fig. 6. This table also shows the correlation between the observed discrimination performance and predicted discrimination performance for each object pair. *$P < 0.05$, **$P < 0.01$.

the canonical viewpoint but not from View 2, and CP was found for the Bottle–Bell pair from View 2 only.

4.2.1. RTs

The mean RTs to image pairs which lay on the ends of the continua and those image pairs which straddled the category boundary are plotted in Fig. 7. For all the objects, the mean RT to discriminate image pairs at the end of the continua was slower than the mean RT taken to discriminate image pairs which straddled the category boundary. A two-way, within subject ANOVA was conducted on the participants' RTs with category position (image pairs at the end points of the continua or straddling the category boundary) and object pair (15 object pairs) as factors. A significant effect of category position was found ($F(1,23) = 30.053,\ P < 0.001$). A significant effect of object was also found ($F(14,322) = 3.153,\ P < 0.001$). Post-hoc Newman–Keuls analyses revealed that the RTs to the Glass–Vase were significantly faster than those to the Bottles, Lamps, Glasses and Lamp–Bell. There was no interaction between the factors ($F(14,322) = 1.110$, n.s.).

4.3. Discussion

In this experiment we found evidence that the effects of CP found in Experiment 1 generalize across different instances of an object, namely changes in viewpoint. On the whole, those object pairs which were perceived as categorical from the canonical view-

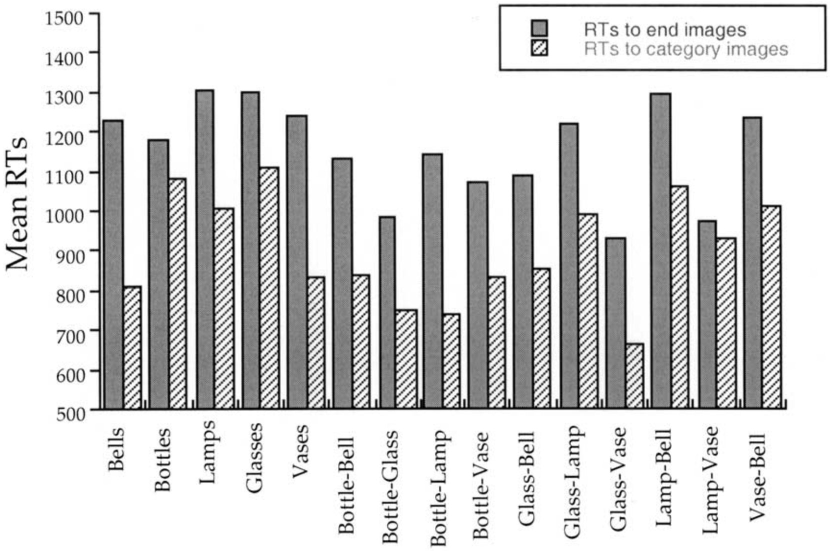

Fig. 7. Plot showing the mean RT taken to discriminate images at the end of each object continuum and images that straddled each category boundary, for all of the object pairs in Experiment 2. For all objects, the mean discrimination time to images at the ends of the continua (within-category images) were slower than the discrimination times to images on either side of the category boundary (across-category images). In this experiment, objects were matched across different viewpoints.

point were also perceived as categorical from View 2. By changing the viewpoint of the objects in a trial, participants had to discriminate between objects based on shape characteristics alone, and not on low-level differences between images (as may have occurred in Experiment 1). Our findings here provide evidence that the CP effects found are object-based, in that, different instances of the same object were perceived as equivalent if they belong within the category. Objects which lay either side of the category boundary were more easily discriminated, even across changes in view.

There were two object pair exceptions to our finding that CP effects generalize across viewpoint. CP effects were found for the Bottle–Glass pair from the canonical viewpoint only, and CP was found for the Bottle–Bell pair from View 2 only. We can only assume that these differences were due to subtle shifts in the discriminability of the category boundary with changes in viewpoint and not, for example, changes in the presence of the categorical boundary. For example, some features of objects may be more diagnostic of the position of the category boundary than others (see Sigala et al., 2002) and changes in viewpoint, which may make such features more or less available, would change the discriminability of the category boundary. This could be particularly true for the Bottle–Bell pair: View 2 reveals the presence of the clapper underneath the Bell and this feature is not so visible in the canonical view. To highlight our point, imagine we take the extreme case of showing two different category object images from a very foreshortened view; then it would be much more difficult to discern the categorical differences between these shapes (thus giving rise to the much reported error-prone recognition to these views (Newell & Findlay, 1997)). Although we deliberately chose viewpoints which reduced the risk of part occlusion and accretion, it may be inevitable that some viewpoints have a different effect on different object pairs.

