The Pigeon's Recognition of Drawings of Depth-Rotated Stimuli

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Four experiments used a four-choice discrimination learning paradigm to explore the pigeon's recognition of line drawings of four objects (an airplane, a chair, a desk lamp, and a flashlight) that were rotated in depth. The pigeons reliably generalized discriminative responding to pictorial stimuli over all untrained depth rotations, despite the birds' having been trained at only a single depth orientation. These generalization gradients closely resembled those found in prior research that used other stimulus dimensions. Increasing the number of different vantage points in the training set from one to three broadened the range of generalized testing performance, with wider spacing of the training orientations more effectively broadening generalized responding. Template and geon theories of visual recognition are applied to these empirical results.

Depth rotation dramatically alters the information present in any two-dimensional view of an object; yet, we readily recognize most objects—even those we have never seen before—despite enormous variations in vantage point. How is such robust visual recognition accomplished? Do nonhuman animals also show generalization over rotation in depth?

These questions are central to this article, which experimentally examines the pigeon's recognition of drawings of objects that have been rotated in depth from the orientation(s) shown during initial discrimination training. Experiments 1a and 1b first document the pigeon's ability to respond discriminatively to line drawing stimuli over a broad range of untrained testing orientations after training at only a single orientation in depth. Experiments 2a and 2b then explore the effects of training at one versus three different orientations in depth on later generalization performance over a broad range of untrained testing orientations.

Overall, the results of this series of experiments disclose that pigeons very ably generalize discriminative responding to pictorial stimuli over numerous untrained depth rotations, despite the birds' having been trained at just one depth orientation. The depth rotation generalization gradients closely resembled those obtained in prior research that used many different stimulus dimensions. Beyond the robust generalization of discriminative responding after training at only one orientation, increasing the number of different vantage points in the training set from one to three broadened the range of generalized testing performance, with wider spacing of the training orientations more effectively broadening generalized responding. These effects also resemble those obtained in testing generalization over very different stimulus attributes.

Before we introduce the specific experimental investigations, it will be useful to give a brief review of earlier research into the control of learned behavior by stimulus orientation.

Stimuli Rotated in the Frontal Plane

Generalization Studies

In 1956, Guttman and Kalish published a landmark paper reporting single-subject stimulus generalization gradients from a color training task. Pigeons were first taught to peck a keylight of a particular color. They were then tested with colors that differed in wavelength from the training stimulus by an increasing amount, to both shorter and longer values along the visual spectrum. The highest responding in testing was to the training color, the next highest responding was to the two adjacent values closest to this color along the visual spectrum, and so on, which thus created a decremental gradient along which the rate of responding to a testing stimulus was an inverse function of its distance from the

training color. This basic function is now known as the stimulus generalization gradient.

The work of Guttman and Kalish (1956) yielded empirical evidence of stimulus generalization in individual subjects and gave experimental psychologists an incisive new procedure for exploring diverse stimulus control phenomena (for a review of this work see Honig & Urcuioli, 1981). One familiar application of Guttman and Kalish's method by Honig, Boneau, Burstein, and Pennypacker (1963) was to stimulus rotation. Their pigeons learned to discriminate between a black vertical line (90°) on a white key as the S+ and a white key with no line as the S−. Subjects were then tested with the S+, the S−, and the black line presented at 0°, 30°, 60°, 120°, and 150° of tilt on a white key. The results yielded a decremental stimulus generalization gradient, as in Guttman and Kalish's original study.

Wilkie (1973) later showed that this decremental gradient was a function of the orientation of the line stimulus relative to the context of the experimental enclosure. In that study, pigeons were trained with a vertical line as the S+ and a horizontal line as the S−. Line orientation testing was given with the operant chamber tilted 22.5° in one direction and the floor tilted 22.5° in the opposite direction; thus, the floor remained in the horizontal plane, but the side walls of the chamber were slanted 45° from vertical. During testing, maximal responding was to the line orientation that was perpendicular to the floor—not to the gravitational vertical. Wilkie's results are consistent with Massaro's (1973) findings with humans that the perception of shape from a rotated orientation depends not only on the extent of rotation but on the encoding of the figure–ground relationship.

The research of Honig et al. (1963), Wilkie (1973), and many other investigators has clearly shown that the orientation of a single line may control highly systematic stimulus generalization gradients. What about more complex visual stimuli? In a study by Reynolds (1961), an isosceles triangle was used as the training stimulus; the triangle was mounted on a synchronous motor that slowly, but continually, rotated the stimulus about its geometric center. The 0° condition was designated by the apex pointing straight up. As the triangle rotated, every 36° sweep designated the boundary of a geometric section called a decant. Thus, 10 decants are contained in a full sweep of 360°. Pigeons' responding during a 72° sweep of two successive decants was reinforced, whereas responding during a 288° sweep of the other eight decants was not. Decremental gradients similar to those of Honig et al. (1963) resulted, thus showing the robustness of rotation generalization with moving as well as static visual stimuli.

Later research by Vetter and Hearst (1968) and Ferraro and Grisham (1972), who used even more complex polygons, indicated that with some geometric forms, rotation of the testing stimuli away from the training stimuli may not always lead to progressively decremental stimulus generalization gradients. In those cases, other aspects of the visual stimuli may control behavior, such as whether a testing figure shared the same diagonal- or side-parallel orientation as the S+. Unfortunately, little subsequent work has addressed the nature of that stimulus control.

Matching-to-Sample Studies

Perhaps the best known study investigating the pigeon's discrimination of stimuli rotated in the frontal plane is that of Hollard and Delius (1982). They taught pigeons a matching-to-sample task that involved a nonsense figure composed of nine unoutlined squares as the sample and the same figure and its mirror image as the comparisons. After pigeons had learned this task, new samples and comparisons were introduced, but this time the comparison figures were both displayed at a rotation 45°, 90°, 135°, or 180° from the sample. In all cases, the pigeons chose the correct comparison figure at levels reliably above chance. (Vauclair, Fagot, and Hopkins [1993] reported related findings with baboons in a similar matching-to-sample study in which the stimuli were directed to the left cerebral hemisphere.)

A possibly more interesting finding emerged when the researchers compared the reaction times of pigeons to those of humans who performed a similar task. For humans, reaction time increased as a linear function of the extent of rotation of the comparison figures, whereas for pigeons, the reaction times remained constant, producing a flat function across the different rotations (Hollard & Delius, 1982). The finding for human subjects is well-documented (Kubovy & Podgorny, 1981; Shepard & Cooper, 1982; Shepard & Metzler, 1971) and has suggested to many theorists that humans use a "mental rotation" or a "normalization of orientation" to contrast the comparison figures to the sample figure. However, the constant reaction times exhibited by the pigeons suggest that their behavior involved a different recognition process. (For more recent research and discussion of this issue see Cerella, 1990, and Delius & Hollard, 1995.)

Stimuli Rotated in Depth

One manipulation that may be more ecologically meaningful than rotation of images in the frontal plane is rotation of images in depth. Planar rotation over small angles is usually the result of an animal's head turning, whereas depth rotation is commonly the consequence of an animal's locomotion or an object's turning. When a three-dimensional stimulus is rotated in depth, different features may be gained or lost as they come into or move out of view.

Humans can readily recognize depth-rotated stimuli in many experimental paradigms (e.g., Biederman & Gerhardstein, 1993).[1] If pigeons can successfully perform similar tasks, then that performance may suggest that they are able to perceive two-dimensional photographs or drawings as

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[1] Some workers have suggested that humans respond to depth-rotated stimuli in a manner similar to their response to images rotated in the frontal plane, because reaction times have been found to be a linear function of the angular rotation of the stimulus (Shepard & Metzler, 1971). But Biederman and Gerhardstein (1993) have found depth-invariant visual performance in name priming, matching individual sample components, and classifying unfamiliar objects that can be decomposed into separate, distinctive components.

representing three-dimensional objects. (This idea initially seemed improbable [Cabe, 1980], but it has received strong recent support in the form of substantial object–picture discrimination transfer [Delius, 1992]). Two-dimensional cues may thus be sufficient to support generalization over rotations in depth.

One bit of evidence that supports the latter possibility comes from a small study by Lumsden (1977). He presented a single pigeon with three sets of testing stimuli: a three-dimensional geometric object (a brick with a smaller attached semicircle) rotated in depth at 0°, 45°, 90°, 135°, and 180°; photographs of the object at each of the rotations; and outline drawings of the object at each of the rotations. Earlier discrimination training consisted of the designated object at 45° as the S+ and two different objects (wedge and hourglass shapes) as the S−s. Generalization testing was conducted with all of the rotations of the S+ object, its photographs, and its drawings. Generalization gradients were obtained in which the S+ entailed the highest rate of responding, with responding generally falling as a function of rotation away from the S+, except for a secondary peak at 135°—the mirror image of the 45° S+ orientation. Notably, the gradients were almost identical for the actual object and for the photographs of it, whereas the drawings of the object supported a similarly shaped gradient but a lower rate of responding.

In contrast to these findings, Cerella (1977) reported his pigeons' failure to discriminate rotated drawings of three-dimensional cubelike objects. In his first experiment, Cerella initially trained pigeons to discriminate a square from a set of random quadrilaterals. Training progressed slowly, but the birds eventually learned the discrimination. Next, random rotations of proper cubes replaced the squares as the S+s, and random rotations of distorted cubes— generated by slightly displacing the vertices of a proper cube—replaced the quadrilaterals as the S−s. Discrimination of these modified stimuli dropped to chance and remained there for over 150 sessions. In a second experiment, Cerella's pigeons also did not reveal generalization over depth rotations—even when their initial training involved regular and distorted cubes.

