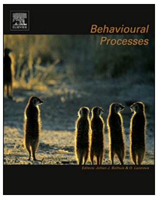
Behavioural Processes 158 (2019) 70–76

Contents lists available at ScienceDirect

Behavioural Processes

journal homepage: www.elsevier.com/locate/behavproc



Pigeons spontaneously form three-dimensional shape categories☆

Jessie J. Peissig[a,*], Michael E. Young[b], Edward A. Wasserman[c], Irving Biederman[d]

[a] *Department of Psychology, California State University Fullerton, P.O. Box 6846, Fullerton, CA 92834, United States*
[b] *Department of Psychological Sciences, Kansas State University, United States*
[c] *Department of Psychological and Brain Sciences, University of Iowa, United States*
[d] *Department of Psychology and Program in Neuroscience, University of Southern California, United States*

ARTICLE INFO

Keywords:
Pigeons
Object recognition
Visual perception
Categorization
Pseudocategory

ABSTRACT

We explored the pigeon's representation of the shape of simple three-dimensional objects (geons) rotated in depth (four views each of four geons). Pigeons assigned to the Categorization group had to respond differentially to images of four different geons—termed arch, barrel, brick, and wedge—based on their 3D shape, regardless of the orientation of the object. Pigeons assigned to the Pseudocategorization group had to respond differentially to the same objects based on groupings that did not correspond to object identity, which required the learning of local orientation-dependent features (e.g., a concave curve on top, or the position of an illumination hotspot). The Categorization group, which could employ object-identity representations, quickly achieved highly accurate responding. The Pseudocategorization group, however, failed to achieve reliable above-chance responding. In addition, the reaction times for the Categorization group were significantly shorter than for the Pseudocategorization group. These results indicate that pigeons show a strong, spontaneous tendency to categorize the shapes of different orientations in depth of the same 3D object as similar, if not equivalent; they do so despite the vast differences in image characteristics caused by the variations in orientations, even when such categorization is contrary to the reinforcement contingencies.

1. Introduction

A three-dimensional object of even moderate complexity can project a near infinity of images when we consider the variations that are produced by changes in orientation, scale, and lighting direction. Humans' accuracy in classifying an object, as when it is named, is only minimally improved, if at all, by the addition of color and surface texture (Biederman and Ju, 1988). Moreover, the speed and accuracy of object identification or matching is only minimally affected by rotation around the vertical axis as long as the same part structure is present in the image (e.g., Biederman and Gerhardstein, 1993). These findings for human participants suggest that recognition heavily weights those aspects of shape that are invariant (or "nonaccidental") with orientation in depth, such as whether a contour is straight or curved, or whether pairs of contours are parallel or not (Biederman, 1987).

Nonverbal observers perform visual object recognition when they choose to approach one object, e.g., a token that they can exchange for food, versus another, a token that cannot be so traded (Wolf, 1936). This differential behavior is a clear indication that a visual stimulus has been recognized as a member of a class (e.g., exchangeable or not for an edible morsel). Researchers studying object recognition in nonverbal species can assign different responses to different stimuli to determine if their subjects will respond in a consistent way to one object rather than another (Jitsumori and Delius, 2001; Wood and Wood, 2017).

In previous object recognition research involving pigeons, scientists have examined generalization across viewpoint (Peissig et al., 2002; Spetch and Friedman, 2003), lighting (Young et al., 2001), size (Delius, 1992; Peissig et al., 2006), and mild deformations (Cerella, 1979; Delius, 1992; Herrnstein and Loveland, 1964), inter alia. To determine whether the same object is responded to independently of variations in its orientation, the most common approach is to train a subject to make the same response to multiple views of the same object. For example, Peissig et al. (2000a) trained pigeons to choose the upper left key when the stimulus was a barrel, the upper right key when the stimulus was an arch, etc. Each object type, or geon (Biederman, 1987), was presented at one of five viewpoints by rotating the geon in depth. If the stimuli corresponding to different objects are sufficiently distinct, then subjects should readily learn to respond differentially to the stimuli.

☆ These data were included in the doctoral dissertation of Jessie J. Peissig at The University of Iowa. This research was supported by a National Institute of Mental Health Grant, MH 47313. We would like to thank C. Antes, T. Barclay, M. Prier, and B. J. Terrones for their assistance in collecting and analyzing these data.

* Corresponding author.
E-mail address: jpeissig@fullerton.edu (J.J. Peissig).

https://doi.org/10.1016/j.beproc.2018.11.003
Received 6 July 2018; Received in revised form 7 November 2018; Accepted 9 November 2018

Furthermore, if a new orientation of an object is encountered, then subjects should choose the response that was paired with the trained exemplars of the same object.

This many-to-one choice task assesses whether a subject can respond in the same way to one collection of stimuli and in a different way to other collections of stimuli. Presumably, the ability to do so is facilitated by subjects identifying something in common among the various stimuli representing the same object—a generalized object representation. The generalization to novel exemplars supports this conclusion, although it is possible that this behavior is based on the similarity of a novel object to only one of the exemplars (Tarr, 1995).

To assess the relative similarity of multiple exemplars of objects, a go/no-go task has been used, in which responding to one exemplar of one object is reinforced (the S+), whereas responding to other exemplars of that same object or to exemplars of different objects are not reinforced (the S-s). This task allows the researcher to determine the relative similarity of stimuli in the absence of any explicit training designed to create a generalized class of objects (as occurs in the many-to-one choice task). Peissig et al. (2000b) explored object recognition in pigeons using this go/no-go paradigm, in which one view of a target object served as the S+ and nine views (created by rotating the objects in depth by 36° increments) of the same object were S-s; in addition to the target object, pigeons were shown 10 views of a foil object for which all views were S-s. Pigeons made significantly fewer errors (pecks to an S−) to nonreinforced views of the foil object than to nonreinforced views of the target object. These data suggest that pigeons do indeed perceive different views of the same object as more similar to one another than to views of different objects.