4.3.1. A note on image-based distance measurement between object pairs

It is important to note that the manifestations of CP reported here and in Experiment 1 cannot be explained away by simply appealing either to the nature of the morphing method we used, or to the physical properties of the image stimuli. First, although the stimuli were created by a linear parametric interpolation in high-dimensional shape space, our participants effectively perceived them as varying categorically, as described above. Second, we computed an objective measure of image pair distances for all objects: we found that an analysis of the pixel-wise distance between alternate images (in this calculation we used distance to be defined as the Frobenius norm of the image difference matrix) in each of the morphing sequences showed that image space is not entirely uniform and indeed for some image pairs the distances were greater in mid-sequence. However, these image-based measurements did not determine the behavioural data found. Image distances correlated with only four of the eight object pairs where CP effects were found: Bells ($r = 0.809$, $P < 0.01$), Bottles ($r = 781$, $P < 0.05$), Lamps ($r = 0.891$, $P < 0.01$) and Glasses ($r = 0.881$, $P < 0.01$). We also found significant correlations between the observed CP data and computed image distances for four object pairs where no effects of CP were found: Bottle–Lamp ($r = 0.975$, $P < 0.001$), Glass–Bell ($r = 0.881$, $P < 0.01$), Glass–Lamp ($r = 0.704$, $P < 0.05$) and Lamp–Bell ($r = 0.77$, $P < 0.05$). There were no significant correlations found for the remaining object pairs. Therefore, the low-level, image-distance measurements do not explain all our findings on CP.

5. Experiment 3

The results from the previous experiments indicated that some object pairs were perceived categorically by the observers whereas there was no evidence for CP for other objects. One point of note from these results was that the objects that were categorically perceived were objects that appeared to be visually similar to each other. For example, objects from within the same basic-level category tend to appear similar to each other rather than objects from different categories (Rosch et al., 1976). In our results object pairs from the same basic-level categories were all perceived categorically whereas only some object pairs from different categories were perceived categorically. These data beg the question whether visual similarity can effect the perceptual categorization of objects. To this end we asked a number of participants to rate each object pair used in our experiments in terms of how visually similar the objects were to each other. We then correlated the mean rated similarity scores with the amount of CP found for each object pair (i.e. the size of correlation between the observed and predicted functions for the discrimination data).

5.1. Method

5.1.1. Participants

Thirty students from the Eberhard-Karls University of Tübingen participated in this study. Fourteen of these participants were female. The participants' ages ranged from 18 to 28 years old. All participants had normal or corrected-to-normal vision. The students had not participated in any of the previous experiments.

5.1.2. Stimuli

Each of the 15 pairs of objects located at the extreme of each of the shape continua described above was organized into a 5×3 object pair matrix. The images of the objects were grey-scale, shaded images (see Experiment 1 for a description of the image rendering). The object matrix was then printed out for each participant using a Laserprinter with (600) dpi resolution. The order of the object pairs on each printout was randomized across all participants.

5.1.3. Procedure

Participants were presented with a printout of a matrix of object pairs. They were instructed (in German) to study each pair of objects individually and to rate each pair of objects according to how similar the objects were to each other. Participants were instructed to base their judgements of similarity on the shape of the objects only and to ignore other properties such as the object's name or function. A rating scale was demonstrated to the participants. This scale ranged from 1 (*very dissimilar*) to 7 (*very similar*). Participants were encouraged to use all of the scale in their judgements.

5.2. Results and discussion

Participants' mean similarity ratings for each of the object pairs are shown in Fig. 8. Kendall's coefficient of concordance was calculated across the participants ratings (0.41) which indicated a significant concordance across participants' rating scores ($\chi^2(N = 30, \text{d.f.} = 14) = 170.46, P < 0.01$).