Any single image can be the possible projection of an infinity of objects, and any complex object can project an enormous number of different images. Cerella's experiments addressed one presumed mechanism for determining the shape of an object from its projection on the retina—the inverse optics problem—one in which the real three-dimensional shape of the object is inferred from the metrics of the two-dimensional image and an estimate of the orientation of the object. For example, the classical solution to the classical problem of why dinner plates look circular when their retinal images are elliptical can be solved by estimating the slant angle of the object and correcting the shape of the retinal image to recover the true circular shape of the object. Although this is a possible solution, it does not appear to be one that humans readily use, especially in a photograph, where there can be no perception of true object slant. But, even if real dinner plates were really elliptical, they still can look circular (King, Meyer, Tangney, & Biederman, 1976)!

Rather than apply inverse mathematics, people reveal a strong bias toward interpreting asymmetrical stimuli under depth rotation as being symmetrical, near parallel lines as being parallel, and near orthogonal angles as being orthogonal (see Pani, 1993). The familiar trapezoidal room and window illusions (e.g., Haber & Hershenson, 1980) have their origins in these regularization biases, biases that are particularly apparent under conditions where the judgments of slant can be in error, as in a photograph, where stereo or motion parallax is absent (King et al., 1976).

Cerella (1977) essentially tested whether the pigeon can use metric information to solve the inverse optics problem, and it is not implausible that his pigeons had the same biases toward regularity that would have interfered with their generalization. (In the General Discussion we consider alternative algorithms for achieving generalization over depth rotations.)

Perhaps the clearest evidence to date on stimulus generalization with drawings of depth-rotated objects comes from a recent report by Logothetis, Pauls, Bülthoff, and Poggio (1994). After training monkeys for 8 months on a successive same–different discrimination, these researchers tested their subjects with drawings of either the target shape at its given orientation or the target shape at different depth-rotated orientations. "Same" report responses were found to be highest when the test drawing depicted the target shape at its given orientation, these reports systematically falling as the test drawings depicted greater rotations away from this orientation. Stronger stimulus generalization was obtained with rendered drawings of realistic objects than with computer-generated wire-frame and bloblike shapes and with exposure to multiple views of the target shape than with single views of it.

Experiment 1a

To assess further the pigeon's discrimination and generalization of pictures of three-dimensional objects rotated in depth, we used line drawings of multipart objects (an airplane, a chair, a desk lamp, and a flashlight) in the hope of providing the birds with more effective three-dimensional information than that afforded by the stimuli used by Lumsden (1977) and Cerella (1977; cf. the different kinds of shapes used by Logothetis et al., 1994).

Method

Subjects

Twelve experimentally naive feral pigeons maintained at 85% of their free-feeding body weights served as subjects.

Apparatus

Four 29 × 38 × 38 cm operant chambers, located in a room with white noise, were used. Through a large hole in the back of each chamber, a Kodak Carousel projector (Ektagraphic III E, with a 76-mm/3.5 Ektagraphic FF lens and a GE EXR 82-V DC bulb

through a rheostat) presented slides onto the back of a 7 × 7 cm frosted plastic viewing screen located 10 cm from the top edge and 14 cm from each of the side edges of the response panel. A 1.9-cm diameter key was located diagonally 2.3 cm from each corner of the screen. Behind each of these four keys was a miniature projector. When illuminated, each projector produced a different color field: orange on the top left, white on the top right, green on the bottom left, and red on the bottom right. A microswitch behind each of the keys and the viewing screen recorded responses exceeding a force of 0.05 N. Chamber illumination was provided by a CM 44 lamp (5 V DC) mounted 6.5 cm above the screen. A 5.0 × 6.3 cm opening below the screen allowed access to a food hopper containing mixed grain. A Sonalert tone generator was located behind the response panel. A Hewlett Packard Vectra Q5/20 computer and MED PC interfacing and software provided the experimental control and data collecting facility (see Bhatt, Wasserman, Reynolds, & Knauss, 1988, for more details about the apparatus).

Stimuli

Figure 1 shows the stimuli used in Experiment 1a. Line drawings of four human-made objects (the airplane, desk lamp, flashlight, and chair in Experiments I and II of Biederman & Gerhardstein, 1993) at three depth rotations (nominally 0°, 33°, and 67°) were used. The 0° orientation of each object was randomly chosen. The objects were created on a Macintosh II computer with a three-dimensional drawing package (Swivel 3D, Paracomp, San Francisco, CA). The images were then redrawn with a line width of 2 pixels and saved in PICT format with Adobe Illustrator 88 (Adobe Systems, Mountain View, CA). Finally, the computer renderings were output with a laser printer. The height and width of each of the 12 black-on-white stimuli were measured, and the largest dimension for each of the four kinds of objects was noted. The drawing with the largest measurement for each object was photographed so that this value would be 1.9 cm when made into a slide. Slides of the other orientations of each object were made by keeping the camera at the same distance used to make the slide with the largest dimension for each object. This process was followed for each of the four objects. The stimuli were presented to the subjects so that the largest dimension nearly filled the viewing screen.

Procedure

Pretraining. Each pigeon was first magazine trained and then shaped by successive approximations to peck the four circular report keys and the square viewing screen. When this step ended, the pigeons were trained with a computerized pretraining program. Each pretraining session began with the illumination of the houselight, followed by an intertrial interval (ITI) of either 9, 14, or 19 s, each having an equal probability of occurring. Then, one of the four keys or the viewing screen was illuminated. After the required response was made, the food hopper swung up to allow the pigeon access to mixed grain. We varied access time to grain from day to day as a means of controlling each subject's weight. During each session, 20 presentations of the screen and 5 presentations of each of the four keys were randomly displayed. Over time, the response requirement was gradually raised from a fixed ratio (FR) 1 to an FR 30 schedule.

Discrimination training. Three groups of 4 pigeons each were randomly assigned to Group 0°, Group 33°, and Group 67°. Using a four-alternative forced-choice procedure, we trained each group to discriminate the drawings of the four objects. During discrimination training, subjects saw only those stimuli corresponding to their group affiliation. Thus, subjects in Group 0° saw the airplane, the desk lamp, the flashlight, and the chair at the 0° orientation depicted in Figure 1, Group 33° saw the four depicted objects at the 33° orientation, and Group 67° saw the four depicted objects at the 67° orientation. Each stimulus was assigned to one of the four keys, and these assignments were counterbalanced in such a way that, across the 4 birds in each group, each key represented each of the four stimuli. Each session consisted of 12 semirandom presentations of each of the four stimuli. Each block of four trials entailed each of the four depicted objects. Four separate slide trays arranged the 48 slides in different orders, and the four trays were used one time each in every 4 days of discrimination training.

Each 48-trial session began with illumination of the houselight, followed 50 s later by the first trial. After an ITI (as in pretraining), the carousel advanced to display the first slide, and an FI 15-s observing response requirement to the viewing screen was begun. When the observing response requirement was satisfied, the stimulus remained on the screen, the four report keys were illuminated simultaneously, and the tone produced by the Sonalert was sounded; the tone served as an additional cue to the pigeon that the response keys were illuminated. The pigeon was then required to peck the report key designated as the correct one for that stimulus. If a correct response was made, then the carousel advanced and its internal shutter closed to show a dark screen, the four keys and the Sonalert were turned off, and the hopper swung up to allow the pigeon access to mixed grain. The delivery of reinforcement was followed first by the ITI and then by the next trial. If an incorrect response was made, then the stimulus remained on the screen and the four keys and the Sonalert were turned off. The observing response requirement was reset to 0 s and the pigeon was allowed a correction trial. This process continued until the subject made the correct response. We considered only the outcome of the first response for each stimulus when calculating performance accuracy. Training continued for 80 days, by which time 11 of the 12 subjects consistently chose the correct key across all four stimuli (1 pigeon from Group 33° was dropped from the study prior to testing because of poor discriminative performance during training).