The present project re-examined the issue of object recognition in the pigeon to assess a related issue from a fresh perspective. We used a task designed to determine whether any arbitrary collection of stimuli of the kind used in previous studies can be grouped together in the creation of a new object category (cf. Wasserman et al., 1988). Given that previous object recognition research in the pigeon has involved training with a relatively small number of exemplars of each object (usually fewer than 20, e.g., Delius and Hollard, 1995; Peissig et al., 2000a,b; Spetch and Friedman, 2003; Wasserman et al., 1996), it is possible that the pigeons were simply memorizing the correct response to each stimulus. If so, then the ability to generalize discriminative responding to novel exemplars could have been driven by the greater similarity of these stimuli to one or more of the trained exemplars (although the pigeon's generalization to novel views created by rotating an object along an *orthogonal* axis undermines this argument, Peissig et al., 2002).

We determined the extent to which pigeons would group exemplars of different objects into the same category when such categorization was reinforced as a basis of comparison for the extent to which different views of the same object would be grouped to form a natural category for pigeons. Although the earlier work documenting greater similarity among different views of the same object suggests that it should be quite easy for the pigeon to group together different viewpoints of the same object, it is still possible that this category coherence may produce only a small improvement in performance.

Pigeons have occasionally been reported to have difficulty learning categories for artificial stimuli. For example, Cerella (1980) found that pigeons struggled to learn to categorize different images of Charlie Brown. However, Herrnstein and de Villiers (1980) had no trouble teaching pigeons to categorize images of fish. The objects used in the present study are two-dimensional images of three-dimensional objects. They include shading and surface reflectance, but it is uncertain whether pigeons perceive these stimuli as more like natural images or artificial images. If we are to feel confident that previous studies using the same or similar stimuli involve the use of normal object recognition mechanisms, we need to be assured that these objects are treated similarly to other natural categories. In addition, we have ample evidence that humans easily recognize that different views of the same object belong together (e.g., Biederman and Gerhardstein, 1993). If pigeons possess visual recognition mechanisms similar to those of humans, then it is important to see that they too exhibit the same perceptual proclivities.

In this study, we employed the category-pseudocategory technique previously used by Wasserman et al. (1988) to test whether the groupings of different views of the same object (a geon) would be learned reliably faster than groupings of different views of different objects (i.e., different geons). The method of using pseudocategories to test perceptual coherence has a long history in the field of animal cognition. To our knowledge, this method was first used by Herrnstein and de Villiers (1980), who explored whether pigeons learned to discriminate between images that contained a fish and those that did not. This group was compared to a group that Herrnstein and de Villiers called a "quasi-category" group, in which the same two sets images (fish and non-fish) were randomly assigned to reinforced and nonreinforced clusters. They found that pigeons learned the quasi-categories much more slowly than they learned the natural categories (images with fish and images without fish).

Numerous other researchers have also used pseudocategories to study concept formation in nonhuman animals, and this methodology continues to be useful in understanding the nature of categorization in nonhuman animals (Cook, 2002; Ditrich et al., 1998; Roach et al., 2017; Sturdy et al., 1999a,b; Wright et al., 2017). According to Lea and Ryan (1990), there are two possible ways of implementing pseudocategories: random and perverse. In random pseudocategories, the categories are created in a truly random fashion; thus two items from the same category could end up randomly assigned together. In perverse pseudocategory assignment, the groupings are formed such that items from the same category are explicitly assigned to different groupings.

In two different studies, Vaughan and Greene (1983, 1984) used random groupings to study concept formation in pigeons. They found that pigeons were able to successfully learn these random group assignments. In another study using pseudocategories, Sturdy et al. (1999a,b) tested whether distinct song note categories of zebra finch songs (as determined by a song note classification scheme developed by Sturdy et al., 1999a,b) would be relevant to zebra finches. To test this possibility, they selected four-note song subcategories to use to test zebra finches in a discrimination task, with 20 sample notes in each category. In the categorization group, one of the song note categories was assigned as the S+ and the remaining three categories were assigned as the S-s. In the pseudocategory group, the S+ group consisted of 20 randomly selected notes, and the remaining 60 notes were the S-s. The random assignment led to nearly equal distribution of the four-note categories across the S+ and S− groups. Sturdy et al. found that the birds in the pseudocategory condition learned the discrimination 36% more slowly than the birds in the categorization condition.

In studies in which perverse groupings are assigned (e.g., Wasserman et al., 1988 and the current study), the stimuli were grouped so that different orientations of the same geon were assigned to different responses; this grouping can be done either by systematically or by randomly assigning stimuli to different groups using a rule that assures that the different categories are equally represented in each group. In Wasserman, Kiedinger, and Bhatt, the categorization group was given assignments of the four visual categories to different responses, e.g., all cars were assigned to the upper right button, all the cats to the upper left button, all the chairs to lower right button, and all the flowers to the lower left button. In the pseudocategorization group, the stimuli were intentionally assigned so that the visual categories would cut across the button assignments. For example, the upper right key would have assigned to it an equal number of cars, cats, chairs, and flowers. The categorization group learned far faster and to much higher levels of accuracy than did the pseudocategorization group.

In many ways, the randomly assigned categories often function similarly to the perverse categories (e.g., those in which examplars are explicitly assigned to different responses), in that what we presume to be natural category boundaries are violated by the assignment of members of the same category to these two different response groups. Doing so allows us to test whether the animals behave according to the category boundaries, as defined by the experimenter, or if they treat all of the stimuli as perceptually independent of one another.

