

Discrimination of Contour-Deleted Images by Pigeons

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Three experiments attempted to determine which properties of pictorial representations of objects control their discrimination by pigeons. A particular focus was whether the representation mediating such discriminations could be described by the simple viewpoint-invariant primitive volumes of Biederman's (1987) recognition-by-components theory of object recognition or by Cerella's (1990) particulate features. In all 3 experiments, pigeons were first trained to discriminate drawings of 4 stimulus objects with half of the contour deleted but with the component *geons* postulated by Biederman's theory recoverable. Discrimination accuracy was then compared for test items containing the original particulate features, affording the retrieval of the original component geons, or having neither of these properties of the training stimuli. Although response accuracy was significantly greater when the component geons of the original objects were retrievable, measurable control over recognition by the particulate features of the objects and by their specific locations was also found. The results are consistent with the idea of component geon recognition as one of the important factors in object discrimination.

Visual object recognition requires the identification of particular exemplars as well as the ability to treat similar instances as members of the same object class. A theory that would account for these capacities must be constrained by the variability of the retinal images that may be projected by the same object. Objects that are viewed from novel orientations, degraded, or partially occluded are still readily identified by human observers, although a different image configuration is projected to the retina in each case.

Shapes must also be distinguished from their surroundings in complex visual contexts. The perceptual information that is the basis for object recognition must be relatively invariant with respect to such variability and visual noise. A successful theory of visual object recognition will have to provide an analysis of the perceptual basis of identification in terms of the specific invariant features and physical properties of objects that control their recognition.

Current theories of visual object recognition can be distinguished according to whether the representation mediating recognition is assumed to be (a) a template (with a capacity for spatial transformations), (b) a viewpoint-invariant, parts-based structural description, or (c) a collection of particulate image features, such as vertices and edges.

One type of contemporary theoretical approach to visual object recognition involves the matching of visual input to metrically specific memory representations or templates (Lowe, 1987; Ullman, 1989). The memory representation of an object is proposed to be specific with regard to size, position, and orientation. This type of model thus requires that a normalization process occur before object matching and recognition. In this process, the size, position, and orientation of the visual input are transformed to bring them into alignment with the memory representation of the object.

Although template-matching models have had some success in computer-vision applications (e.g., Lowe, 1987; Ullman, 1989), there are several critical difficulties with such models when they are applied to human and animal object recognition. The large number of templates that must be stored in naturalistic visual contexts makes the extension of template-matching models to such applications implausible. Also, these models cannot account for the classification of an unfamiliar object, because there would be no previously stored template of the object. Still other problems with metrically specific template models of object recognition are discussed by Hummel and Biederman (1992) and by Pinker (1984).

The second contemporary type of object recognition theory proposes the alternative idea that memory representations for objects are viewpoint invariant. Variable images projected by different sizes, positions, and orientations of an object would activate this invariant representation (Cooper, Biederman, & Hummel, 1992; Hummel & Biederman, 1992). In this type of object recognition theory, the memory representation of an object is generally conceptualized as a structural description, which specifies the type and spatial relations of the object's parts but whose activation is invariant with respect to the size, position, and orientation of the object (Biederman, 1987; Cooper, 1990; Marr, 1982; Marr & Nishihara, 1978; Pinker, 1984; Quinlan, 1991).

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Biederman's (1987; also see Hummel & Biederman, 1992) recognition-by-components (RBC) theory is an example of an invariant-parts theory of object recognition. The RBC theory proposes that object recognition occurs in stages involving the following: extraction of edges corresponding to the orientation and depth discontinuities of the object, segmentation of the parts of the object, activation of units for each part corresponding to a particular member of a set of geometric primitives (*geons*) and to the properties of these units (such as orientation, aspect ratio, and spatial relations of the geons), and the activation of an object representation based on the identified components and their spatial relations to one another. The edge-extraction stage, which is responsive to changes in surface characteristics, such as texture, luminance, and color, provides a description from which nonaccidental properties (described in the next paragraph) of image edges (collinearity, curvature, symmetry, parallelism, and cotermi- nation) are detected. Along with the detection of nonaccidental properties, the image is parsed, or segmented, at points of deep concavity, particularly at cusps, where discontinuities in curvature occur (Marr & Nishihara, 1978). Each segmented region of an image is then approximated by one of a set of *geons*, for geometric ions. These geons are the primitive components of the RBC theory. They can be modeled as volumes swept out by a cross section moving along an axis and are generated through variations in nonaccidental properties.

The central organizational principle for generating a set of geons is that some properties of edges in two-dimensional images are taken by the visual system as evidence that the edges in three-dimensional reality contain the same properties. These properties have been described as nonaccidental (Witkin & Tenenbaum, 1983), because such properties would be unlikely to be produced in a retinal image through the accidental alignment of viewpoint and object features. The nonaccidental property of collinearity, for example, results in an inference by the visual system that a straight line in an image is produced by a straight line in the three-dimensional context. It is highly improbable that such an image would be produced by a curved edge at an accidentally precise alignment with the eye. The RBC theory proposes that simple contrasts in the nonaccidental properties of collinearity, curvature, parallelism, and cotermi- nation may constitute a perceptual basis for generating this set of primitive components (geons) and that geons are rapidly identifiable and invariant over viewpoint and visual noise.

The fundamental perceptual assumption of RBC theory is that the geons can be distinguished on the basis of traditional principles of perceptual organization, such as good continuation, symmetry, and *pragnanz*. The RBC theory's account of object recognition thus proposes that these traditional Gestalt organizational principles constrain recognition of the object's components but not of the complete object. A complete, complex, and asymmetrical object will contain primitive components, which are simple volumes, such as blocks, wedges, spheres, and cylinders. These volumes will typically be symmetrical and lack sharp concavities. According to the RBC theory, these components will be stable and recognizable despite visual noise, because geons can be recovered through

visual contour restoration mechanisms involving collinearity and curvature—the perceived continuation of lines and curves.

These mechanisms for the restoration of occluded contour will not bridge cusps (Biederman, 1987; Kanizsa, 1979). The RBC theory holds that geons are organized from the contours between cusps and that the locations of object parsing will be at these joining points. Because object perception is based on the components and their particular arrangement, objects are recognized despite moderate noise—if the components can be recovered. Furthermore, the components are recoverable if the concavities occurring at cusps are not interrupted and there is enough contour present to provide a nonaccidental description of the volume. The RBC theory goes on to predict that if an arrangement of two or three geons can be recovered, most objects can be quickly recognized despite partial occlusion, degradation, rotation, or lack of usual surface detail.