Generalization testing. Each pigeon was next tested with drawings of the four objects at each of the two rotations that had not been shown during original training. For example, subjects in Group 0° were tested with drawings of the four objects presented at 33° and 67° of rotation. Therefore, each subject was tested with eight previously untrained stimuli. During a generalization testing session, the eight testing stimuli were embedded within 40 presentations of the stimuli used in original training, which yielded a 48-trial session, as in training. Two new and different stimulus presentation orders were used during testing, and these orders were alternated for each subject in a semirandom manner. The testing stimuli did not appear within the first 8 or the last 8 training stimuli presented, and these 16 training stimuli were not considered in the data analysis. The procedure for the original training stimuli during generalization testing was identical to that used during discrimination training. On testing trials (i.e., trials with stimuli that were not shown during training sessions), however, food reinforcement was given after the first choice response, regardless of the "accuracy" of the response.[2] Thus, no correction was needed on testing

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[2] The reasons for giving nondifferential reinforcement during testing trials are twofold. First, no differential feedback is given to the subjects after "correct" or "incorrect" choices; thus, no further explicit training of the correct choice response is given on these
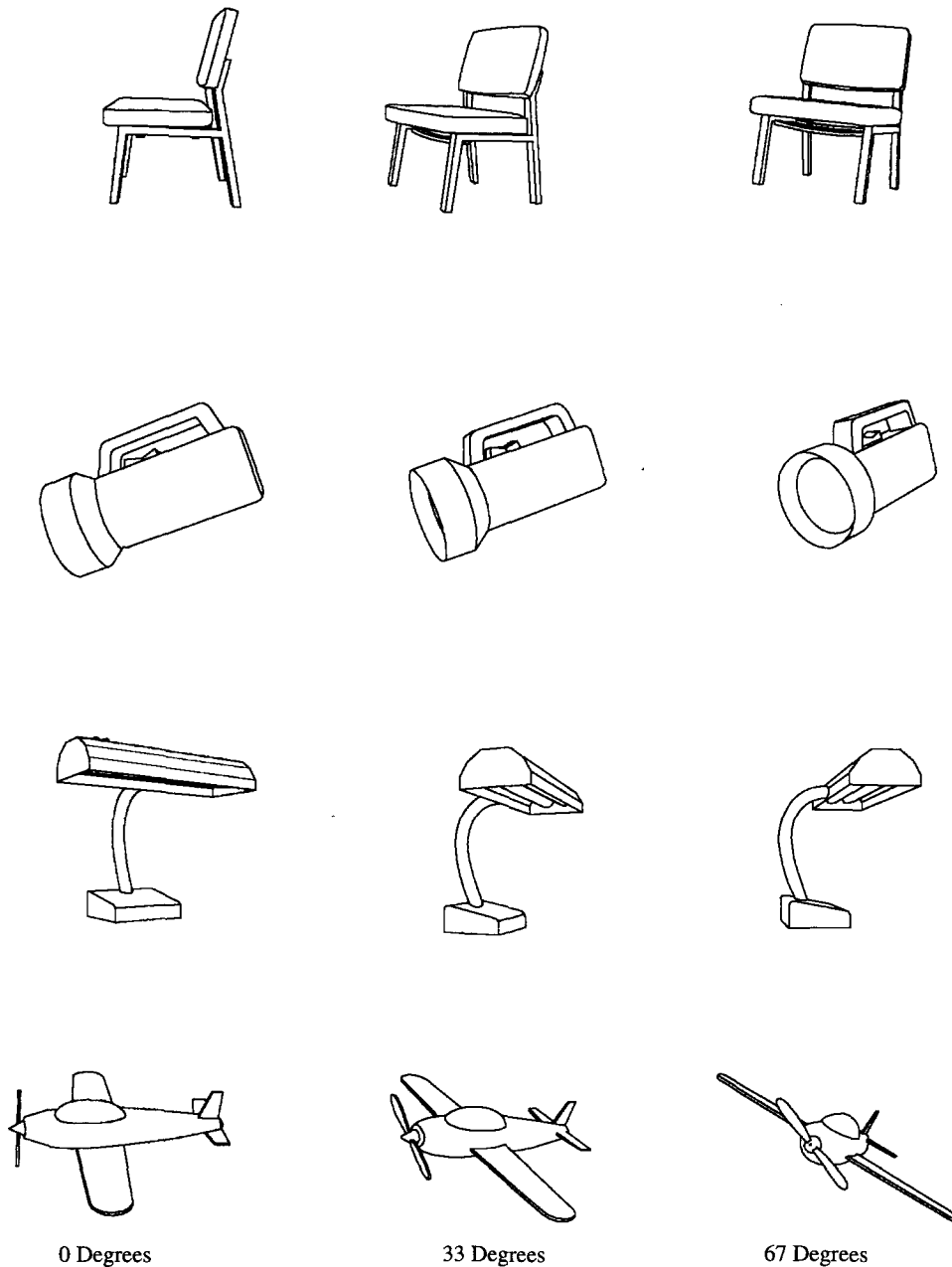
0 Degrees   33 Degrees   67 Degrees

Figure 1. Drawings of the chair, the flashlight, the desk lamp, and the airplane at the 0°, 33°, and 67° orientations used in Experiment 1a. These versions of the stimuli are of comparable quality to those shown to the pigeons.

trials. Again, responses were scored based on the performance of the first response of all trials. The testing regimen consisted of a sequence of 2 days of testing followed by 2 days of retraining, during which the pigeons were not exposed to any testing stimuli. This sequence was repeated until 12 data points were collected for each testing stimulus. Only data collected on the 12 testing days were used in the final analysis.

trials. Second, each testing trial ends with the presentation of a reinforcer, thereby duplicating a training trial.

Results

Discrimination Training

The 11 birds who proceeded through all stages of training and testing reached progressively high performance levels of 40%, 55%, and 70% correct choice responses across all four types of object drawings during discrimination training in means of 15, 21, and 33 days, respectively. (Of the 11

subjects, 10 later reached the 85% level and 4 reached the 100% level.) A two-way Discrimination Performance Level (3) × Orientation Group (3) analysis of variance (ANOVA) on the number of days needed to reach the first three discrimination levels yielded a significant main effect of performance level, $F(2, 16) = 20.21$, $p < .001$, but no significant effect of orientation group, $F(2, 8) = 2.26$, $p > .15$, and no significant Level × Group interaction, $F(4, 16) < 1$. Thus, the three sets of training stimuli did not differ reliably from one another in their original discrimination.

During the last 8 days of discrimination training, the mean percentage of correct choice responses across all 11 birds was 85.94%. A one-way orientation group (3) ANOVA on these choice scores failed to find a significant difference among the three training groups, $F(2, 8) < 1$.

Generalization Testing

Figure 2 shows the results of generalization testing for all three groups of pigeons across all four types of line drawings.[3] In all three groups, mean accuracy scores peaked at the training orientation, with discriminative performance falling as the testing stimuli rotated away from the training value either unidirectionally (in Groups 0° and 67°) or bidirectionally (in Group 33°).

Table 1 depicts the group mean percentage correct scores from which Figure 2 was constructed along with the scores
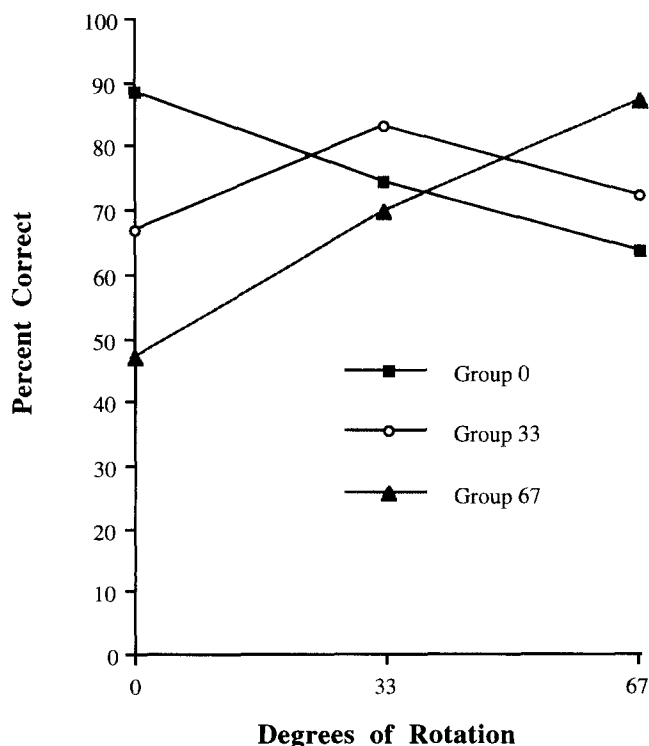

Figure 2. The mean percentage of correct choice responses to all of the stimuli shown to all three groups of pigeons during generalization testing in Experiment 1a.

of the individual pigeons in each of the three training groups. Each individual pigeon showed the same performance trends exhibited by the group mean scores: Choice accuracy was highest at the training value, with discriminative performance dropping as the testing stimuli rotated away from the training value. Table 1 also shows the results of one-tailed binomial tests which ascertained whether the recorded levels of accuracy significantly exceeded the 25% level expected by chance. All of the group mean scores were significantly greater than chance at the $p < .01$ level ($N = 144$ at the two testing orientations and $N = 864$ at the training orientation in Group 33°; $N = 192$ at the two testing orientations and $N = 1,152$ at the training orientation in Groups 0° and 67°). All of the individual subject data points except one, that of Bird 3 in Group 67° to the 0° stimuli, were significantly greater than chance at the $p < .01$ level ($N = 48$ for individual subject data at the two testing orientations and $N = 288$ for individual subject data at the single training orientation).

Experiment 1b

The results of Experiment 1a clearly showed substantial generalization of discriminative responding from drawings of four objects at their single training orientation to two untrained rotations in depth. The testing orientations used in that first study differed from the training orientations at most by ±67°. In Experiment 1b, we increased the maximum range of generalization testing to orientations of ±133°.

Method

Subjects, Apparatus, and Stimuli

The same 11 pigeons from Experiment 1a served in Experiment 1b. The chambers used in Experiment 1a were again used in Experiment 1b. Line drawings of the same four objects used in Experiment 1a were used in Experiment 1b, but a greater rotational sweep was given in testing. Orientations at 33° decrements and increments yielded images at −100°, −67°, −33°, 0°, 33°, 67°, 100°, 133°, and 167° of rotation. Figure 3 shows the full range of stimuli used in Experiment 1b.