In general, virtually all of the studies have found that animals experience much great difficulty learning the pseudocategories than the "true" categories (Cook, 2002; Ditrich et al., 1998; Roach et al., 2017; Sturdy et al., 1999a,b; Wright et al., 2017). This finding suggests that the nonhuman animals that were assigned to the true category groups indeed abided by the perceptual boundaries established by the human experimenters; working against these perceptual categories must have made the task exceedingly difficult for the nonhuman animals assigned to the pseudocategorization groups.

In most studies using pigeons as research participants, including our own, experimenters have assumed that the pigeons perceived different views of an object as all deriving from a single object, similar to how they would treat different views from any natural object category. It is possible, however, that when pigeons view stimuli one at a time on a computer monitor, the stimuli may appear distinctly different from one another. If pigeons can rapidly learn to group together an arbitrary collection of views of different objects, then at least part of the learning of a more natural grouping of different views of the same object could merely be a byproduct of learning simple associations between each individual stimulus and its correct response. By comparing the rate of learning categories when the constituent stimuli are grouped according to object object identity to that when the stimuli are grouped arbitrarily, we were able to assess both the learnability of such arbitrary groupings and the degree of advantage that holds when the stimuli represent different views of the same object.

1.1. *The present study*

In the present study, we taught pigeons to peck four different buttons to each of four different collections of computer renderings of four different geons each at four different orientations. The entire set of 16 drawings involved four depth-rotated views of each of four discriminatively different objects: an arch, a barrel, a brick, and a wedge (see Fig. 1). These objects were chosen from the larger set of 36 basic object components, or geons, described by Biederman (1987). One group of pigeons (the Categorization group) was trained to peck the same button to the four different views of the same geon, whereas the second group of pigeons (the Pseudocategorization group) was trained to peck the same button to one view of each of the four different geons. If pigeons perceive the related nature of different views of the same geon, then the first task should be far easier to master because each of these different views of the same geon is associated with the same response; for example, the pigeon would only have to learn to peck the upper left button whenever it saw the barrel-shaped object at any orientation. Looked at in a different way, if pigeons perceive the related nature of different views of the same geon, then the second task should be far more difficult to master because each of these different views of the same geon is associated with different responses; here, for example, the birds should be quite confused as to which button is the correct one to peck to the particular view of the barrel-shaped object they happen to be viewing on that trial.

Of course, if the pigeons see all of the 16 drawings as equivalently similar to one another, then both groups of pigeons should learn their respective discriminations at the same speed. Whether this equivalent learning would be fast or slow would depend on the relative uniqueness of the stimuli. Given that the stimuli used in the present study were of a similar size, color, and shading, they may have been too similar to support rapid discrimination of all 16 stimuli, so we gave the pigeons an extended period (45 days) of training.

2. Materials and method

2.1. *Subjects*

The participants were eight feral pigeons maintained at 85% of their free feed weights by controlled daily feeding. The pigeons were obtained from the Office of Animal Resources at The University of Iowa. This office abides by all federal regulations for procurement, housing, and care of animals on the campus. The protocol for this study was approved by the Institutional Animal Care and Use Committee of The University of Iowa. The pigeons had previously participated in unrelated visual perception studies. The sex of the pigeons was unknown. The pigeons were kept on a 14-h/10-h, light/dark schedule and were given free access to water and grit throughout the experiment.

2.2. *Apparatus*

The pigeons were trained in four specially-constructed plywood chambers. One side of each chamber consisted of a large opening with an aluminum frame attached to the outside; inside the frame was a clear touchscreen (Accutouch Model #002744-FTM-K1; Elographics, Oak Ridge, TN) that was coated with mylar for durability. These touchscreens used resistive technology to detect pecks. The pigeons' pecks to the touchscreen were processed by a serial controller board (Model #E271-2210, Elographics). A brushed aluminum panel was placed directly in front of the screen to allow birds access to limited portions of the video monitor. There were five openings in the aluminum panel: the center opening was a 7.0 cm × 7.0 cm square opening in which the visual stimuli appeared and the remaining four openings were circular, 1.9 cm in diameter, and were located 2.3 cm from each corner of the center display opening. The four corner openings served as report buttons. In the rear of the chamber, a clear Plexiglas food cup was placed level with a wire mesh floor to prevent the pigeons from perching on the food cup. Noyes 45-mg pigeon pellets were delivered through a vinyl tube into the food cup using a rotary pellet dispenser (Model #ENV-203M; MED Associates, Lafayette, IN). During experimental sessions, constant illumination was provided by a 2-watt bulb mounted on the upper rear wall of the chamber. A digital I/O interface board (National Instruments Model #NB-DIO-24, Austin, TX) controlled the pellet dispenser and the houselight.

Control of peripheral stimuli (via the I/O interface) and recording of pigeons' responses (via the serial controller board) were accomplished by four Apple Macintosh 7100/66 Power PC computers. The pigeon's monitor and an identical monitor located in an adjacent room were connected by a distribution amplifier (Model #MAC/2 DA2; Extron Electronic, Santa Fe Springs, CA). The programs were developed in Hypercard 2.3.

2.3. *Stimulus materials*

The geon stimuli were an arch, a barrel, a brick, and a wedge that varied from one another by a variety of nonaccidental properties (Biederman, 1987). The geons were rotated in depth by 90° intervals to yield four different views of each geon (see Fig. 1). The four objects were rotated in a similar manner using Raydream Designer 4.0 to yield similarly oriented depth rotations across the four objects. The stimuli ranged from 2 to 4 cm in width and from 2 to 4 cm in height; they were rendered at a resolution of 300 dots per inch (dpi).