Experimental support for a parts-based representation mediating object recognition was reported for humans by Biederman and Cooper (1991b) and Cooper et al. (1992). These investigations ruled out a representation based on the particular lines and vertices present in an image. The present investigation was designed to evaluate whether a parts-based or a particulate feature representation best characterizes pigeons' discriminative performance.

Prior research demonstrating visual categorization of objects by pigeons has not allowed determination of the specific features and properties of the stimuli that control this discriminative behavior. Herrnstein and his collaborators (Herrnstein, 1984, 1985; Herrnstein & deVilliers, 1980; Herrnstein & Loveland, 1964; Herrnstein, Loveland, & Cable, 1976) have trained pigeons to discriminate photographs containing a particular class of stimuli from photographs not containing objects from that class (e.g., trees vs. nontrees, fish vs. nonfish, water vs. nonwater). Wasserman and his colleagues (Bhatt & Wasserman, 1989; Bhatt, Wasserman, Reynolds, & Knauss, 1988; Wasserman, Kiedinger, & Bhatt, 1988) have shown that pigeons readily learn to discriminate diverse color slides from four object categories: cats, flowers, cars, and chairs. Pigeons can thus concurrently classify complex, variable, and naturalistic stimuli into human language categories. The complexity of the stimuli, however, makes an analysis of the properties affording these discriminations extremely difficult.

Other researchers investigating pattern recognition by pigeons have attempted to analyze the features extracted in this process (Blough, 1985; Lea & Ryan, 1983). These studies have generally involved cluster analysis or multidimensional scaling procedures using stimuli such as letters of the alphabet or dot patterns. Such correlational procedures, although they suggest possible attributes, do not provide evidence that those attributes are actually used. Furthermore, because the features chosen for analysis in such procedures depend on the data being explained, there has been no general agreement on the set of features detected during pattern recognition (Blough, 1985; Heinemann & Chase, 1990).

Cerella (1977, 1979, 1980, 1982, 1986, 1990) attempted to determine more precisely the properties of pictorial stimuli that control their discrimination by pigeons. The collective results of this work led Cerella to suggest that the pigeon's

visual perception is particulate, and that more global and relational properties of complex stimuli are ignored. Cerella has proposed that pigeons represent natural object classes as random, unstructured sets of local features. (We refer to Cerella's proposal as particulate-feature theory, or PFT). This proposal has been supported by studies in which pigeons were unable to discriminate two pattern classes that were composed of the same local features but differed in global structure (e.g., perspective transformations of cubes and noncubes or letter trigrams). However, this research has involved a wide variety of stimulus items (e.g., leaves, cartoon characters, letters of the alphabet, or dot patterns), and the results have not been integrated into a broad theoretical framework.

In the present article, we used a modification of an experimental paradigm (Biederman & Cooper, 1991b) originally designed to assess whether local features mediate human object recognition. In Experiment 1, pigeons were first trained to discriminate either the elephant, mushroom, chair, and

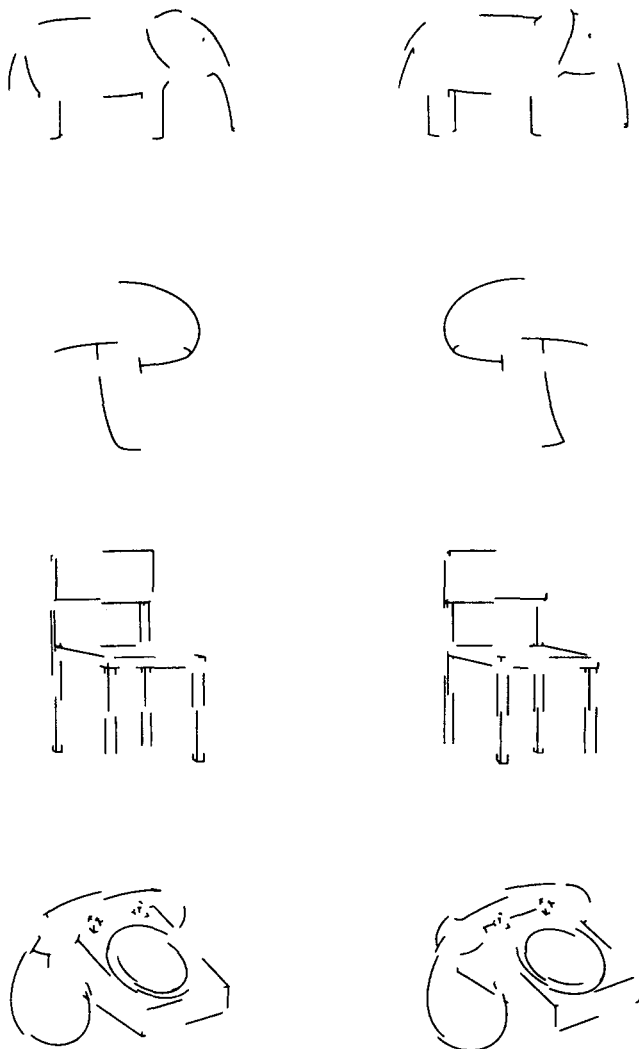


Figure 1. Experiment 1 stimulus objects (elephant, mushroom, chair, and telephone).

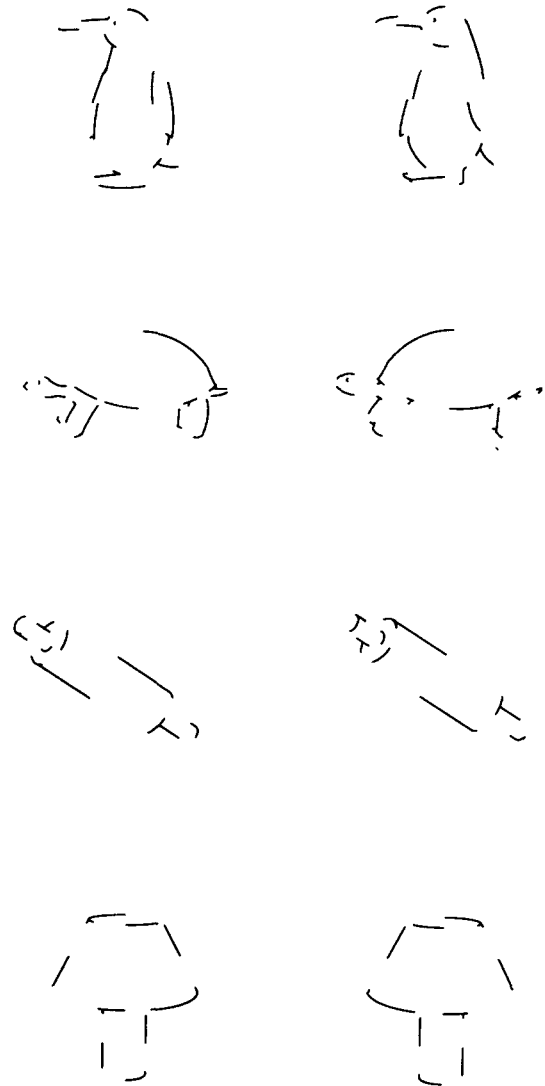


Figure 2. Experiment 1 stimulus objects (penguin, turtle, lamp, and rolling pin).

telephone (EMCT) or the penguin, turtle, lamp, and rolling pin (PTLR) images shown in the left columns of Figures 1 and 2.