The similarity ratings for each object pair were then correlated with the degree of correlation found between the predicted and observed discrimination data in Experiment 1(a) and in Experiment 2. We found that the similarity ratings were highly correlated with the amount of CP in each object pair in Experiment 1(a) ($r = 0.743$, $P < 0.01$), and also in Experiment 2 ($r = 0.6702$, $P < 0.01$). These results suggest that inter-object perceptual similarity has a role to play in whether the objects are categorically perceived or not.

6. General discussion

In the experiments reported above we investigated whether familiar objects are categorically perceived. Specifically we asked whether the shape of an object has a psychological salience in representational space that is not completely determined by its physical difference from other shapes. In other words, we tested whether an object may be perceived as qualitatively different from another object such that a continuum of shape

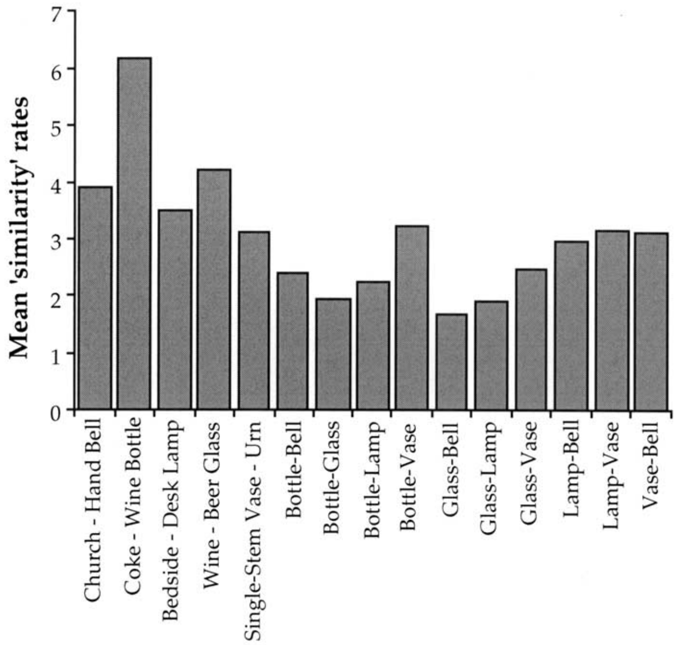

Fig. 8. Plot showing participants' mean rated scores of their judged visual similarity between the objects in each object pair. Participants used a scale from 7 (very similar) to 1 (very dissimilar). To allow for easier comparison the object pairs are arranged in the same order as the object plots shown in Figs. 3 and 6.

change between two objects would result in a discontinuity of categorization performance, reflecting the category boundary between the two objects. Moreover, such a categorical distinction should occur independent of incidental changes to an object's image, such as changes in viewpoint. Alternatively, the shape of any one object may not be qualitatively different from another object and in this case we would observe identification performance varying as a smooth continuous function between the two shapes. Our findings suggest that some familiar objects are indeed perceived categorically.

In Experiment 1, 15 pairs of familiar objects were tested. We found that eight of the 15 objects were perceived as categorical. We then increased the level of difficulty of the discrimination task for those seven object pairs where no CP was previously found. Our data showed that the change in task difficulty promoted CP in a further two of the seven object pairs. Therefore, we found no evidence for CP in five object pairs. In Experiment 2 we tested whether CP effects generalize across changes in viewpoint. Here we found that seven of the eight object pairs which were categorically perceived from a canonical viewpoint were also perceived as categorical from a new viewpoint. We argued that CP of objects is object-based because effects of CP generalized across changes in image instances of the same object. Furthermore, the differences in physical distances between image pairs did not determine our findings, suggesting again that CP is based on information about the objects and not just the images. Finally, in Experiment 3 we found a correlation between rated similarity judgements and the degree of CP found for each object pair in each viewpoint.

The first question that needs to be addressed is why some object pairs were categorically perceived whereas others were not. We initially hypothesized that CP is most likely to be found for objects that can exist as continuous shapes within a class in the real world because CP may be a procedure for differentiating between similar objects. Furthermore, a continuum of shape change between objects from different classes is unlikely to occur in the real world. However, we found no evidence for this prediction since some objects from across different basic-level classes were also perceived as categorical.