2.4. *Procedure*

At the beginning of a trial, the center display area was illuminated with a black cross centered on a white background. A single peck anywhere within that area displayed a single-geon stimulus in the center. The pigeons were required to peck the center screen a fixed number of times; the required number of pecks was individually

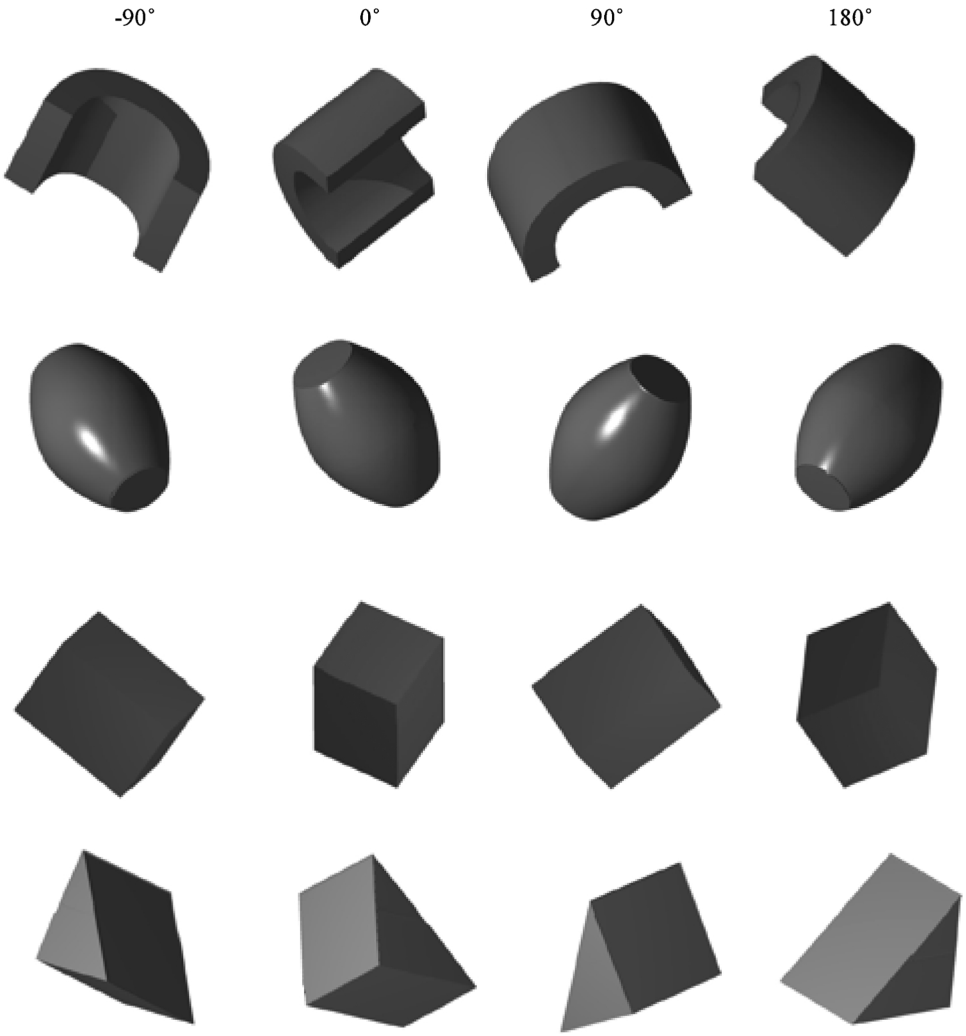


Fig. 1. The four views of the arch, the barrel, the brick, and the wedge geons that served as training stimuli, shown at 90° intervals.

adjusted for each bird, depending on its level of performance. Completing the final peck illuminated the four corner report buttons. After a correct choice, the stimulus was removed from the display area, the report buttons were darkened, and a food pellet reinforcer was delivered. After an incorrect choice, the stimulus was turned off for 1 s, the report buttons were darkened, and the houselight was turned off from 4 to 6 s ($M = 5$ s). The pigeon then proceeded through one or more correction trials, repeating the incorrect trial until a correct choice was made (there was no upper to limit to the number of correction trials, but the pigeons quickly learned a response switch strategy). Only the first response was recorded and used for analysis; correction trials were *not* recorded or scored for analysis. Intertrial intervals ranged from 6 to 10 s ($M = 8$ s).

The pigeons were randomly assigned to one of two groups, with four pigeons in each. For this procedure, each object "view" refers to a different 90° orientation in depth. In the Categorization group, all four views of an object were associated with the same button response (the rows in Fig. 1). For example, the 0°, 90°, 180°, and 270° views of the arch were associated with the upper left button for one bird. The assignment of correct response buttons to the four different geons was counterbalanced across birds using a Latin-square design. In the Pseudocategorization group, one view of each object was randomly assigned to the same button response. For example, the 0° view of the brick, the 90° view of wedge, the 180° view of the arch, and the 270° view of the barrel were associated with the upper left button for one bird. The assignment of combinations of four views to a single response was made using a partial counterbalancing across birds, with the restriction that each combination included one of each of the four rotations (0°, 90°, 180°, and 270°) and one of each of the four geons (arch, barrel, brick, and wedge). The assignment of correct response buttons was made so that each object view was associated with at least two different response buttons across birds. Table 1 shows the stimulus and report button assignments for each bird in the Pseudocategorization group.

The experimental training procedure used a randomized block design. Each block comprised two presentations of each of the four views of the four objects, for a total of 32 trials. Daily sessions comprised five blocks for a total of 160 trials. The pigeons in each group completed a total of 45 daily sessions.

3. Results

Two pigeons in the Pseudocategorization group failed to complete all 160 trials every day. Bird 87Y did not complete 2 of its sessions (it finished 133 and 143 trials on these days). Another pigeon, 55Y, did not complete 12 of its 45 sessions with 84 as the fewest number of trials completed. To minimize differential attrition, all of the data were analyzed. The statistical approach used, multilevel modeling using likelihood maximization, appropriately weights the imbalance produced by such incomplete data.

The pigeons in the Categorization group achieved a much higher level of accuracy over the 45 daily sessions (72% correct overall) than the pigeons in the Pseudocategorization group (whose 28% correct

Table 1
The Response Button Assignments for Pigeons in the Pseudocategorization Group.