These original (ORIG) training pictures were constructed by deleting every other edge and vertex from each part (geon) of the intact image of the object so that approximately 50% of the total contour remained in each part. In later test sessions, the complements (COMPs) of these training images were presented (Figures 1 and 2, right columns). The complementary images were composed of the edges and vertices that had been deleted from the ORIG training stimuli. The original and the complementary images of an object each contained 50% of the total contour, and both were designed to allow activation of the same geons in the object. When superimposed, the members of a complementary pair create an intact object with no overlap in contour. After completion of the test sessions, the pigeons were trained to discriminate the four

stimuli (Figures 1 and 2, left columns) they had not seen previously and then were tested on the complements of these images (Figures 1 and 2, right columns). All 4 of the pigeons in the experiment were trained and tested on both sets of stimuli in counterbalanced order. If a components-based representation, such as that assumed by RBC theory developed during training, then the pigeons should show the same assignment of objects to responses. If, on the other hand, the representation of an object consisted only of the actual lines and vertices in the image, as in PFT, then the pigeons should fail to recognize the complementary images, because they contain no edges or vertices identical to the training stimuli.

In Experiment 2, the training stimuli were the PTLR images of Experiment 1, and 4 new experimentally naive pigeons served as subjects. In the test phase, the complementary images of Experiment 1 were presented along with versions of the objects composed of the same features (edges and vertices) as the complementary images, but with the features in a spatially scrambled (SCR) configuration, thereby precluding geon activation (see Figure 3; from left to right, ORIG, COMP, and SCR). The purpose of this variation in the test

stimuli was to consider the possibility that recognition of the complementary images in Experiment 1 might have been the result of stimulus generalization to similar but nonidentical line-segment features (edges and vertices) rather than to geon activation. For example, the two complements of a brick will each contain several straight lines of similar orientations and both L-shaped and arrow vertices. Assuming that RBC theory characterizes the behavior of pigeons and not just humans, RBC theory and PFT make different predictions. The RBC theory predicts that the SCR versions should be less recognizable than the COMP figures, whereas PFT predicts accurate discrimination of the SCR test items if the COMP items are also recognizable, because the COMP and SCR versions contain the same isolated features.

Experiment 3 involved further testing of the pigeons from Experiment 2 on two additional scrambled-feature configurations. Here, the test images were constructed using the features of the ORIG stimuli rather than those of the COMP stimuli, which had been used in all prior testing. Thus, the training stimuli and the stimuli used for generalization testing contained identical features. Both versions of the SCR test



Figure 3. Experiment 2 stimulus objects (penguin, turtle, lamp, and rolling pin).



Figure 4. Experiment 3 stimulus objects (penguin, turtle, lamp, and rolling pin).

stimuli for Experiment 3 were constructed with the features spatially scrambled, so that geon recovery presumably was precluded. Figure 4 (center column) shows the SCR1 configuration, in which all of the features remained in their original quadrants. The right column of Figure 4 contains the SCR2 version, in which half of the line-segment features remained in their original quadrants and half were shifted one quadrant clockwise. We tested the SCR1 figures to investigate the possibility that the objects might be recognized by the pigeons without the opportunity of geon recovery if the line-segment features were identical to and appeared in the same general locations as those presented in training. The SCR2 images were constructed to investigate the possible effect of feature location on recognition accuracy. PFT predicts accurate discrimination of both types of SCR test images, whereas RBC theory again predicts that, because of the nonrecoverability of geons, there should be reduced recognition of either type of test image. In the event that the pigeons recognized either or both of the SCR images, a significant difference between the accuracy of responding to the SCR1 and SCR2 images

would indicate that feature location is a factor in object recognition.

Experiment 1

Method

Subjects

Four experimentally naive feral pigeons were studied. They were housed in individual cages in a room in which a 14:10-hr light-dark cycle was maintained, with lights on at 0700. The pigeons were maintained at 85% of their free-feeding weights. Grit and water were continuously available in their home cages.

Apparatus

The pigeons were trained and tested in $29 \times 38 \times 38$ cm operant chambers, in which amplified white noise masked external sounds. One of the side walls of the experimental chamber was the response

panel, which contained a 7 × 7 cm plastic viewing screen. The viewing screen was located 10 cm from the top edge and 14 cm from each of the side edges of the response panel. Slides were back projected onto the viewing screen by a Kodak Carousel slide projector (Ektagraphic IIIIE, with a 76-mm/3.5 Ektagraphic FF lens and a GE EXR 82-Vdc bulb controlled by a rheostat). Situated 2.3 cm diagonally from each corner of the viewing screen were 1.9-cm diameter response keys. Responses to the viewing screen and the four corner keys of at least 0.05 N force were recorded by microswitches mounted behind the response panel above the screen and behind each corner key. Located behind each of the four circular keys was a miniature projector containing a small lamp. The lamps produced an orange field on the top-left key, a white field on the top-right key, a green field on the bottom-left key, and a red field on the bottom-right key. The house-light was a small lamp located 6.5 cm above the viewing screen and encased in a housing that directed the light toward the ceiling of the chamber. A tone was sounded in the chamber by a Sonalert auditory system mounted behind the response panel. Located 5.8 cm below the viewing screen was a 5.0 × 6.3 cm opening in the response panel that allowed access to a food hopper containing mixed grain. The food hopper contained a lamp, which was illuminated when the hopper was raised during reinforcement periods. A DEC PDP 8/A computer was used for experimental control and data collection.

Stimuli

The stimuli were black-and-white slides containing the images shown in Figures 1 and 2. Two degraded versions of intact images were used, each of which contained 50% of the contour and every other edge and vertex from each geon. (The original and complementary images were constructed by Biederman and Cooper, 1991b.) The size of the images, when projected on the screen, varied slightly across stimulus items. The largest dimension, either height (h) or width (w), was always 5.70 cm. The remaining dimension (in centimeters) varied as follows: elephant, 3.05 (h); mushroom, 3.05 (w); chair, 4.20 (w); telephone, 4.20 (h); penguin, 3.80 (w); turtle, 3.05 (h); lamp, 4.95 (w); and rolling pin, 4.20 (h). When superimposed, the two versions of the image formed a complete object with no overlap in contour. The edges and vertices present in one version were absent from the other. Contour was deleted from one version of the image in a manner that allowed recovery of the same geons, according to RBC theory. Some of the geons of the intact object might not have been recoverable, but this would have been true for both members of a complementary pair. A small portion of deleted edges was retained to define the adjacent vertex, and long edges were considered to be two separate edges (see Biederman & Cooper, 1991b).