Procedure

Training. We trained all of the pigeons for 8 days in the same manner as in the discrimination training in Experiment 1a to allow them a period of uninterrupted retraining before they were given

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[3] The generalization gradients for all of the individual stimuli for each individual subject in all of the experiments are reported in Cook (1994) and Gagliardi (1994). They are not included here because to do so would have greatly increased the length and complexity of the present article and because these data did not importantly differ from those reported here. Also, despite considerable efforts to do so, we were unable to correlate specific properties of the observed generalization gradients with specific features of each of the four types of drawings.

Table 1

Individual Subject and Group Mean Choice Accuracy in Percentage Correct Across All Four Objects at All Orientations Given During Testing in Experiments 1a and 1b

Bird	-100°	-67°	-33°	0°	33°	67°	100°	133°	167°
				Orientation					

Group 0°, Experiment 1a

Bird	-100°	-67°	-33°	0°	33°	67°	100°	133°	167°
1				**94.79***	83.33*	70.83*			
2				**90.97***	52.08*	50.00*			
3				**85.42***	83.33*	62.50*			
4				**82.29***	79.17*	70.83*			
M				**88.37***	74.48*	63.54*			

Group 0°, Experiment 1b

Bird	-100°	-67°	-33°	0°	33°	67°	100°	133°	167°
1	66.67*	62.50*	68.75*	**96.64***	66.67*	77.08*	54.17*		
2	14.58	22.92	75.00*	**82.87***	50.00*	41.67*	27.08		
3	60.42*	47.92*	77.09*	**92.83***	85.42*	54.17*	56.25*		
4	37.50	52.09*	89.59*	**79.75***	58.33*	47.92*	45.83*		
M	44.79*	46.36*	77.61*	**88.02***	65.10*	55.21*	45.83*		

Group 33°, Experiment 1a

Bird	-100°	-67°	-33°	0°	33°	67°	100°	133°	167°
1				70.83*	**75.35***	68.75*			
2				64.58*	**93.40***	72.92*			
3				64.58*	**81.25***	75.00*			
M				66.66*	**83.33***	72.22*			

Group 33°, Experiment 1b

Bird	-100°	-67°	-33°	0°	33°	67°	100°	133°	167°
1	22.92	35.42	60.42*	83.34*	**87.24***	79.17*	35.42	58.33*	50.00*
2	27.08	22.92	52.08*	62.50*	**95.05***	87.50*	52.08*	52.09*	60.42*
3	77.08*	45.83*	72.92*	77.09*	**92.88***	83.33*	77.09*	85.42*	56.25*
M	42.36*	34.72*	61.81*	74.31*	**91.72***	83.33*	54.86*	65.28*	55.56*

Group 67°, Experiment 1a

Bird	-100°	-67°	-33°	0°	33°	67°	100°	133°	167°
1				62.50*	81.25*	**88.19***			
2				50.00*	72.92*	**84.03***			
3				14.58	52.08*	**88.19***			
4				60.42*	72.92*	**85.42***			
M				46.88*	69.79*	**86.46***			

Group 67°, Experiment 1b

Bird	-100°	-67°	-33°	0°	33°	67°	100°	133°	167°
1			58.33*	60.42*	68.75*	**90.74***	79.17*	58.33*	56.25*
2			52.09*	60.42*	85.42*	**91.21***	58.34*	58.33*	56.25*
3			50.00*	43.75*	41.67*	**92.71***	68.75*	41.67*	27.08
4			54.17*	52.08*	68.75*	**90.45***	81.25*	68.75*	50.00*
M			53.65*	54.17*	66.15*	**91.28***	71.88*	56.77*	47.40*

Note. Scores in bold type are to the training orientations.
$^* p < .01$.

the more rigorous and prolonged testing procedure in Experiment 1b. This training was sufficient to ensure that the subjects' level of discriminative performance was similar to that established in Experiment 1a.

Testing. The generalization testing procedure was identical to that of Experiment 1a, but more testing orientations were used. For all three groups, equal numbers of orientations to the left and to the right of the training orientation were shown. Group 0° was tested with -100°, -67°, -33°, 33°, 67°, and 100°; Group 33° was tested with -100°, -67°, -33°, 0°, 67°, 100°, 133°, and 167°; and Group 67° was tested with -33°, 0°, 33°, 100°, 133°, and 167°. We used more testing stimuli in Group 33° than in the other two groups to retain the symmetry of testing in each of the groups and to utilize as many of the available stimulus orientations as possible.

On any given testing day, two testing rotations of each of the four stimulus objects were presented, which yielded eight testing stimuli per testing session, as in Experiment 1a. The combinations of orientations were presented randomly without replacement until all of the orientations were shown. At least 2 days of retraining followed each period of generalization testing. Thus, Groups 0° and 67° received 3 days of testing and 2 days of retraining before the process was repeated, whereas Group 33° received 4 days of testing and 2 days of retraining in the testing cycles. From time to time in this and in subsequent experiments, we extended the periods of retraining to return performance levels to those exhibited prior to the testing phase. These rare extensions did not usually entail more than 2 extra days. Testing continued in this manner until 12 data points were collected for each of the testing stimuli.
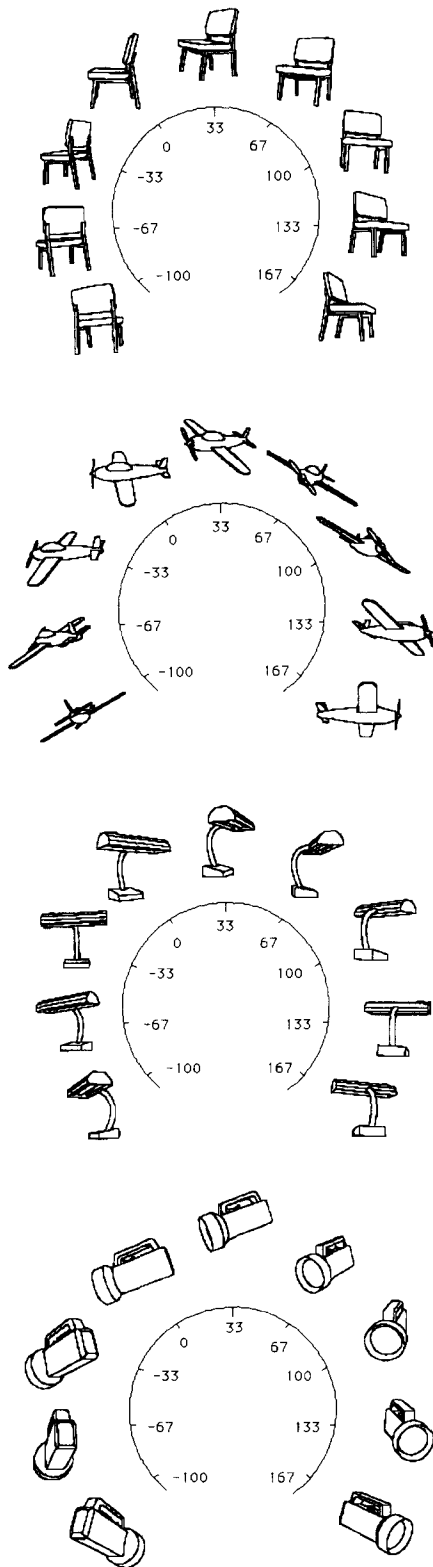
Thus, Groups 0° and 67° were exposed to 36 testing sessions and Group 33° was exposed to 48 testing sessions.

Results

Table 1 shows individual subject and group mean percentage correct scores averaged by stimulus orientation. The same general trends appeared here as in Experiment 1a: The best discriminative performance occurred at the original training value, and performance dropped off as the stimuli rotated away from the training orientation. One-tailed binomial tests were significantly above chance performance at the $p < .01$ level for a high percentage (74/83 = 89.16%) of the individual subject scores ($N = 48$ to each individual testing orientation in all three groups; $N = 864$ at the training orientation in Groups 0° and 67° and $N = 576$ at the training orientation in Group 33°).

Perhaps an even clearer picture can be obtained from Figure 4, which is a between-groups comparison of the stimulus generalization gradients constructed from the group means contained in Table 1. Here, decremental gradients quite similar to those reported by Guttman and Kalish (1956) and by numerous other investigators over the past 4 decades are evident. Binomial tests revealed that all points of the three gradients were significantly above chance at the $p < .01$ level ($N = 144$ for Group 33°; $N = 192$ for Groups 0° and 67°; see Table 1).

Figure 5 shows the mean percentage of correct choice responses (collapsed across groups) for Experiments 1a and 1b as a function of the number of 33° steps from the original training value. The same trends of highest performance to the original training value and progressive drop-off in performance as the testing stimuli increasingly departed from the training value are seen in both experiments. Even more important is the close similarity of the common points in the two functions. From this similarity (and from that arising from detailed scrutiny of Table 1), it is evident that there was no material difference in performance to identical stimuli tested in both experiments (cf. Guttman & Kalish, 1956, Figure 3). The nondifferential reinforcement procedure that we used in testing seems not to have either steepened or flattened the resulting stimulus generalization gradients.

Experiment 2a

In the first two experiments, our pigeons displayed strong stimulus control over a wide range of untrained rotations of object drawings despite their having been trained at only a single depth orientation of each object drawing. However, rarely if ever do we see objects at a single orientation; usually we see familiar objects from a vast number of different vantage points. Indeed, after its very first presentation, even a novel object is usually seen on later occasions at new angles. With so much prior training at multiple viewpoints, is it any wonder that we are able to recognize objects at novel rotations in depth?