Bird	Response Buttons			
	Button 1	Button 2	Button 3	Button 4
87Y	Arch 0°	Arch 90°	Arch 180°	Arch −90°
	Barrel 180°	Barrel −90°	Barrel 0°	Barrel 90°
	Brick 90°	Brick 180°	Brick −90°	Brick 0°
	Wedge −90°	Wedge 0°	Wedge 90°	Wedge 180°
11Y	Arch 0°	Arch 90°	Arch 180°	Arch 180°
	Barrel 90°	Barrel 180°	Barrel −90°	Barrel 90°
	Brick −90°	Brick 0°	Brick 90°	Brick 0°
	Wedge 180°	Wedge −90°	Wedge 0°	Wedge −90°
73W	Arch 90°	Arch −90°	Arch 0°	Arch 180°
	Barrel 0°	Barrel 180°	Barrel −90°	Barrel 90°
	Brick −90°	Brick 90°	Brick 180°	Brick 0°
	Wedge 180°	Wedge 0°	Wedge 90°	Wedge −90°
2W	Arch 90°	Arch −90°	Arch 0°	Arch −90°
	Barrel −90°	Barrel 0°	Barrel 180°	Barrel 0°
	Brick 180°	Brick 90°	Brick −90°	Brick 180°
	Wedge 0°	Wedge 180°	Wedge 90°	Wedge 90°

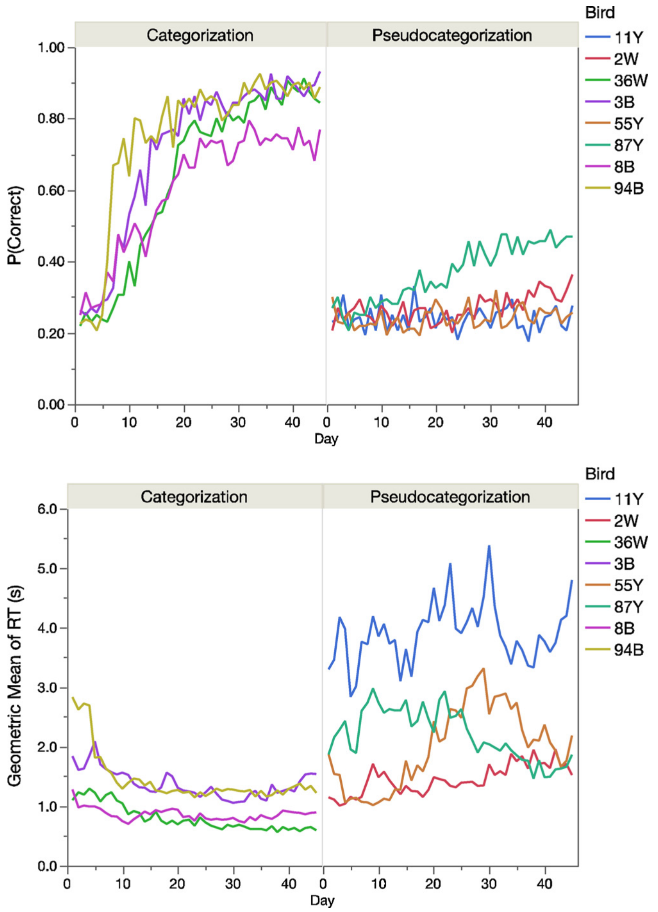


Fig. 2. The choice accuracy and reaction times for individual pigeons in the Categorization and Pseudocategorization groups across the 45 days of the experiment.

responding was barely above the 25% chance level). Marked learning was evident by all four birds in the Categorization group and only modest improvement by one bird in the Pseudocategorization group. The top of Fig. 2 shows the choice accuracies of both groups over training. For greater detail, the supplemental material provides a graphical depiction of the response pattern for each category and the results of a hierarchical cluster analysis of the specific response patterns produced by each stimulus.

To confirm these initial observations, we analyzed the choice accuracies using a full-factorial multilevel logistic regression of Group (Categorization vs. Pseudocategorization) and Day (treated as a continuous factor); both factors were centered for the analysis. The main effect of Group was significant [$z = 9.09$, $p < 0.001$], indicating that birds in the Categorization group attained a higher overall level of accuracy than birds in the Pseudocategorization group (which was not significantly above chance, $z = 0.91$). The main effect of day was also significant [*slope* = 0.042 increase in log odds per day, 95% CI = [0.033, 0.051], $z = 9.35$, $p < 0.001$], indicating that accuracy increased over days. These main effects were qualified by a significant Group × Day interaction [*slope difference* = .066 difference in logs odds per day, $z = 7.30$, $p < 0.001$]; the Categorization group produced an estimated slope of 0.075 log odds per day (95% CI = [0.063, 0.088]), whereas the Pseudocategorization group produced an estimated slope of only 0.009 log odds per day (95% CI = [−0.003, 0.022]), suggesting robust learning in the former group and little learning in the latter group.

In short, pigeons in the Categorization group learned significantly faster and to much higher final levels of accuracy than pigeons in the Pseudocategorization group. The Pseudocategorization group showed very little evidence of any learning over the 45 days of training (see Fig. 2). These results provide strong evidence that pigeons perceive greater similarity among different views of the same geon than they do among randomly chosen views of different geons.