Procedure

Pretraining. The pigeons were first shaped by hand to eat from the hopper and then to peck the screen and each of the four corner keys once whenever the screen or the keys were illuminated. Daily pretraining sessions consisting of 40 trials were then initiated. After a variable intertrial interval averaging 40 s, either the screen was illuminated with white light by advancing the slide carousel containing empty slide frames or one of the four corner keys was lit. The 40 trials consisted of 20 presentations of the screen and 5 presentations of each of the four corner keys. After the pigeons completed the required number of responses on the illuminated screen or key, the screen or key was darkened and the hopper was raised to allow the pigeons 3 s of access to grain. The required number of pecks to the key or screen was gradually increased from 1 to 30. Pretraining was terminated when all 4 pigeons were reliably pecking the screen or corner keys 30 times whenever these displays were illuminated. The length of the pretraining period was 28 days.

Training. Commencing 1 day after the end of pretraining, the pigeons were trained to discriminate four images (see Figures 1 and 2, left columns). All 4 pigeons were eventually trained and tested on both sets of stimuli (EMCT and PTLR). The order of learning the two sets of stimuli was counterbalanced such that Birds 1 and 3 learned EMCT first and Birds 2 and 4 learned PTLR first. The description that follows proceeds as though EMCT were being trained simultaneously with all 4 pigeons to simplify explanation of the counterbalancing procedures for correct response keys.

The pigeons were trained each day with 48 slides: 12 copies each of the elephant, mushroom, chair, and telephone. Correct discrimination required a peck to one of the four corner keys in the presence of the slide image assigned to that key. Assignment of keys to objects was counterbalanced so that each key represented each of the objects across all 4 pigeons.

Daily sessions started with the illumination of the houselight followed 50 s later by the first trial. The slide carousel advanced once and a slide was displayed on the screen. After the pigeon made a required number of observing responses to the screen (increased daily in increments of 5 pecks from 5 to 30 for the first 6 days; a constant 30 pecks were required thereafter), the four corner keys were simultaneously illuminated and the tone was sounded. The tone remained on and the keys remained illuminated until a peck was made to one of the keys. A peck to the correct key (depending on which object was depicted on the screen) darkened the screen and all of the corner keys, turned off the tone, and raised the hopper, allowing the pigeon 2.5 s of access to grain. A peck to an incorrect key darkened all of the corner keys and turned off the tone; the pigeon was required to make the appropriate number of observing responses to the screen before the corner keys and tone came on again. This correction process was repeated until the pigeon pecked the correct key and received grain reinforcement. After a correct response and a variable intertrial interval averaging 15.0 s, the carousel was advanced and the next slide was presented. Correction trials were not included in the daily total of 48 slide presentations, and data from correction trials were not used in analyses of performance.

Four slide tray arrangements (A, B, C, or D) were used to display the 48 slides. Within each tray, the slides were randomly ordered, with the restriction that every block of 4 slides included one slide of each of the four objects. Each pigeon was shown the slides in one of the four trays in each daily session. Order of presentation of the trays was randomly determined, with the constraint that within each 4-day block of sessions, each bird saw all four slide orders. Pigeons were trained to what appeared to be an asymptotic level of performance, measured as the percentage of trials on which the correct key was chosen averaged over a 5-day period of training. The number of days of training required (36–92 days, $M = 61$ days) and the level of accuracy attained (54.58%–86.25%, $M = 70.89%$) varied across the 4 pigeons and the two stimulus sets. The pretraining and four-key choice procedures were developed by Bhatt et al. (1988).

Tests of generalization to complementary images. Two new slide trays (E and F) were prepared for the generalization tests. Each tray contained 40 of the training slides (10 each of elephant, mushroom, chair, and telephone) and 8 new test slides (2 each of the COMP versions of elephant, mushroom, chair, and telephone). Two new random slide orders were determined, again with the restriction that every block of four slides included one slide of each of the four objects. Two of each ORIG image were replaced with the corresponding COMP image in each test tray. Substitutions were made in the following positions in the tray orders: Tray E, elephant (penguin), slides 9 and 35; mushroom (turtle), slides 19 and 37; chair (lamp), slides 15 and 27; and telephone (rolling pin), slides 23 and 31; and Tray F, elephant (penguin), slides 18 and 26; mushroom (turtle), slides 15 and 38; chair (lamp), slides 22 and 30; telephone (rolling pin), slides 12 and 34.

Generalization testing for each pigeon began the day after termination of training. Tests were conducted in four blocks of two daily sessions, with 4 days of refresher training (using Trays A, B, C, and D) between each 2 days of testing. In each 2-day test block, the pigeon was shown Tray E on one of the days and Tray F on the other. Order of presentation of the two trays within a block was varied across blocks (e.g., EF, FE, FE, and EF). During the first four test sessions, no responses made in the presence of the COMP image slides were reinforced. During the last four test sessions, all pecks made to any key in the presence of the COMP image slides were reinforced by presentation of the grain hopper. Thus, there was never any differential reinforcement for correct and incorrect responses to any of the test images. The first four test sessions were conducted in extinction to provide what many would consider to be the most uncontaminated evidence of transfer from ORIG to COMP images. Nondifferential reinforcement of all choices was introduced for the remaining four tests to prevent a specific decrement in responding to test items due to prolonged testing in extinction. Such nondifferential reinforcement was evidently effective, as test performance in this and in all subsequent experiments was statistically indistinguishable on extinction and reinforcement test sessions. Data for all test sessions were thus combined in all reported analyses. During all test sessions, correction trials were used only for the training (ORIG) slides.

The entire learning and generalization procedure was then repeated, with the pigeons being trained and tested on the four ORIG and four COMP images they had not previously seen.

Behavioral measure and designated alpha level. During training and generalization testing, the behavioral measure used was the percentage of trials on which the correct key was pecked. Responses during correction trials were excluded from analysis during both training and generalization testing. During generalization testing, responses to ORIG slide images in Tray Positions 1 to 8 and 41 to 48 were excluded from analysis, because none of the test items fell within this range. An alpha level of .05 was designated for the rejection of null hypotheses.