Our aim in this and the following experiment was to explore the effects on discrimination learning and general-

Figure 3. Drawings of the chair, the flashlight, the desk lamp, and the airplane at the −100°, −67°, −33°, 0°, 33°, 67°, 100°, 133°, and 167° orientations used in Experiments 1b, 2a, and 2b. These versions of the stimuli are of inferior quality to those shown to the pigeons (cf. Figure 1).
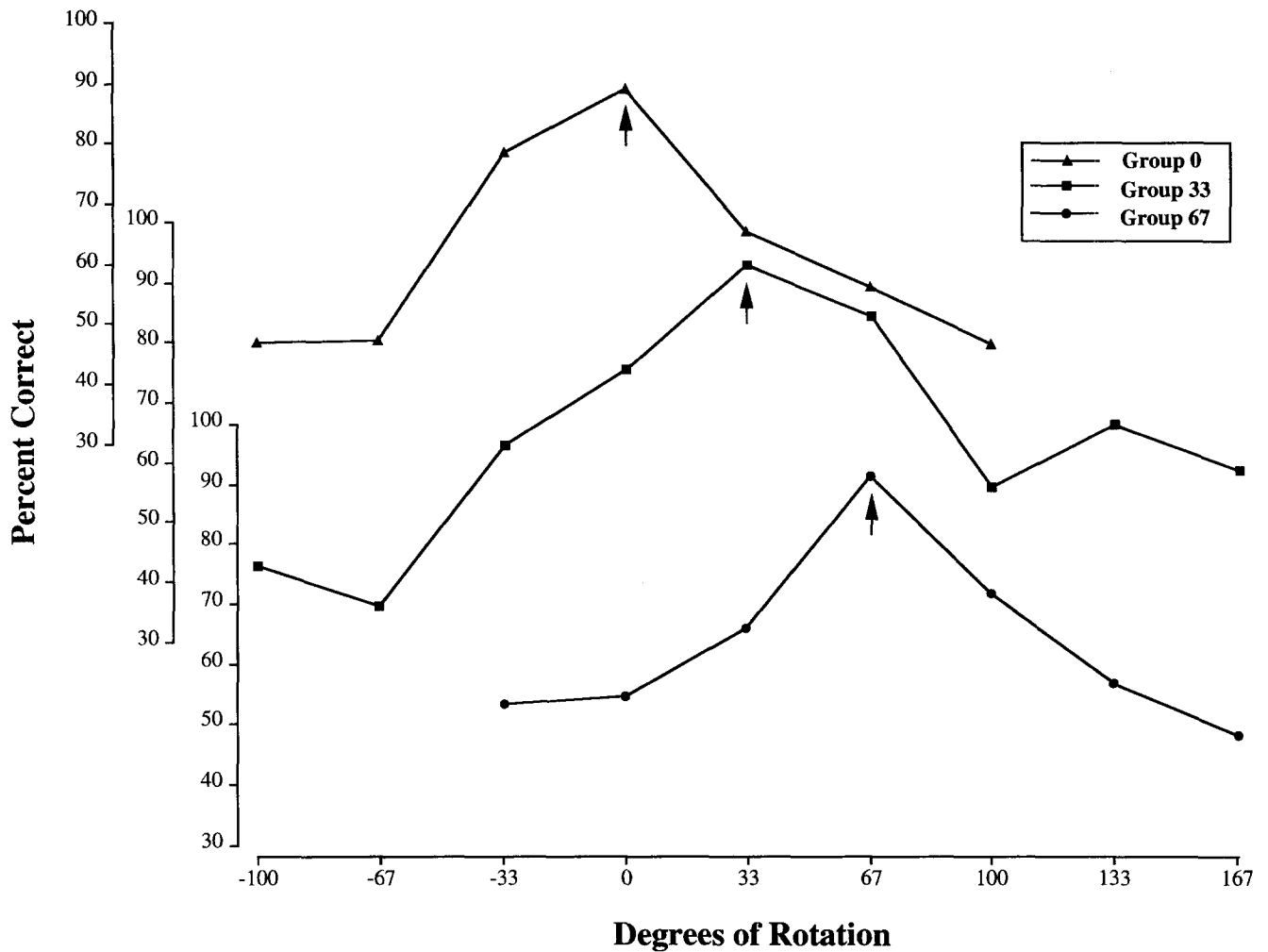
Figure 4. The mean percentage of correct choice responses to all of the stimuli shown to all three groups of pigeons during generalization testing in Experiment 1b. The arrows indicate the orientations at which differential reinforcement was given in training.

ization testing of teaching pigeons to discriminate drawings that depicted the same objects at one versus three different rotations in depth, in order to gain a better appreciation of how the orientations seen during training affect recognition performance. We were also interested in whether more widely distributed training orientations would more effectively support stimulus generalization than more closely distributed training orientations.

In Experiment 2a we used the same drawings as in Experiment 1b, except that we studied the effects on the shape of the generalization gradient of training birds with one versus three different depth-rotated illustrations. Prior research suggested that gradient shape was affected by discrimination training at multiple orientations. Kalish and Guttman (1957) first trained pigeons with two colors and then trained pigeons with three colors (Kalish & Guttman, 1959). Their results showed that the gradients became flatter as more stimuli were added to the training set. Also, wider spacing of a constant number of stimuli in the training set

more effectively broadened the gradients. Furthermore, Logothetis et al. (1994) recently reported that these results might apply as well to monkeys' recognition of depth-rotated wire-frame and bloblike shapes.

Method

Subjects, Apparatus, and Stimuli

Sixteen experimentally naive feral pigeons maintained at 85% of the their free-feeding body weights served as subjects. The same chambers were used as in Experiments 1a and 1b. The same line drawings used in Experiment 1b were used here.

Procedure

Discrimination training. After pretraining like that used in Experiment 1a, each of four different groups of four pigeons was assigned a different combination of depth-rotated training stimuli.
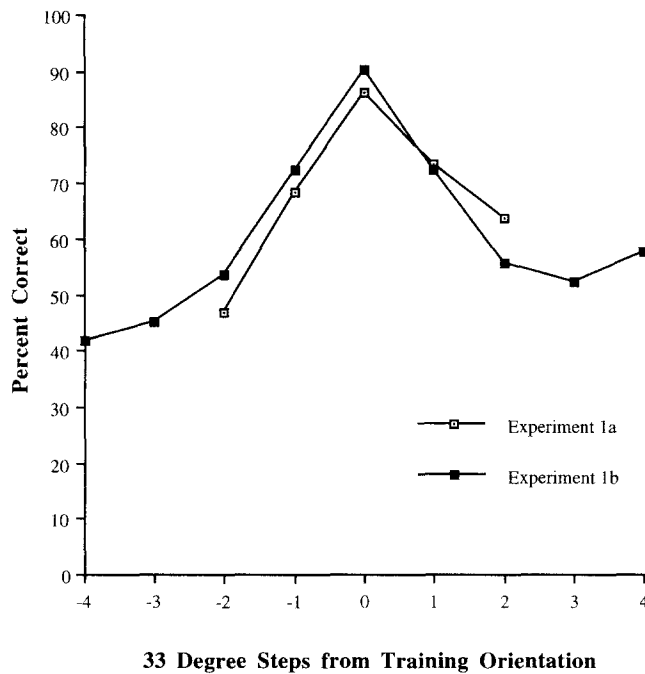
33 Degree Steps from Training Orientation

Figure 5. The mean percentage of correct choice responses to all of the stimuli shown during generalization testing in Experiments 1a and 1b. Performance is plotted as a function of the number of 33° steps from the training orientation (0) and collapsed across all three groups of pigeons in each experiment.

One group was trained with drawings of the four training objects at a nominal orientation of 33°. A second group was trained with the drawings at orientations of 0°, 33°, and 67°. A third group was trained with the drawings at orientations of −33°, 33°, and 100°. The fourth group was trained with the drawings at orientations of −100°, 33°, and 167°. Each training session comprised random presentations of each of the four objects for a total of 48 trials; in the three groups trained at three orientations, each object was seen at each orientation one third of the time. Each object was assigned to one of the four keys, and the assignments were counterbalanced so that across all birds each key represented each of the four objects. Training lasted for 120 days.

Generalization testing. During this phase, each pigeon in each group was tested with the entire set of 36 drawings (9 orientations × 4 objects). This testing plan entailed a relatively small number of nondifferentially reinforced testing trials with drawings at the orientation(s) used in training. This plan was adopted because subjects in each group had seen different orientations of the four object drawings in training; testing with a common set of stimuli was thus required so that meaningful comparisons of responding to trained and untrained orientations could be made among the four training groups. In each testing session, 9 of the 36 total testing stimuli were randomly incorporated into a set of 39 stimuli from the training sessions; these testing stimuli all involved nondifferential reinforcement, and they were never scheduled in either the first eight or the last four trials of a testing session. The remaining 39 trials involved differentially reinforced presentations of drawings at the training orientation(s). Four different stimulus presentation orders were used during the testing sessions, each of which was given to each pigeon during a 4-day block of testing. During this 4-day testing period, each bird was exposed to each of the 36 testing stimuli only once. Testing was complete when all

groups were exposed to each of the testing slides 12 times for a total of 48 days of testing.