We also examined how long it took the pigeons on individual trials to categorize each object. These reaction times were taken from all of the choice trials (examination of *RT*s from correct trials yielded highly similar results). The bottom of Fig. 2 reveals that pigeons in the Categorization group responded much more quickly than did those in the Pseudocategorization group. This observation was confirmed by a full-factorial multilevel gamma regression of Group (Categorization vs. Pseudocategorization) and Day (treated as a continuous factor) as predictors of reaction time in seconds using a log link function. The main effect of group was significant [$t(6) = -3.50$, $p < .001$] with the Categorization group making much faster decisions ($RT = 1.2$ s, CI = [0.9, 1.6]) than the Pseudocategorization group ($RT = 2.6$ s, CI = [1.9, 3.5]), but the main effect of day was not [$t(6) = 0.64$, $p = 0.638$]. These main effects are also qualified by a significant Group × Day interaction [$t(6) = 2.58$, $p = 0.001$]; the Categorization group produced a downward trend in their reaction times across sessions (*slope* = -.009 log seconds per day, 95% CI = [−0.017, −0.001]), whereas the Pseudocategorization group produced an upward trend in their reaction times across sessions (*slope* = 0.006 log seconds per day, 95% CI = [−0.002, 0.014]).

4. Discussion

The purpose of this study was to use the categorization-pseudocategorization method for assessing the extent to which the pigeon would spontaneously represent the underlying 3D shape of an object, in this case a geon. This representation allowed fast and accurate responding when the four different views of a geon were assigned to the same response, consistent with the underlying representation. In contrast, the Pseudocategorization group barely, if at all, learned the stimulus-response assignments, suggesting that the proclivity to respond to the same key for the four images of the same geon severely interfered with the learning of the arbitrary groupings, despite the support of the reinforcement contingencies. Whether there was actual interference with the Pseudocategorization condition would require comparison of that condition with a condition with 16 different objects, four of which were arbitrarily assigned to each key. The prediction would be that performance of such a group would be intermediate between the Categorization and Pseudocategorization groups in that they would show none of the facilitation from having a common representation

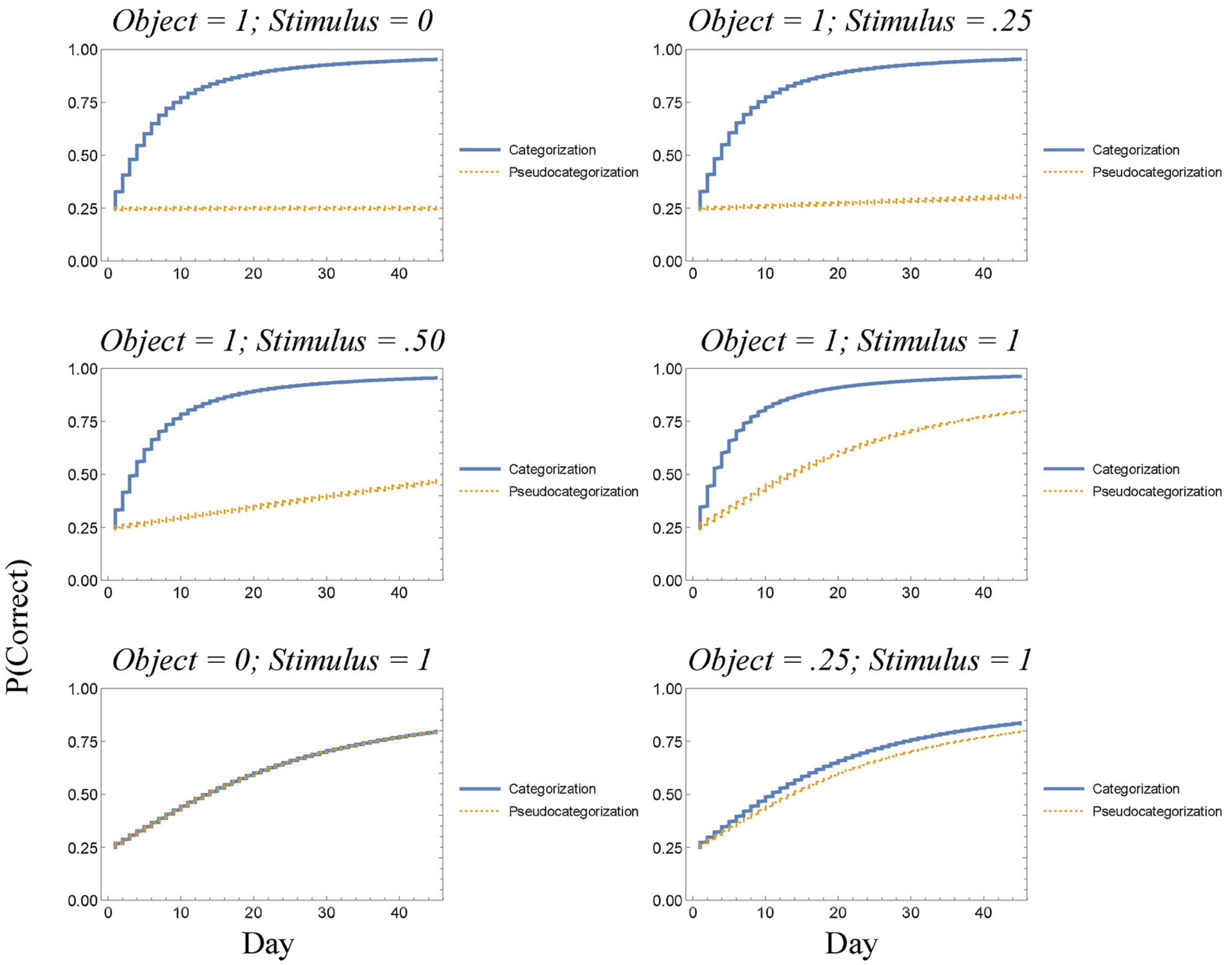


Fig. 3. Simulated accuracy for the Categorization and Pseudocategorization tasks under various assumptions regarding the relative salience of object-specific and stimulus-specific features.

assigned to each response (as in the Categorization group), but suffer none of the interference when the same underlying representation were assigned to different responses (as in the Pseudocategorization group).