Results and Discussion

Table 1 presents the mean percentage of correct choice responses made by each pigeon to the ORIG and COMP versions of the EMCT and PTLR images during the eight generalization tests. Table 2 displays the same generalization test data for each stimulus item averaged across the 4 pigeons. Table 1 shows that all 4 pigeons' discrimination of the COMP images in both stimulus sets was above the chance level of

Table 1
Correct Choice Responses (Mean Percentages) by Each Pigeon to Two Types of Images Across Eight Generalization Test Sessions in Experiment 1

Bird	EMCT		PTLR	
	ORIG	COMP	ORIG	COMP
1	88.02	70.31*	83.85	67.19*
2	84.90	79.69*	73.96	70.31*
3	72.92	64.06*	65.63	62.50*
4	62.50	53.13*	84.37	62.50*
<i>M</i>	77.08	66.80	76.95	65.63

Note. Binomial tests were only conducted on complement (COMP) images for each of the 4 pigeons. EMCT = elephant, mushroom, chair, and telephone images; PTLR = penguin, turtle, lamp, and rolling pin images; ORIG = original.

* $p < .01$, binomial test ($N = 64$).

Table 2
Correct Choice Responses (Mean Percentages) to Two Types of Images for Each Stimulus Object Across Eight Generalization Test Sessions Averaged Over the 4 Pigeons in Experiment 1

Object	Image	
	ORIG	COMP
Elephant	81.25	73.44**
Mushroom	70.31	39.06*
Chair	76.04	79.69**
Telephone	80.73	75.00**
Penguin	82.81	78.13**
Turtle	79.17	56.25**
Lamp	61.46	54.69**
Rolling pin	84.37	73.44**
<i>M</i>	77.02	66.21

Note. Binomial tests were only conducted on complement (COMP) images for each of the eight stimulus objects. ORIG = original.

* $p < .05$. ** $p < .01$, binomial test ($N = 64$).

accuracy (25%); binomial tests disclosed that the accuracy levels were all statistically different from chance. Thus, it is clear that the pigeons' recognition of the original stimulus items did effectively generalize to the complementary versions. These complementary stimuli allow activation of the same geons as the original training items, but on a point-by-point basis they neither share identical local features nor overlap in contour. These results are contrary to a strict particulate, local-feature-based explanation of pigeon object recognition.

Nevertheless, Table 1 shows that the ORIG images were discriminated with greater accuracy than the COMP images in both stimulus sets by all 4 pigeons. This result suggests some control of discriminative performance by local line-segment features, as both versions of the images presumably allowed equivalent geon activation, but only the ORIG versions contained the features of the training items. As can be seen from close scrutiny of Figures 1 and 2, the ORIG and COMP figures contain a number of line segments that are at least similar in shape, orientation, and location.

A 2×8 (Type \times Stimulus) within-subjects analysis of variance (ANOVA) (types were ORIG and COMP; stimulus items were elephant, mushroom, chair, telephone, penguin, turtle, lamp, and rolling pin) was conducted to determine if there was a difference in response accuracy between the ORIG and COMP items. We were also interested in discovering whether particular objects produced higher levels of response accuracy than other stimulus items. There was a significant difference for type, $F(1, 3) = 10.97$, $p < .05$, indicating a reliable difference in accuracy for the COMP images in comparison to the ORIG figures. The stimulus factor was not significant, indicating that there was no difference in accuracy to the different objects. The interaction of the two factors was significant, $F(3, 14)$, $p < .05$, but, as accuracy for all of the COMP images was significantly above chance (25%), as shown by binomial tests ($p < .05$ for mushroom, $p < .01$ for all other objects; see Table 2), no further follow-up analysis was undertaken. (No binomial tests were performed to analyze accuracy for the ORIG items, as this accuracy level was, for

all items except the chair, greater than that for the COMP items, and the COMP figures were always recognized at greater-than-chance levels of accuracy. A similar story held for the analyses of responding to ORIG images in Experiments 2 and 3.)

It is possible that stimulus properties other than geons or particulate features may have accounted in part for the levels of response accuracy in generalization testing. In terms of maximum height by maximum width, the aspect ratio remained constant across all versions of each stimulus figure. In addition, we analyzed the choice matrix based on responding during the Experiment 1 tests (see Table 3) to assess the possible contribution of the horizontal or vertical orientation of the objects to the pattern of results. If the eight stimulus items are categorized as having a longer vertical dimension (mushroom, chair, penguin, and lamp) or a longer horizontal dimension (elephant, telephone, turtle, and rolling pin), it can be seen from Table 3 that there was no systematic or consistent effect of the global orientation of the objects on the pattern of errors. The global horizontal or vertical orientation of the objects does not appear, therefore, to account for the results.

The generalization decrement indicated by the superior response accuracy for the ORIG over the COMP images and the general similarity in appearance of some of the features in the two object versions suggest the possibility that the pigeons' recognition of the COMP images may in some measure have been due to stimulus generalization to similar local features. The purpose of Experiment 2 was to investigate this possibility more directly. In addition to testing with the COMP images, another set of test images was constructed which was composed of the same line-segment features as the COMP images but displayed these features in a manner not predicted to allow geon recovery according to RBC theory. We hoped that this experimental design would allow assessment of the separate contributions to object recognition made by geon retrieval and by particulate-feature discrimination.

Experiment 2

Method

Subjects

Four new experimentally naive feral pigeons (Birds, 5, 6, 7, and 8) were studied. They were housed and maintained in the same manner as the pigeons in Experiment 1.

Apparatus

Pigeons were trained and tested with the same apparatus used in Experiment 1.

Stimuli

The stimuli were black-and-white slides displaying the images shown in Figure 3. In the left column are the ORIG training stimuli, the PTLR stimuli used in Experiment 1. The test phase involved the figures shown in the center column, the COMP images of Experiment

Table 3
Choice Responses (Mean Percentages) to All Stimulus Items
In Experiment 1 Tests

Stimulus	Response			
	Elephant	Mushroom	Chair	Telephone
Original				
Elephant	81.25	6.25	2.08	10.42
Mushroom	15.63	70.31	5.21	8.85
Chair	5.21	15.63	76.04	3.12
Telephone	14.06	2.60	2.60	80.73
Complement				
Elephant	73.44	6.25	6.25	14.06
Mushroom	37.50	39.06	6.25	17.19
Chair	9.38	6.25	79.69	4.69
Telephone	15.63	6.25	3.12	75.00
Stimulus	Penguin	Turtle	Lamp	Rolling pin
Original				
Penguin	82.81	2.60	9.38	5.21
Turtle	7.81	79.17	5.21	7.81
Lamp	20.31	13.54	61.46	4.69
Rolling pin	3.12	4.69	7.81	84.38
Complement				
Penguin	78.13	1.56	6.25	14.06
Turtle	15.63	56.25	14.06	14.06
Lamp	17.19	12.50	54.69	15.63
Rolling pin	3.12	9.38	14.06	73.44

Note. Boldface numbers represent correct responses. Other numbers indicate which incorrect response was made to each visual stimulus.