Results

Two birds were eliminated from the study because of poor discriminative performance (1 bird in Group −33°, 33°, 100° was dropped because it failed to reach the 70% level during discrimination training; 1 bird in Group − 100°, 33°, 167° was dropped because of poor discriminative performance to the training stimuli during generalization testing).

Discrimination Training

The 14 birds who proceeded through all stages of training and testing reached progressively high performance levels of 40%, 55%, and 70% correct choice responses across all four types of object drawings during discrimination training in means of 17, 27, and 46 days, respectively. (Of the 14 subjects, 11 later reached the 85% level and 1 reached the 100% level.) A two-way Discrimination Performance Level (3) × Orientation Group (4) ANOVA on the number of days needed to reach the first three discrimination levels yielded a significant main effect of performance level, $F(2, 20) = 22.37, p < .001$, but no significant effect of orientation group, $F(3, 10) < 1$, and no significant Level × Group interaction, $F(6, 20) < 1$. Thus, the four sets of training stimuli did not differ reliably from one another in their original discrimination. One might have expected to see more training stimuli slow the course of discrimination learning; this result was previously reported by Bhatt (1988), who used 1, 4, or 12 different color photographs in each category of a four-category learning task.

During the last 8 days of discrimination training, the mean percentage of correct choice responses across all 14 birds was 81.92%. A one-way orientation group (3) ANOVA on these choice scores failed to find a significant difference among the four training groups, $F(3, 10) < 1$.

Generalization Testing

Table 2 and Figure 6 show the main results of generalization testing. As in Experiment 1b, subjects in Group 33° exhibited maximal discriminative performance at the training orientation, with discrimination accuracy falling as the testing stimuli were rotated in either direction away from the training value. Still, at all eight testing orientations, discrimination performance for this group of subjects exceeded the chance level of 25% ($N = 192$ for Group 33°).

Conducting discrimination training with three different depth-rotated drawings of each of the four objects affected the resulting generalization gradients by making them flatter. Gradient flattening was clearest after training at − 100°, 33°, and 167° and at −33°, 33°, and 100°; however, some flattening can even be seen after training at 0°, 33°, and 67°. Scrutiny of the group mean percentage correct scores in Table 2 reveals that the discrimination scores in the three-

Table 2

Individual Subject and Group Mean Choice Accuracy in Percentage Correct Across All Four Objects at All Nine Orientations Given During Testing in Experiment 2a

Bird	Orientation								
	$-100°$	$-67°$	$-33°$	$0°$	$33°$	$67°$	$100°$	$133°$	$167°$
	Group $33°$								
1	35.42	43.75*	50.00*	47.92*	**85.42***	66.67*	47.92*	35.42	8.33
2	37.50	58.33*	64.58*	68.75*	**91.67***	72.92*	68.75*	75.00*	47.92*
3	56.25*	60.41*	70.83*	75.00*	**95.83***	75.00*	64.58*	81.25*	50.00*
4	45.83*	31.25	43.75*	66.67*	**89.58***	66.67*	50.00*	37.50	25.00
M	43.74*	48.44*	57.29*	64.59*	**90.63***	70.32*	57.81*	57.29*	32.81*
	Group $0°$, $33°$, $67°$								
1	58.33*	56.25*	64.58*	**75.00***	**83.33***	**81.25***	77.08*	64.58*	58.33*
2	31.25	54.17*	64.58*	**72.91***	**81.25***	**72.92***	56.25*	72.92*	62.50*
3	33.33	62.50*	81.25*	**85.42***	**89.58***	**83.33***	72.92*	81.25*	62.50*
4	54.17*	52.08*	75.00*	**75.00***	**87.50***	**89.58***	64.58*	64.58*	58.33*
M	44.27*	56.25*	71.35*	**77.08***	**85.42***	**81.77***	67.71*	70.83*	60.42*
	Group $-33°$, $33°$, $100°$								
1	62.50*	77.08*	**93.75***	89.58*	**87.50***	93.75*	**83.33***	81.25*	54.17*
2	64.58*	75.00*	**87.50***	77.08*	**81.25***	81.25*	**77.08***	70.83*	56.25*
3	47.92*	75.00*	**68.75***	68.75*	**77.08***	83.33*	**89.58***	75.00*	58.33*
M	58.34*	75.69*	**83.33***	78.47*	**81.94***	86.11*	**83.33***	75.69*	56.25*
	Group $-100°$, $33°$, $167°$								
1	**89.58***	70.83*	70.83*	66.67*	**81.25***	83.33*	64.58*	68.75*	**87.50***
2	**68.75***	58.33*	60.42*	58.33*	**56.25***	56.25*	47.92*	47.92*	**62.50***
3	**87.50***	72.92*	75.00*	66.67*	**70.83***	72.92*	54.17*	77.08*	**79.17***
M	**81.94***	67.36*	68.75*	63.89*	**69.44***	70.83*	55.56*	64.58*	**76.39***

Note. Scores in bold type are to the training orientations.

$* p < .01.$

stimulus groups were not only higher at all of the two added training orientations (in 6/6 cases) but also at most of the testing orientations that were untrained and common to both the one-stimulus and the three-stimulus training groups (in 16/18 cases). Both of these results contributed to the flatter three-stimulus generalization gradients in Figure 6.

We performed a two-way Testing Orientation (9) × Training Group (4) ANOVA on the accuracy scores of the four training groups across the four stimulus objects to determine if the stimulus generalization gradients differed reliably from one another. A significant main effect of testing orientation was found, $F(8, 80) = 20.16, p < .001$, but there was no significant main effect of training group, $F(3, 10) = 2.80, p = .095$. There was a significant interaction between testing orientation and training group, $F(24, 80) = 7.25, p < .001$. Significant Testing Orientation × Training Group interactions that resulted from follow-up pairwise ANOVAs on each gradient versus every other gradient suggested that the shapes all differed reliably from one another; the smallest interaction was $F(8, 48) = 2.69, p < .025$. Finally, simple effects tests along the dimension of testing orientation in each of the four groups were all statistically significant at the $p < .001$ level. In accord with the progressive flattening of the gradients in the four groups seen in Figure 6, the percentages of variance accounted for

by the main effect of stimulus orientation in each of the groups were as follows: Group $33° = 83.37\%$; Group $0°$, $33°, 67° = 81.86\%$; Group $-33°, 33°, 100° = 81.38\%$; and Group $-100°, 33°, 167° = 78.42\%$. Also in accord with the progressive flattening of the gradients in the four groups seen in Figure 6, the F statistics associated with each of the groups were as follows: Group $33° = 15.04$; Group $0°, 33°, 67° = 13.54$; Group $-33°, 33°, 100° = 8.74$; and Group $-100°, 33°, 167° = 7.27$.

Experiment 2b

The between-subjects gradients generated by the different training conditions in Experiment 2a supported the conclusion that stimulus generalization along the dimension of depth rotation is a clear function of the number and spacing of the orientations shown to the pigeons during discrimination training. In the present experiment, we wanted to see how those subjects who were trained with one depth rotation of drawings of each training object would respond when they were later trained with three depth-rotated drawings of the same objects. Such a within-subject comparison might then corroborate the results of the earlier between-subjects comparison of the effects of single versus multiple training views on depth rotation generalization.
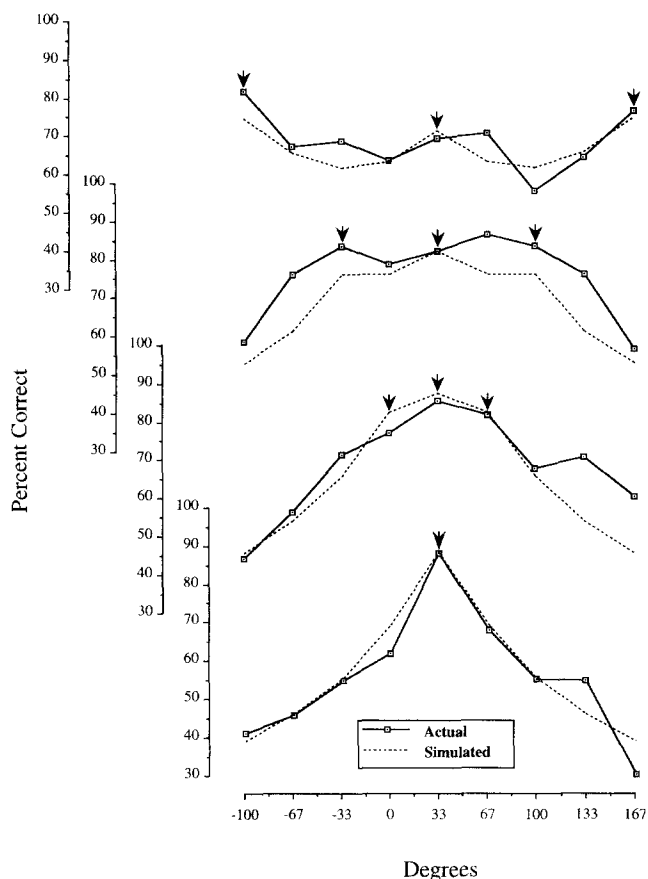
Figure 6. The mean percentage of correct choice responses to all of the stimuli shown to all four groups of pigeons during generalization testing in Experiment 2a (solid lines with symbols); the arrows indicate the orientations at which differential reinforcement was given in training. Also depicted are the scores that were simulated with the Spencian model described in the General Discussion (dashed lines without symbols).