4.1. Simulations of learning in categorization and Pseudocategorization tasks

To better understand the relative impact of each drawing's stimulus-specific features versus those shared by different views of the same object, we conducted a set of simulations of the learning process in the Categorization and Pseudocategorization tasks. We created vectors representing each stimulus that comprised 20 features, one for each of the 16 stimuli (the stimulus-specific features) and one for each of the 4 objects (the object-specific features)—(see Soto and Wasserman, 2010 for a more fully developed theory of category learning involving stimulus-specific and category-specific elements). The vector for each of the 16 stimuli contained a "1" for exactly one of the 16 stimulus-specific features and a "1" for one of the four object-specific features depending on its object identity; all other vector values were "0." Thus, two views of the same object shared one feature, whereas any views of different objects shared no features. Although we could also have modeled a set of features that were shared among all of the stimuli (e.g., size and shading), doing so would not change the ordinal results of the simulations. Furthermore, each stimulus is composed of a complex set of features such that each stimulus has differential similarity to one another, but the effect of this differential similarity will produce small metric variations on the simulations presented here.

To examine the predicted accuracy for various situations, we changed the relative salience of the stimulus-specific and object-specific features by multiplying each set of features by a different constant. In the upper left panel of Fig. 3, each feature vector only comprised object-specific features; the stimulus-specific features received a weight of zero. Thus, each view of the same object was assumed to be identical and thus indistinguishable from one another. Under this unrealistic assumption, it is not surprising that the Categorization task would be easily learned, whereas accuracy on the Pseudocategorization task would be at chance. In the upper right panel, the salience of the stimulus-specific features is modeled to be one-fourth as strong as the object-specific features; this situation predicted very slow learning of the Pseudocategorization task. Although not obvious, the Categorization task was also learned slightly faster in the presence of stimulus-specific features. As the relative salience of the stimulus-specific features increased to match that of the object-specific features (second row of Fig. 3), there was more rapid learning of the Pseudocategorization task, but learning always lagged behind that of the Categorization task.

The bottom row of Fig. 3 reveals that only when the object features were given zero weight was learning of the Categorization and Pseudocategorization tasks comparable. Even a slightly higher degree of similarity among different views of the same object produced a benefit for the Categorization task (lower right panel). A comparison between the results of this set of six simulations and the data observed in the present experiment (Fig. 2) suggests that the features specific to each stimulus had much lower relative salience than those features shared among views of the same geon.

4.2. Conclusions

The results of the current experiment and the accompanying simulations clearly revealed that when assigning multiple objects with different shapes to different response categories, the pigeon's dominant response is to abstract out the underlying, view-invariant shape of the objects (geons in the present case). This response tendency ignores all non-shape and "appearance" information, such as that produced by variations in the orientation of the object and the particular pattern of illumination hotspots that vary with the orientation of the geon. Although pigeons may be capable of forming arbitrary groupings of stimuli, when the groupings do not conform to the strong inclination of the pigeon to appreciate the underlying 3D shape of the objects, then arbitrary stimulus-to-response mappings will be difficult, if not impossible, to learn.

The data presented in this study have provided additional evidence of the robustness of previously published results showing that pigeons are readily able to generalize based on object shape, even in the face of large variations in the orientation of the object (Peissig et al., 2000a, 2002; Wasserman et al., 1996). Despite the variations in orientation generating marked differences in the surface appearance of the objects—such as the position of straight vs. curved contours and convex vs. concave regions of the objects—pitting these variations in competition with the underlying 3D representation of the objects appears to be extraordinarily difficult for the pigeon to resolve.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.beproc.2018.11.003.

References

Biederman, I., 1987. Recognition-by-components: a theory of human image understanding. Psychol. Rev. 94, 115–147. https://doi.org/10.1037/0033-295X.94.2.115.

Biederman, Gerhardstein, 1993. Recognizing depth-rotated objects: evidence and conditions for three-dimensional viewpoint invariance. J. Exp. Psychol. Hum. Percept. Perform. 19 (6), 1162–1182. https://doi.org/10.1037/0096-1523.19.6.1162.

Biederman, I., Ju, G., 1988. Surface vs. edge-based determinants of visual recognition. Cogn. Psychol. 20, 38–64. https://doi.org/10.1016/0010-0285(88)90024-2.

Cerella, J., 1979. Visual classes and natural categories in the pigeon. J. Exp. Psychol. Hum. Percept. Perform. 5, 68–77. https://doi.org/10.1037/0096-1523.5.1.68.

Cerella, J., 1980. The pigeon's analysis of pictures. Pattern Recognit. 12 (1), 1–6. https://doi.org/10.1016/0031-3203(80)90048-5.

Cook, R.G., 2002. The structure of pigeon multiple-class same-different learning. J. Exp. Anal. Behav. 78 (3), 345–364. https://doi.org/10.1901/jeab.2002.78-345.

Delius, J.D., 1992. Categorical discrimination of objects and pictures by pigeons. Anim. Learn. Behav. 20, 301–311. https://doi.org/10.3758/BF03213385.

Delius, J.D., Hollard, V.D., 1995. Orientation invariant pattern recognition by pigeons (*Columba livia*) and Humans (*Homo sapients*). J. Comp. Psychol. 109 (3), 278–290. https://doi.org/10.1037/0735-7036.109.3.278.

Ditrich, W.H., Lea, S.G., Barrett, J., Gurr, P.R., 1998. Categorization of natural movements by pigeons: visual concept discrimination and biological motion. J. Exp. Anal. Behav. 70 (3), 281–299. https://doi.org/10.1901/jeab.1998.70-281.

Herrnstein, R.J., de Villiers, P.A., 1980. Fish as a natural category for people and pigeons. In: In: Bower, G. (Ed.), Psychology of Learning and Motivation Vol. 14. Academic Press, Inc., New York, NY, US, pp. 60–94.