1. In addition, we constructed a new set of SCR images for generalization testing, as shown in the right column of Figure 3. The SCR images were composed of the same line segments (edges and vertices) as the COMP figures; however, in the SCR figures, the features were translated to a random configuration to reduce the likelihood of geon activation according to RBC theory. All of the edges and vertices in the SCR versions were displayed so that these line segments were oriented at the same angle relative to the other segments and to the top of the display as they were in the COMP version of the test stimuli.

Procedure

Pretraining. The pigeons were pretrained with procedures identical to those of Experiment 1 for 19 days.

Training. Training was identical to Experiment 1, except that only the PTLR stimuli were presented. The pigeons were all trained for 100 days. Levels of accuracy attained for discrimination of the training items, measured as the mean percentage of trials on which the correct key was chosen for Days 96 to 100, were 70.42% for Bird 5, 92.08% for Bird 6, 97.50% for Bird 7, and 80.83% for Bird 8. The mean discrimination accuracy of 85.21% here was higher than the mean level of accuracy achieved by the birds in Experiment 1 (70.89%), possibly because of the longer training period in Experiment 2.

Tests of generalization to COMP and SCR images. Two new slide trays (E and F) were prepared for the generalization tests in a manner identical to Experiment 1, except that two of each ORIG image were replaced with their corresponding COMP and SCR images. Because there were eight test items rather than four as in Experiment 1, the pigeons saw each test item only once on each test day. Generalization testing began the day after termination of training. Tests were conducted in four blocks of two daily test sessions,

with 2 days of refresher training on Trays A, B, C, and D between each 2 days of testing. Order of presentation of test trays, manner of reinforcement for test stimuli, correction trials, behavioral measure, and designated alpha level were identical to those of Experiment 1.

Results and Discussion

Table 4 presents the mean percentage of correct choice responses by each pigeon to the ORIG, COMP, and SCR versions of the PTLR images during the eight generalization tests. Table 5 displays the same generalization test data for each stimulus item averaged across the 4 pigeons. The pigeons' recognition of the ORIG stimulus items again generalized to the COMP versions. Accuracy to the COMPs was well above chance. However, all 4 pigeons discriminated the ORIG items more accurately than the COMP items. There was also a difference in discrimination accuracy between the COMP and the SCR figures. The COMP images were discriminated with greater accuracy than the SCR images by all 4 pigeons, a result more consistent with geons than with particulate features as the controlling factor in the pigeons' recognition of the object drawings; the COMP and SCR images contained the same line-segment features, but only the COMP images should have allowed geon activation, according to RBC theory.

A 3×4 (Type \times Stimulus) within-subjects ANOVA (types were ORIG, COMP, and SCR; stimulus items were PTLR) disclosed a significant effect of type, $F(2, 6) = 35.02$, $p < .001$, with the stimulus factor and interaction being nonsignificant. Follow-up tests showed a significant difference in accuracy between the ORIG and COMP images ($p < .05$, Neuman-Keuls); accuracy for the SCR figures was also significantly different from both the ORIG and COMP versions ($p < .01$, Neuman-Keuls).

Although the binomial tests indicated responding significantly above chance for two of the four scrambled figures (turtle, $p < .01$; lamp, $p < .05$), follow-ups to the ANOVA had indicated a reliable difference in accuracy for the SCR images in comparison with both the ORIG and COMP images. The overall response accuracy to the SCR figures was significantly lower than that for either the ORIG or the COMP figures (see Table 4). However, any amount of above-chance

Table 4
Correct Choice Responses (Mean Percentages) to Three Types of Images Across Eight Generalization Test Sessions in Experiment 2

Bird	Image		
	ORIG	COMP	SCR
5	69.80	62.50**	37.50*
6	94.27	90.63**	43.75*
7	92.19	59.38**	31.25*
8	80.21	65.63**	34.38*
<i>M</i>	84.11	69.53	36.72

Note. Binomial tests were only conducted on complement (COMP) and spatially scrambled (SCR) images for each of the 4 pigeons. ORIG = original.

* Nonsignificant.

* $p < .05$. ** $p < .01$, binomial test ($N = 32$).

Table 5
Correct Choice Responses (Mean Percentages) to Three Types of Images for Each Stimulus Object Across Eight Generalization Test Sessions Averaged Over the 4 Pigeons in Experiment 2

Object	Image		
	ORIG	COMP	SCR
Penguin	77.08	78.13**	37.50*
Turtle	92.18	65.63**	50.00**
Lamp	71.88	56.25**	43.75*
Rolling pin	95.31	78.13**	15.63*
<i>M</i>	84.11	69.53	36.72

Note. Binomial tests were only conducted on complement (COMP) and spatially scrambled (SCR) images for each of the four stimulus objects. ORIG = original.

* Nonsignificant.

* $p < .05$. ** $p < .01$, binomial test ($N = 32$).

responding to items that should not allow geon activation precluded an interpretation that geons are the only essential feature controlling pigeons' object recognition.

We constructed test figures for Experiment 3 using the line-segment features of the ORIG training images so as to preclude geon recovery according to RBC theory, to determine if presentation of test items composed of features identical to those given in training might produce accurate discrimination of the objects without geon activation. Two versions of the test images were constructed in which the amount of feature relocation was varied to allow consideration of the spatial position of features as a factor in discriminative control. The purpose of Experiment 3 was to consider further the relative contributions of geon recoverability and the presence of particulate local features to pigeons' object recognition.

Experiment 3

Method

Subjects

The 4 pigeons studied in Experiment 2 were also the subjects in Experiment 3. They were housed and maintained in the same manner as in Experiment 2.

Apparatus

The pigeons were trained and tested with the same apparatus used in Experiments 1 and 2.

Stimuli

The stimuli used in this experiment were black-and-white slides displaying the images shown in Figure 4. In the left column are the ORIG training stimuli, which were the same as those used in Experiments 1 and 2. Test figures are shown in the center (SCR1) and right (SCR2) columns. Both the SCR1 and SCR2 figures were constructed using the line segments from the ORIG training stimuli and configured so that the geons would not be recoverable. In the SCR1 figures, all of the line-segment features remained in their original quadrants;

in the SCR2 figures, half of the features remained in their original quadrants and the other half were moved to the adjacent (clockwise) quadrant. Each line segment in the SCR versions was displayed so that it was oriented at the same angle relative to the other line segments and to the top of the display as it was in the ORIG training stimuli.