We found some evidence that CP was dependent on the difficulty of the discrimination task. In Experiment 1(a) the discrimination task was found not to be sensitive enough to allow for effects of CP to emerge in some of the object pairs. More objects were perceived as categorical in Experiment 1(b) where we increased the difficulty of the discrimination task. Of course the possibility remains that the level of difficulty in Experiment 1(b) was also not sensitive enough to allow for effects of CP to emerge in all other objects. However, this is unlikely since the average discrimination performance was not at ceiling (on average 67% correct responses), suggesting that if any effects of CP were present then the level of discrimination was not the factor obscuring such effects.

A further possibility why some object pairs were not perceived as categorical is that a morphing procedure may introduce visual events such that additional categories would emerge along the shape continuum. To illustrate our point here, consider morphing between a spindle and a barrel. Somewhere along this morph sequence, because of the change in curvature between concave and convex, a cylinder may be perceived (Foster, 1983). This cylinder may constitute a distinct perceptual category for the observer. Consequently, for some object pairs in our experiments the task may produce effects that reflect the perceptual categorization of three (or more) objects. The result could, therefore, be additional peaks in discrimination performance along the shape continua resulting in a lack of observable effects of CP. Clearly further research is required to investigate the effects of emergent categories on the perceptual categorization of shapes.

Several mechanisms have been proposed to account for effects of learning on CP (see Goldstone, 1998 for a review). For example, familiarity of the items in a task can emphasize physical differences between categories thus producing effects of CP that did not exist prior to training. Goldstone (1994) found evidence for an increase in distinctiveness along a dimension which was relevant to the categorization task. Conversely, he found acquired equivalence for items that belonged within the same category, i.e. items that varied along a category-irrelevant dimension were considered equivalent. Similarly, Livingston, Andrews, and Harnad (1998) recently reported that learning produced within-category compression effects (i.e. that inter-item similarity increases when categories are learned), and cross-category expansion effects. However, their effects were observed only when the categories were defined along many feature differences at once (e.g. cilia length and head shapes), and not when the categories were defined along a single feature difference (e.g. size difference).

Categorization can also be acquired by selectively attending to the relevant dimension along which the categories differ (Nosofsky, 1984) or to certain features by which they differ (Livingston & Andrews, 1995). Categorization may also occur through a process called differentiation. This process effectively separates items that are psychologically equivalent and once they are separated, fine discriminations can be made between items that were originally indistinguishable. To illustrate differentiation Goldstone (1998) offers the example of wine tasters who can distinguish between the upper and lower halves of a bottle of Madeira by taste.

We might argue that our findings were due to effects of differentiation rather than other effects, such as selective attention. For example, the reason why some objects and not others were categorically perceived is that CP is related to the degree of perceptual similarity between the objects such that objects that are highly similar are more likely to be perceived as categorical. Therefore, objects that were once confusable or indistinguishable because they are highly similar have become separated to allow for categorization. We found that subjective similarity ratings were correlated with the degree of perceptual categorization in the objects from two different viewpoints. The results of Experiment 1(b) also indirectly support this argument in the following manner: by changing the difficulty of discrimination in Experiment 1(b) it could be argued that we were effectively increasing the similarity between the objects. Objects are either intrinsically similar, such as objects from within the same category (Rosch, 1975), or can be made more similar by changing the difficulty of the discrimination task. For example, images 1 and 2 are more similar to each other on any shape continuum than images 1 and 3 and consequently the discrimination task is more difficult between images 1 and 2. Changing the level of discrimination in a task does not increase the similarity between the original end objects in the shape continuum. However, if these two end objects are quite dissimilar then discriminating between images 1 and 2 on the shape continuum may be equivalent to discriminating between images 1 and 3 on a shape continuum between two more similar end objects. Therefore, the distances between two images in the discrimination task are equivalent across object pairs in representational similarity space.

If CP occurs when inter-object similarity is high, we could ask why the recognition of similar objects is, generally, less efficient than the recognition of objects from different basic levels. For example, the recognition of objects from within the same class is often found to be dependent on viewpoint (Bülthoff & Edelman, 1992; Bülthoff et al., 1995) whereas the recognition of objects from different basic-levels categories is not (Biederman & Gerhardstein, 1993; Newell, 1998). If CP is a tool for qualifying differences between similar objects then it might be argued that discriminating between category members might be just as good as discriminating between objects from different categories.