Herrnstein, R.J., Loveland, D.H., 1964. Complex visual concept in the pigeon. Science 146, 549–551. https://doi.org/10.1126/science.146.3643.549.

Jitsumori, M., Delius, J., 2001. Object recognition and object categorization in animals. In: Matsuzawa, T. (Ed.), Primate Origins of Human Cognition and Behavior. Springer Publishing Company, Tokyo, Japan, pp. 269–292. https://doi.org/10.1007/978-4-431-09423-4_13.

Lea, S.E.G., Ryan, C.M.E., 1990. Unnatural concepts and the theory of concept discrimination in birds. In: Commons, M.L., Herrnstein, R.J., Kosslyn, S.M., Mumford, D.B. (Eds.), Quantitative Analyses of Behavior. Vol. 8. Behavioral Approaches to Pattern Recognition and Concept Formation. Lawrence Erlbaum Associates, Inc., Hillsdale, NJ, US, pp. 165–185.

Peissig, J.J., Young, M.E., Wasserman, E.A., Biederman, I., 2000a. Seeing things from a different angle: the pigeon's discrimination of single geons rotated in depth. J. Exp. Psychol. Anim. Behav. Process. 26, 115–132. https://doi.org/10.1037/W097-7403.26.2.115.

Peissig, J.J., Young, M.E., Wasserman, E.A., Biederman, I., 2000b. The pigeon's perception of depth-rotated shapes. In: Fagot, J. (Ed.), Picture Perception in Animals. Psychology Press, Ltd., East Sussex, England, pp. 37–70.

Peissig, J.J., Wasserman, E.A., Young, M.E., Biederman, I., 2002. Learning an object from multiple views enhances its recognition in an orthogonal rotational axis in pigeons. Vision Res. 42, 2051–2062. https://doi.org/10.1016/S0042-6989(02)00128-1.

Peissig, J.J., Kirpatrick, K., Young, M.E., Wasserman, E.A., Biederman, I., 2006. The effects of varying stimulus size on object recognition in pigeons. J. Exp. Psychol. Anim. Learn. Behav. 32, 419–430. https://doi.org/10.1037/0097-7403.32.4.419.

Roach, S.P., Mennill, D.J., Phillmore, L.S., 2017. Operant discrimination of relative frequency ratios in black-capped chickadee song. Anim. Cogn. 20, 961–973. https://doi.org/10.1007/s10071-017-1115-5.

Soto, F.A., Wasserman, E.A., 2010. Error-driven learning in visual categorization and object recognition: a common elements model. Psychol. Rev. 117, 349–381. https://doi.org/10.1037/a0018695.

Spetch, M.L., Friedman, A., 2003. Recognizing rotated views of objects: interpolation versus generalization by humans and pigeons. Psychon. Bull. Rev. 10 (1), 135–140. https://doi.org/10.3758/BF03196477.

Sturdy, C.B., Phillmore, L.S., Weisman, R.G., 1999a. Note types, harmonic structure, and note order in the songs of zebra finches (*Taeniopygia guttata*). J. Comp. Psychol. 113, 194–203. https://doi.org/10.1037/0735-7036.113.2.194.

Sturdy, C.B., Phillmore, L.S., Price, J.L., Weisman, R.G., 1999b. Song-note discriminations in zebra finches (*Taeniopygia guttata)*: categories and Pseudocategories. J. Comp. Psychol. 113, 204–212. https://doi.org/10.1037/0735-7036.113.2.204.

Tarr, M.J., 1995. Rotating objects to recognize them: a case study on the role of viewpoint dependency in the recognition of three-dimensional objects. Psychon. Bull. Rev. 2, 55–82. https://doi.org/10.3758/BF03214412.

Vaughan, W., Greene, S.L., 1983. Acquisition of absolute discrimination in pigeons. In: Commons, M.L., Herrnstein, R.J., Wagner, A.R. (Eds.), Quantitative Analysis of Behavior. Vol. 4, Discrimination Processes. Ballinger, Cambridge, MA, pp. 231–238.

Vaughan, W., Greene, S.L., 1984. Pigeon visual memory capacity. J. Exp. Psychol. Anim. Behav. Process. 10 (2), 256–271. https://doi.org/10.1037/0097-7403.10.2.256.

Wasserman, E.A., Kiedinger, R.E., Bhatt, R.S., 1988. Conceptual behavior in pigeons: categories, subcategories, and pseudocategories. J. Exp. Psychol. Anim. Behav. Process. 14, 235–246. https://doi.org/10.1037/0097-7403.14.3.235.

Wasserman, E.A., Gagliardi, J.L., Cook, B.R., Astley, S.L., Kirkpatrick-Steger, K., Biederman, I., 1996. The pigeon's recognition of drawings of depth-rotated stimuli. J. Exp. Psychol. Anim. Behav. Process. 22, 205–222. https://doi.org/10.1037/0097-7403.22.2.205.

Wolf, J.B., 1936. Effectiveness of token-rewards for chimpanzees. Comp. Psychol. Monogr. 12, 1–72.

Wood, J.N., Wood, S.M.W., 2017. Measuring the speed of newborn object recognition in controlled visual worlds. Dev. Sci. 20, e12470. https://doi.org/10.1111/desc.1247.

Wright, H.F., Wilkinson, A., Croxton, R.S., Graham, D.K., Harding, R.C., Hodkinson, H.L., Keep, B., Cracknell, N.R., Zulch, H.E., 2017. Animals can assign novel odours to a known category. Sci. Rep. 7 (1), 9019. https://doi.org/10.1038/s41598-017-09454-0.

Young, M.E., Peissig, J.J., Wasserman, E.A., Biederman, I., 2001. Discrimination of geons by pigeons: the effects of variations in surface depiction. Anim. Learn. Behav. 29, 97–106. https://doi.org/10.3758/BF03192819.