Procedure

Training. On the day immediately following completion of the Experiment 2 tests, the pigeons were returned to baseline training on the ORIG (PTLR) stimuli for refresher training to ensure that the accuracy of responding to the ORIG stimuli approximated prior levels. Procedures were identical to those of Experiment 2. After 4 days of retraining, accuracy levels were 66.67% for Bird 5, 95.83% for Bird 6, 93.23% for Bird 7, and 75.00% for Bird 8. As accuracy remained close to previous baseline levels, we decided to proceed to the generalization tests.

Tests of generalization to SCR1 and SCR2 images. Two new slide trays (E and F) were prepared for the generalization tests in a manner identical to Experiment 2, except that two of each ORIG image were replaced with their corresponding SCR1 and SCR2 images. The pigeons saw each test item once on each test day. Generalization testing began the day after termination of retraining. Tests were conducted in four blocks of two daily test sessions with 2 days of refresher training on Trays A, B, C, and D between each 2 days of testing. Order of presentation of test trays, manner of reinforcement for test stimuli, correction trials, behavioral measure, and designated alpha level were identical to those in the two previous experiments.

Results and Discussion

Table 6 shows the mean percentage of correct choice responses by each pigeon to the original and the two scrambled versions of the PTLR images during the eight generalization tests. Table 7 displays the same generalization test data for each stimulus item averaged across the 4 pigeons. Although there was a decrement in responding to the SCR1 items compared to the ORIG versions, across stimuli, all 4 pigeons recognized the SCR1 items at above-chance levels; and, across pigeons, three of the four stimuli (penguin, turtle, and lamp)

Table 6
Correct Choice Responses (Mean Percentages) to Three Types of Images Across Eight Generalization Test Sessions in Experiment 3

Bird	Image		
	ORIG	SCR1	SCR2
5	67.19	53.13**	34.38 ^a
6	96.87	68.75**	56.25**
7	91.67	62.50**	43.75*
8	80.21	50.00**	34.38 ^a
<i>M</i>	83.99	58.59	42.19

Note. Binomial tests were only conducted on spatially scrambled (SCR) images for each of the 4 pigeons. In SCR1 figures, all line segment features remained in their original quadrants, and in SCR2 figures, half the features remained in their original quadrants and the other half were moved to the adjacent (clockwise) quadrant. ORIG = original.

^a Nonsignificant.

* $p < .05$. ** $p < .01$, binomial test ($N = 32$).

Table 7
Correct Choice Responses (Mean Percentages) to Three Types of Images for Each Stimulus Object Across Eight Generalization Test Sessions Averaged Over the 4 Pigeons in Experiment 3

Object	Image		
	ORIG	SCR1	SCR2
Penguin	81.25	68.75**	43.75*
Turtle	85.94	78.13**	59.37**
Lamp	71.36	50.00**	36.88 ^a
Rolling pin	97.40	37.50 ^a	18.75 ^a
<i>M</i>	83.99	58.59	42.19

Note. Binomial tests were only conducted on spatially scrambled (SCR) images for each of the four stimulus objects. In SCR1 figures, all line segment features remained in their original quadrants, and in SCR2 figures, half the features remained in their original quadrants and the other half were moved to the adjacent (clockwise) quadrant. ORIG = original.

^a Nonsignificant.

* $p < .05$. ** $p < .01$, binomial test ($N = 32$).

were recognized at above-chance levels. This pattern of data indicates some control over discrimination accuracy by particulate features in the absence of geon recoverability. There was a further reliable decrement in responding to the SCR2 items, indicating that relocation of particulate segments had a significant effect on recognition accuracy. Two of the SCR2 items were, however, still recognized at above-chance levels (penguin and turtle).

A 3×4 (Type \times Stimulus) within-subjects ANOVA (types were ORIG, SCR1, and SCR2; stimulus items were PTLR) showed a significant effect of type, $F(2, 6) = 95.04$, $p < .001$. The interaction of type and stimulus was also significant; however, simple-effects follow-up tests showed a significant effect of stimulus type for all four stimulus objects ($p < .01$ for turtle and lamp; $p < .05$ for mushroom and rolling pin). The stimulus factor was nonsignificant. Follow-up tests for the type factor showed that accuracy for the ORIG items was significantly greater than accuracy for either the SCR1 or SCR2 images ($p < .01$, Neuman-Keuls). The SCR1 stimuli were also recognized at a significantly higher level of accuracy than the SCR2 stimuli ($p < .01$, Neuman-Keuls). All 4 pigeons demonstrated a pattern of responding in which the ORIG images were discriminated more accurately than the SCR1 images and the SCR1 images were discriminated more accurately than the SCR2 images (see Table 6). Although response accuracy was significantly greater when geons were recoverable, some control of recognition by particulate features and their locations was also evidenced.

General Discussion

In three experiments, we trained pigeons to discriminate a set of partial figures that had half of the contour (edges and vertices) of the intact figures removed. The pigeons were then tested for generalization of recognition with figures that were composed of (a) the other half of the contour, with all of the geons composing the intact stimuli recoverable; (b) the other

half of the contour, with geons not recoverable because of the random relocation of the line-segment features; (c) the same contour as the training items, with edge and vertex features relocated within the same quadrant in which they had appeared in training and with geons nonrecoverable; or (d) the same contour as the training items, with half of the features relocated within the same quadrant and half relocated in the adjacent quadrant clockwise, and with geons nonrecoverable. We used these particular displays to attempt to identify and quantify the contributions of geon activation, particulate-feature identification, or both to the process of object recognition by pigeons.

Experiment 1 demonstrated that the 4 pigeons accurately recognized complementary test objects that afforded geon recovery, even though the test objects involved none of the identical edges and vertices in their original locations. This result is consistent with control over recognition by geons. However, discrimination accuracy was significantly different for the ORIG and COMP items, with more accurate responding to the ORIG items. This finding indicates some control over discriminative performance by the ORIG particulate features, because only the ORIG items contained the features presented in training.

Experiment 2 was, in part, a replication of Experiment 1 with 4 new pigeons. In addition, the results of generalization tests comparing the COMP and SCR figures indicated that, with the same line-segment features present in both types of test figures, those that presumably afforded geon recovery were much more likely to be recognized by the pigeons than those that did not. This result indicates that not all of the discriminative control could be attributed to local contour (lines and vertices in their original positions), as the same line-segment features were present in both versions of the test images.