So, pigeons in Group 33° of Experiment 2a were later trained on the same discrimination task that had been given to pigeons in Group 0°, 33°, 67° of Experiment 2a. We chose to train birds at 0°, 33°, and 67° in Experiment 2b because the results of Experiment 2a showed that discrimination training at these three values had the smallest effect on the shape of the generalization gradients of all three tasks involving three stimulus orientations. The present experiment seeking reliable within-subject effects would then be exploring the conditions least likely to produce them according to the between-subjects data. Generalization testing was finally conducted as in Experiment 2a.

Method

Subjects, Apparatus, and Stimuli

All 4 subjects in Group 33° of Experiment 2a served in Experiment 2b. The apparatus was the same as in Experiments 1a, 1b, and 2a. The same line drawings used in Experiments 1b and 2a were used here.

Procedure

Discrimination training. All 4 pigeons were trained for 40 days like subjects in Group 0°, 33°, 67° of Experiment 2a.

Generalization testing. The testing procedure was identical to that given to all of the subjects in Experiment 2a.

Results

Discrimination Training

Discrimination training was effective in supporting highly discriminative behavior in the presence of the four object drawings at all three depth rotations. During the last 8 days of training, the mean percentages of correct choice responses across all four object drawings at 0°, 33°, and 67° were, respectively, 84%, 87%, and 86%.

Generalization Testing

As revealed in Table 3 and Figure 7, both the individual and the group mean stimulus generalization gradients were generally flatter after training at depth rotations of 0°, 33°, and 67° relative to initial training at 33° only. This evident flattening was produced by (a) enhanced discriminative performance at the two added training orientations of 0° and 67° (in 8/8 individual cases) and (b) enhanced generalization performance to the six untrained orientations of −100°, −67°, −33°, 100°, 133°, and 167° (in 20/24 individual cases). Three of the 4 pigeons also showed enhanced discriminative performance at the 33° training orientation.

We performed a two-way Testing Orientation (9) × Training Orientation Set (2) ANOVA on the percentage correct scores across the four stimulus objects of the 4 birds given one- and three-orientation training in Experiments 2a and 2b, respectively, to see if the generalization gradients differed reliably from one another. A significant main effect of testing orientation was found, $F(8, 24) = 15.34$, $p < .001$, as well as a significant main effect of one versus three training orientations, $F(1, 3) = 14.68$, $p < .05$. The Testing Orientation × Training Orientation interaction fell just short of the .05 level of statistical significance, $F(8, 24) = 2.10$, $p = .077$. Thus, training at 0° and 67° (along with additional training at the original training value of 33°) reliably raised and generally flattened the stimulus generalization gradient relative to that obtained after training at 33° only.

The results of Experiments 2a and 2b suggest the same conclusion: Adding depth rotations to the training set of object drawings tends to flatten the stimulus generalization gradient along the dimension of rotation in depth. Although more widely distributed training orientations more effectively broadened the stimulus generalization gradient, even the most compactly distributed set of three values (within a range of ± 67°) had a flattening effect on the generalization gradient. Indeed, that particular set of training values (0°, 33°, and 67°) was included in both Experiment 2a (where subjects in Group 0°, 33°, 67° were concurrently trained with these three orientations) and in Experiment 2b (where

Table 3

Individual Subject and Group Mean Choice Accuracy in Percentage Correct Across All Four Objects at All Nine Orientations Given During Testing in Experiment 2b and in Select Groups of Experiment 2a

Bird	−100°	−67°	−33°	0°	33°	67°	100°	133°	167°
				Orientation					

Experiment 2a: Group 33°

Bird	−100°	−67°	−33°	0°	33°	67°	100°	133°	167°
1	35.42	43.75*	50.00*	47.92*	**85.42***	66.67*	47.92*	35.42	8.33
2	37.50	58.33*	64.58*	68.75*	**91.67***	72.92*	68.75*	75.00*	47.92*
3	56.25*	60.41*	70.83*	75.00*	**95.83***	75.00*	64.58*	81.25*	50.00*
4	45.83*	31.25	43.75*	66.67*	**89.58***	66.67*	50.00*	37.50	25.00
M	43.74*	48.44*	57.29*	64.59*	**90.63***	70.32*	57.81*	57.29*	32.81*

Experiment 2b: Group 0°, 33°, 67°, after 33°

Bird	−100°	−67°	−33°	0°	33°	67°	100°	133°	167°
1	33.33	41.67*	75.00*	**81.25***	**77.08***	**68.75***	60.42*	43.75*	41.67*
2	43.75*	60.42*	70.83*	**85.42***	**97.92***	**89.58***	79.17*	77.08*	66.67*
3	56.25*	66.67*	75.00*	**79.17***	**97.92***	**87.50***	97.92*	91.67*	50.00*
4	56.25*	45.83*	93.75*	**93.75***	**100.00***	**77.08***	58.33*	60.42*	77.08*
M	47.40*	53.65*	78.65*	**84.90***	**93.23***	**80.73***	73.96*	68.23*	58.85*

Experiment 2a: Group 0°, 33°, 67°

Bird	−100°	−67°	−33°	0°	33°	67°	100°	133°	167°
1	58.33*	56.25*	64.58*	**75.00***	**83.33***	**81.25***	77.08*	64.58*	58.33*
2	31.25	54.17*	64.58*	**72.91***	**81.25***	**72.92***	56.25*	72.92*	62.50*
3	33.33	62.50*	81.25*	**85.42***	**89.58***	**83.33***	72.92*	81.25*	62.50*
4	54.17*	52.08*	75.00*	**75.00***	**87.50***	**89.58***	64.58*	64.58*	58.33*
M	44.27*	56.25*	71.35*	**77.08***	**85.42***	**81.77***	67.71*	70.83*	60.42*

Note. Scores in bold type are to the training orientations.
*$p < .01$.

these three orientations of each object were given to subjects after they had first been trained at 33°). A direct comparison of these conditions in equivalent testing sessions (shown in Table 3) failed to divulge a reliable difference between their stimulus generalization gradients: By two-way ANOVA neither a training group main effect, $F(1, 6) < 1$, nor a Training Group × Testing Orientation interaction, $F(8, 48) < 1$, was significant.

General Discussion

Empirical Summary

The results of these four experiments lead to the following empirical conclusions: (a) Pigeons trained to discriminate line drawings of four complex objects shown at only a single spatial orientation are able to generalize their discriminative responding to novel depth rotations of the four depicted objects over a range of ± 133°. (b) The depth rotation generalization gradient after single-orientation discrimination training is of the same basic form as that obtained in many other studies that have used a wide range of other physical dimensions (Honig & Urcuioli, 1981). (c) As is the case for other physical dimensions, such as color (Kalish & Guttman, 1957, 1959), training with multiple depth rotations broadens the generalization gradient based on stimulus orientation (also see Logothetis et al., 1994). And, (d) training with more widely spaced depth orienta-

tions more effectively broadens the stimulus generalization gradient (Kalish & Guttman, 1957).

Theoretical Analysis

How are we to account for these empirical findings on the pigeon's visual recognition of drawings of depth-rotated objects? Current theorizing about viewpoint generalization in human vision has coalesced around two proposals.

One posits *templates* of a particular pose of an object as experienced by the viewer (e.g., Edelman & Bülthoff, 1992; Poggio & Edelman, 1990; Rock, 1973; Tarr, 1995). Generalization to nearby orientations can be done through smooth deformations of the template, with only a modest cost in time or accuracy. With greater orientation differences from that originally experienced, a slower process akin to mental rotation may be used.

The second posits a structural description of specified relations among shape primitives, termed *geons,* corresponding to an object's elementary parts, such as bricks, cylinders, wedges, and cones (Biederman, 1987; Biederman & Gerhardstein, 1993; Hummel & Biederman, 1992; Marr & Nishihara, 1978). The geons are distinguished by differences in *viewpoint-invariant properties* (VIPs) of orientation and depth discontinuities, such as whether the edges at the discontinuities are straight or curved, the type of vertex (e.g., L, fork, or arrow) formed by coterminating edges, or whether pairs of edges are approximately parallel. In con-
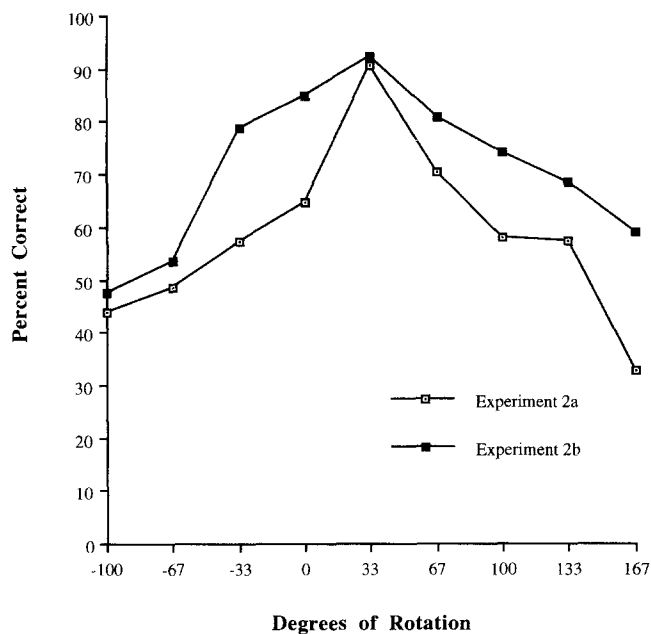
Figure 7. The mean percentage of correct choice responses to all of the stimuli shown during generalization testing to those pigeons who served in both Experiment 2a and Experiment 2b. Discrimination training in Experiment 2a was at the 0° orientation; discrimination training in Experiment 2b was at 0°, 33°, and 67°.

trast to VIPs are *metric properties* (MPs), such as the degree of curvature or the length or aspect ratio of an edge or part. MPs vary continuously with rotation in depth. According to geon theory (Biederman & Gerhardstein, 1993), as long as the same parts and relations are in the image, rotation in depth should have no effect on recognition performance once allowance is made for the resolution of the information. To the extent that depth rotation occludes some parts and reveals others, similarity and recognition would be reduced. (It is also necessary to include a resolution function that allows partial activation as a geon becomes partially occluded or revealed.)