There may be two reasons why discriminating between objects within a class is relatively less efficient. First, the specific objects within a class may be less familiar than the generic category to which they belong. Second, objects from different categories are often differentiated by the structure of their parts, which is unique to each object class (Biederman, 1987), whereas objects from the same category are often differentiated by small metric differences between the parts.

On the first point, it is well known that an increase in object familiarity improves recognition performance (Edelman & Bülthoff, 1992; Newell & Findlay, 1997). This may be because participants learn to create the appropriate object categories for the task thus optimizing discrimination performance (Nosofsky, 1984). There has been a lot of evidence recently to support the idea that categories are learned for the purposes of efficient discrimination. For example, Beale and Keil (1995) reported finding CP for familiar faces but not for unfamiliar faces. Similarly, Levin and Beale (2000) reported that CP effects can be found for unfamiliar faces and races of faces if the experimental procedure allows for learning to occur. Levin and Beale presented face-pair stimuli in separate blocks during the experiment and found that categories of individual faces can be rapidly learned. Furthermore, Livingston et al. (1998) reported that fast learning of category objects can change the structure of representational space through within-category compression.

Finally, given that many across-category objects in the real world can be differentiated on the basis of shape differences that are intrinsic to the classes themselves, it may be that such differences are sufficient for discriminating between many objects. However, the detection of such small differences between objects from the same class may require extra visual processing in order to reliably discriminate between the objects. The performance differences found between object pairs in our study may, therefore, reflect the amount of processing required to complete each task.

6.1. Implications for representational object space

Recent models of object recognition have suggested that objects are represented as multiple views (Bülthoff & Edelman, 1992) and that the inter-object similarity determines the location of the object in representational space (Edelman, 1995b,c; Valentine, 1991; see Tarr & Bülthoff, 1998 for an overview). Edelman suggests that objects which are highly similar lie in closer proximity in representational space than objects that are less similar. To avoid confusion between objects which closely resemble each other, the perceptual system must construct category boundaries between similar object classes. Consequently all different types of round orange objects with bumpy surfaces will be categorized as an 'orange' whereas a basketball will not. Our findings propose that the differences between similar objects are qualified at the perceptual level, and that these differences are perhaps learned and coded at the representational level.

If, as has been argued, objects are located in representational space based on their inter-item similarity then the visual system is faced with the problem of maintaining the uniqueness of an object despite changes with certain transformations such as changes in viewpoint, size or illumination. One way in which this could be achieved is by associating events that are temporally continuous together. A rotating object, for example, projects different image-views smoothly over a continuous time slot. By continuously associating views of objects a rich representation of that object in memory to support later recognition can be created (Wallis & Bülthoff, 2001). At the same time, however, the differences *between* similar objects must be maintained. We suggest that such a process occurs at the perceptual level. As a consequence, effects of CP should generalize across different instances of objects such as different viewpoints or different sizes. Our results provide evidence that CP effects do occur between similar objects and indeed these effects generalize, at least, across different viewpoints.

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Appendix A

The following formula was used to calculate participants' predicted discrimination performance from their identification performance: this formula is adopted from that used by Calder et al. (1996) and Liberman et al. (1957). First, the observers ability to discriminate between images that differ by a constant physical amount was determined by calculating the mean discrimination performance to the pairs of images that lay at either end of the object shape continuum (e.g. discriminating between image pairs 1,3 and image pairs 9,11). These images were assigned to their appropriate categories approximately 100% of the time and therefore any effects of CP would be minimized. Second, in order to predict the effects of CP on the discrimination of image pairs that lay along the entire continuum, the following calculation was conducted: we calculated the difference between the number of times each image in the pair was assigned to a particular object shape in the identification task. These figures were then added together. We then multiplied the identification difference by a constant of 0.3. This had the effect of aligning the predicted function with the observed discrimination function and also made the respective range of variabilities more comparable. The predicted and observed functions are shown in Figs. 3 and 6. The constant had no effect on the correlation between the observed and predicted curves but did help to show the fit between the two curves. In summary, the function used to calculate the predicted discrimination performance for each object pair was the sum of the mean discrimination performance to the pairs of images on either end of the shape continuum and 0.3 of the identification difference for each pair of images tested.

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