Experiment 3 was a further attempt to isolate the contributions of geons and particulate features to the recognition process. Geons in both types of test figures (SCR1 and SCR2) were rendered nonrecoverable, whereas line-segment features were identical to those in the training items. Either all or only half of these edge and vertex features remained in the quadrant in which they were located in the ORIG (training) items. Discrimination accuracy was considerably higher for the ORIG images than for either the SCR1 or SCR2 figures. Because the ORIG, SCR1, and SCR2 images all contained the same line-segment features, but only the ORIG images should have allowed geon activation, this result again is consistent with geon recovery as an important factor controlling object recognition. Some support was also provided for particulate features as a factor in discriminative control, given the generally above-chance accuracy for the SCR1 images. However, this result was obtained for only three of the four objects (penguin, turtle, and lamp), and mean accuracy for the SCR1 images was not high (59%). The spatial location of particulate features also appeared to have some control over discriminative performance, as evidenced by the significant difference in recognition accuracy between the SCR1 and SCR2 figures.

Overall, the results of these experiments indicate that, although pigeons use both geons and local features in the

process of shape discrimination, the intact spatial organization of geons is more likely to produce accurate recognition than is the mere presence of particulate features. Although we did not undertake a statistical analysis of the difference in discrimination accuracy between the COMP images of Experiment 2 and the SCR1 images of Experiment 3 because the order of presentation of these items was not controlled (all pigeons were first exposed to the COMP images), it should be noted that accuracy for the COMP images with recoverable geons was generally higher (70%) than it was for the SCR1 images with nonrecoverable geons (59%). This result was obtained even though the SCR1 images were composed of edges and vertices that were identical to those of the training stimuli, whereas the COMP images contained nonidentical features. Recognition was thus supported to a greater extent by stimulus figures presumed to allow geon activation (without particulate features) than by the presence of local features (without geons). It seems unlikely that this result is due to presentation order, because the features of the ORIG stimuli were never presented in extinction before the generalization tests of Experiment 3. This difference in accuracy also seems unlikely to be the result of differential baseline accuracy, because discrimination of the training items during the generalization tests was very similar in Experiments 2 (84.11%) and 3 (83.99%), which involved the same subjects.

Finally, Heinemann and Chase (1990) proposed another explanation for visual pattern recognition by pigeons that does not involve object features or components. Heinemann and Chase's theory includes a treatment of learning (Heinemann, 1983a, 1983b) and of identification and categorization of unidimensional and multidimensional stimuli (Chase, 1983; Chase & Heinemann, 1989, 1991). However, only the part of the theory that pertains to the identification of simple visual stimuli is directly relevant to this article.

Outline drawings such as those used here are represented by points in two-dimensional space. Individual patterns differ only in the number of points and their spatial coordinates. The Heinemann-Chase model assumes that, following training, the subject's long-term memory contains multiple records of events that occurred on individual trials. Because pigeons view stimuli from different distances on different trials, the stored images of any given stimulus have a variety of different sizes. In addition, the stored images undergo stochastic distortion while they reside in long-term memory. Because experiences are imperfectly remembered, generalization is possible. Each record shows the sensation experienced during the trial, the response made, and the outcome (e.g., reward or nonreward).

According to the Heinemann-Chase theory, the response the subject makes on a given trial is determined as follows: The complex of sensations induced by the current visual stimulation (current input) is compared with that represented on each of a small number of records randomly retrieved from long-term memory. The only records that are used in the comparison process are those that show a response that was followed by reward. The objective of the comparisons is to find the remembered image that is most similar to the current input and then to make the response associated with that image.

Comparison of the current and remembered image involves superimposing the centroids of the images. The decision quantity, that is, the index of similarity on which the comparisons are based, considers the relation of each pixel of the current input to each pixel of the remembered image. During the comparison process, records that are clear mismatches are rejected. If the sample contains only such records, then a new sample is drawn.

In situations in which confusion among possible responses is minimal, computation is simplified by sorting the decision quantities obtained following each comparison into bins defined by the response label. The response made is the one for which the sum of the decision quantities is highest. A detailed treatment of this process is given by Heinemann and Chase (1990).

A simulation of the Heinemann-Chase model was applied to the stimulus items from the present Experiment 2. The simulation was run for 1,200 trials (100 trials for each of the 12 stimulus items) and generated the following predictions for mean percentage of correct choice responses: ORIG, 83.25; COMP, 73.25; and SCR, 43.25. Comparison of these predictions to the results of Experiment 2 shown in Table 5 indicates that the Heinemann-Chase model was able to predict accurately the pigeons' ordering of the mean percentage of correct responses for the three conditions.

Whatever its virtue in accounting for the pigeon discrimination performance, the Heinemann-Chase model would be inadequate as an account of human shape priming. Biederman and Cooper (1991a; 1992) and Biederman and Gerhardstein (in press) documented complete translational, reflectional, size, and rotation-in-depth invariance. In all cases, the difference between priming and primed images leads to changes in the centroids, sometimes dramatic ones. Yet, there is no reduction in the magnitude of priming unless the two images differ in their parts or part attributes.

Future experiments in which precise quantitative predictions can be made for both RBC theory and the Heinemann-Chase model will be necessary to compare the two models adequately. Hummel and Biederman (1992) recently proposed a neural-network model of RBC theory that should be able to provide these quantitative predictions for RBC theory.

Concluding Comments

The results of these experiments are consistent with the proposal that the recoverability of component geons is an important factor in object recognition by pigeons. Particulate object features also exerted measurable control over the pigeons' discriminative performance. Although the experimental task required of the pigeons is necessarily different from that required of human subjects—pecking a specific key associated with a particular well-studied image versus naming novel images of familiar object categories by humans—the priming of object naming in humans has shown that all of the visual priming can be attributed to a representation of the object's parts and none can be attributed to the particulate features or semantic object concepts. (Biederman & Cooper, 1991b). This experimental finding makes the assumption that similar processes are involved in both species more plausible.

Another difference between the Biederman and Cooper (1991b) object-naming tasks used with humans and the pigeons' task in the present experiments is that the humans saw novel stimulus items for only a fraction of a second and were instructed to respond as quickly as possible. The very short exposure and response times, as well as the large and poorly defined stimulus set from which the novel items were drawn, necessitated that the subjects classify the stimulus objects. The procedure did not allow the use of a local-feature strategy. In contrast, the pigeons in the present experiments were given extensive training on a small set of stimuli. This prolonged exposure provided much greater opportunity for the pigeons to discover and use particulate features—and, hence, the centroids of these features—in their discriminative responding. These procedural differences might explain the measurable control over the pigeons' discrimination that was exerted by particulate features and the correlation with the centroid values.

Further work is clearly needed to elucidate how and to what degree RBC participates in the object recognition of pigeons and people. As one instance, the present experiments did not address the important prediction of RBC theory that the presence of the original global spatial arrangement of geons is a necessary factor in object recognition. All generalization test items with recoverable geons were constructed with those geons arranged spatially in a manner identical to that of the training versions of the object. Further experiments in which the spatial organization of intact geons is varied during generalization testing should be useful in providing a more complete determination of the contribution of global, relational properties to the control of object recognition.

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