Template theories essentially regard all shape variation as metric, with no special status accorded to nonaccidental properties or parts. Continuous variation is thus expected as objects are seen at new orientations in depth. Geon theory holds that a template system might exist in humans in the dorsal pathway for motor interaction (Biederman & Cooper, 1992; Biederman & Gerhardstein, 1993, 1995) but that it would serve only as a secondary system for object recognition. The decline in recognition performance that is often observed when complex objects are viewed at novel depth rotations, according to geon theory, is a consequence of the accretion and deletion of parts. If parts do not change, then no cost of rotation in depth may be observed (Biederman & Bar, 1995; Biederman & Gerhardstein, 1993).

Empirically, there is enormous variation in the rotation costs that have been obtained in different studies of human recognition performance (reviewed by Biederman & Ger-

hardstein, 1993). Biederman and Gerhardstein (1993) hypothesized that robust generalization would occur if three conditions were met. First, the image of an object had to be decomposable into viewpoint-invariant parts, so that a structural description specifying the geons and their spatial interrelations could be activated. Second, the geon structural descriptions of the images to be discriminated had to be distinctive from one another. And third, multiple views of the same object had to have the same structural description. When these three conditions were not met, viewpoint invariance was not obtained.

We did not design the present study to distinguish between template, geon, and any other accounts. Nevertheless, it is instructive to see how each of the two highlighted theories might be applied to the results of our study.

Template Theory

According to template theory, separate templates are created for each experienced view of an object. If a given image matches a previously stored view, then object recognition is achieved. If a given image does not match a previously stored view, then a cost in recognition time, accuracy, or both is incurred that is proportional to the angular difference between the present image and its closest stored view. From this perspective, the reason why pictures of the airplane at 33° and 67° in Figure 1 are correctly identified as the same object as that at 0° is either (a) that all three views have been stored in memory with a common association to the response "airplane," (b) that only the 0° view is stored and the other two views are sufficiently similar to it for them to occasion the correct response, albeit with lower probability, or (c) that only the 0° view is stored and the others are mentally rotated until they match it.

According to template theory, then, generalization from a single stored view is to be expected, with recognition dropping as the testing view deviates from the training view. Furthermore, adding different views to the training set and increasing the spacing between those views should enhance stimulus generalization to novel viewpoints by increasing the number and applicability of the stored templates. All of these expectations were realized in our data (cf. Logothetis et al., 1994).

Geon Theory

According to geon theory, our pigeons' visual discrimination performance would show complete generalization to all other viewpoints after having been trained at only a single orientation of the four object drawings only if all three of the previously listed conditions for robust generalization had been fulfilled.

The pigeons' training stimuli were chosen because they were decomposable into specifiable geons. Also, the structural descriptions of all four stimuli—as well as the specific geons from which these four stimuli were constructed— were quite different from one another. But, as drawings of each of these four objects were rotated in depth, parts were

sometimes gained (through revelation) and sometimes lost (through occlusion)—for example, the curved chair supports, the flashlight lens, the desk lamp bulbs, and the airplane tailpieces depicted in Figures 1 and 3. So, generalization decrement from depth rotation is to be expected from geon theory for the present experimental stimuli.

What about the influence of the number and spatial orientation of the training viewpoints on the pigeons' generalization testing performance? Assuming that multiple and increasingly discrepant views of an object portray different geons or structural descriptions of the same object, associating such different visual information with the same response should enhance the birds' ability to choose correctly among the four report alternatives when they are shown untrained viewpoints of those objects during generalization testing. Again, geon theory can explain the details of our pigeons' behavior.

Modeling the Data With a Discrimination Learning Model

Whatever the representation mediating the decline in generalization with rotation, is it compatible with a standard associative learning model? To address this question, we implemented a recent version of Spence's (1937) theory of discrimination learning that also incorporates Rescorla and Wagner's (1972) associative learning assumptions (Astley & Wasserman, 1992; Wasserman & Astley, 1994). (See Guttman and Kalish [1956], Kalish and Guttman [1957, 1959], and Logothetis et al. [1994] for similarly inspired simulation efforts.) Central to this discrimination learning model—which bears a strong affinity to template models of visual recognition performance—is that the tendency to make the correct choice response increases as a direct function of (a) reinforcement in the presence of a particular stimulus and (b) generalization from other similar stimuli along a physical continuum.

To simulate the results of Experiment 2a—the investigation that best allowed us to evaluate the suitability of the model to our data—we used a λ of 100 and a combined α and β of .0001 in the familiar Rescorla–Wagner equations. We selected a generalization parameter of .71 for every 33° of rotation that one stimulus differed from another because this value best eyeball-fit the empirical function of the single-orientation training squad (Group 33°) in Experiment 2a. Each of the four simulated groups was trained for the same total number of trials (1,000).

The simulated scores are shown along with the actual group mean data in Figure 6. The close fit of the actual and the simulated scores in Group 33° is unremarkable; we selected the model's parameters so that this fit would be good. However, the fits in Group 0°, 33°, 67°, Group −33°, 33°, 100°, and Group −100°, 33°, 167° also proved to be good and nicely captured the overall shape of the resulting generalization gradients. The fit in Group −100°, 33°, 167° is particularly noteworthy; here, not only is a gull-shaped gradient produced, but its two endpoints are actually a bit higher than its center point, perhaps owing to the fact that

the endpoints are closer (99° separation) to one another on the circular continuum than either is to the center point (133° separation).

Further evaluation of the stimulus-specific approach could come from examining the latencies of subjects' choice responses. Unfortunately, even though our testing periods were rather protracted, they did not include nearly enough observations for meaningful latency analysis to be conducted. Not only does this analysis require a large number of scores, but these scores must come only from correct trials in order to deal with the problem of speed–accuracy trade-off. Future work should be designed so that latency analysis can be properly performed.

Discriminating Between Rival Theoretical Accounts

There is growing evidence that recognition-by-components not only effectively describes the visual performance of humans (Biederman, 1987; Hummel, 1994; Hummel & Biederman, 1992) but also does a good job of describing the visual performance of pigeons under comparable task demands (Kirkpatrick-Steger & Wasserman, 1996; Van Hamme, Wasserman, & Biederman, 1992; Wasserman, 1993; Wasserman, Kirkpatrick-Steger, Van Hamme & Biederman, 1993). Recent research shows that, at least under some circumstances, humans' recognition of line drawings (Biederman & Gerhardstein, 1993) and rendered images (Biederman & Bar, 1995) of objects can be viewpoint invariant: People can show complete generalization to novel views after exposure to only a single training view.

Both template and geon interpretations can clearly account for our pigeons' accurate and systematic generalization performance after single- and multiple-viewpoint discrimination learning. The next step in our analysis of pigeons' visual performance will be to examine their discrimination and generalization of rendered nonsense objects like those used by Biederman and Bar (1995). These investigators, using a same–different task in which the objects could differ in depth orientation, demonstrated robust discrimination when stimuli differed in a geon but virtually no discrimination when they differed only in metric properties. An important control in their study was that geon- and metric-differing stimuli were equally discriminable when the objects were shown at the same orientation. The same pattern of results with pigeons would suggest that the failure of Cerella's (1977) pigeons to show generalization over depth rotations was due to their having to discriminate metric stimulus differences.

Another way to attack this problem will be to use Biederman and Gerhardstein's (1993) stimuli that, despite substantial rotation in depth, do not change the structural description of the depicted object or add to or subtract from any of the object's component parts. Creating stimuli that have these properties is not an easy chore, but it is possible. And, at least in human beings, these stimulus changes support undecremented visual generalization performance (Biederman & Gerhardstein, 1993) and thereby favor geon over template interpretations of visual recognition.

Eventual discrimination between template and geon interpretations will require many converging lines of empirical evidence. Generalization over rotation in depth is but one of those lines. Generalization over contour deletion (Van Hamme et al., 1992) and generalization over parts jumbling (Wasserman et al., 1993) are others. To date, these other tests with humans (reviewed by Biederman & Gerhardstein, 1995) and pigeons (reviewed by Wasserman, 1993) have been most encouraging for the theory of recognition-by-components. We expect future work by both supporters and critics (Tarr & Bülthoff, 1995) of this theory to help elucidate the mechanisms of visual recognition—in both human and nonhuman animals. We thus share Cabe's (1980) opinion that "comparative behavior analysis may allow both the extrapolation of neurophysiological results to the human case and the demonstration of possible evolutionary patterns in perceptual and cognitive processes" (p. 306).

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