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Recognition of objects and spatial relations in pictures across changes in viewpoint

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Abstract. The ability to recognize objects or places despite variation in viewpoint seems fundamental to many adaptive behaviors. But do animals recognize objects or places in static pictures across changes in view? In Experiment 1, pigeons with prior outdoor experience were trained to locate an unmarked goal in 6 views of a scene presented on a touch-screen monitor. The goal location was fixed relative to landmarks in the scene, but 2-D vectors from landmarks to the goal varied across views. Pigeons learned the task, but showed poor transfer to novel views. Their performance resembled that previously seen in laboratory-raised pigeons with the same images, but differed from that previously seen in outdoor-experienced pigeons trained with more views of a different scene. Thus, stimulus and/or training factors, rather than outdoor experience, may determine degree of transfer to novel views. Experiment 2 explored pigeons' object recognition across changes in viewpoint. One group discriminated objects composed of identical parts and another group discriminated objects composed of different parts. Baseline accuracy was higher for the different-parts group, but transfer to novel views was comparable across groups. Both groups generalized across views, but accuracy decreased with rotation from the nearest training view. Implications for the use of pictorial stimuli to study cognitive processes in animals are discussed.

Key words: Landmark-based search, object recognition, picture processing, pigeons, scene recognition, viewpoint dependence.

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INTRODUCTION

For the past three decades, many cognitive and perceptual processes have been investigated in animals through presentation of pictorial stimuli. Studies investigating processes such as object recognition, categorization, and spatial learning using colored slides or digitized images have clearly shown that pigeons process and remember rich visual details in pictorial stimuli. Although this work has provided sufficient evidence to justify the use of such stimuli for investigation of many cognitive processes, much remains to be known about exactly how pictorial stimuli are perceived by pigeons, and to what extent pigeons' perception of pictorial stimuli is similar to their perception of real-world objects and scenes. For example, questions such as whether pigeons detect three-dimensionality of objects and scenes, and whether they can recognize pictures as representations of real world objects or scenes have been addressed in recent work but remain in need of further investigation (see D'Eath, 1998, for an excellent recent review). Understanding how pigeons perceive pictorial information is important, both because it will advance our understanding of basic avian visual cognition and because it will facilitate interpretation of results of studies using pictorial stimuli to investigate other cognitive processes.

There have been two main approaches to the question of whether pigeons and other avian species recognize pictures as representations of the real world. One has been to test for transfer of a learned response from pictures to real objects or scenes and vice versa. Evidence from studies taking this approach has been mixed, with several studies finding some degree of transfer (Cabe, 1976; Cole & Honig, 1994; Looney & Cohen, 1974; Watanabe, 1993; Wilkie, Willson, & Kardal, 1989), but others not (Bradshaw & Dawkins, 1993; Dawkins, Guilford, Braithwaite, & Krebs, 1996; Lechelt & Spetch, 1997). Another approach has been to look for appropriate behavioral responses, such as courtship, preferences, or aggressive behaviors to pictures of biologically significant stimuli, such as a picture of a conspecific. Again, the results have been mixed. For example, Looney and Cohen (1974) found that pigeons attacked and pecked at the head area of pigeons presented in color photographs when induced to display aggression by interruptions in feeding. However, Dawkins (1996) failed to find evidence of socially appropriate behaviors by hens toward photographs of conspecifics; although the hens chose flock-mates over unfamiliar birds as feeding companions,

they did not show a significant preference for photographs of flock mates. Very recently, Shimizu (1998) found that courtship behavior by male pigeons to video images of female pigeons was equivalent to that shown to live female pigeons, and substantially greater than that shown to video images of a cockatoo. Courtship displays were more vigorous when the video was in motion and when the head region was available. By contrast, Ryan and Lea (1994) failed to observe socially-appropriate responses from pigeons to life-size moving images of pigeons. Differences between studies in stimuli, task requirements, and species investigated could underlie some of the discrepancies in results. Moreover caution must be taken in interpreting failures to treat pictorial stimuli as real objects or scenes. As discussed extensively in a recent review by D'Eath (1998), pictorial stimuli are clearly impoverished representations of the real world and may not portray some visual features, such as color, accurately to non-human visual systems. Further distortions may occur when video stimuli are used, because screen refreshing may result in the perception of flicker for animals with high critical flicker-fusion thresholds.

Evidence has also been mixed on the issue of whether pigeons perceive three-dimensional depth information in pictures. One approach to this question has been to seek evidence of known perceptual illusions that may result from the perception of depth. One such illusion is the Ponzo illusion in which two parallel bars are located between two converging lines. To humans, the bar near the apex of the lines looks longer than the bar further away, possibly because linear perspective cues provide the illusion of depth. Pigeons as well as other animals have been found to show perception of such an illusion (horses, Timney & Keil, 1996; monkeys, Bayne & Davis, 1983; and pigeons, Fujita, Blough, & Blough, 1991, 1993), although the specific characteristics of the illusion are not completely identical with that found in humans (Fujita et al., 1991, 1993). Another known perceptual phenomenon that presumably indicates depth perception is completion of partially occluded objects. Although chicks (Lea, Slater, & Ryan, 1996; Regolin & Vallortigara, 1995), mice (Kanizsa, Renzi, Conte, Compostela, & Guerani, 1993), and monkeys (Osada & Schiller, 1994) have been found to show completion of occluded objects, pigeons have thus far failed to show this effect (Cerella, 1980; Sekuler, Lee, & Shettleworth, 1996).

Another approach has been to assess the ability to discriminate between two-dimensional and three-dimensional objects presented in pictures. Hershberger (1970) trained chicks to discriminate convex and concave dents in an aluminum panel and found that their discrimination transferred to photographs of the training dents, suggesting that they could detect depth from the shading information present in photographic stimuli. More recently, Reid and Spetch (1999) trained pigeons on a "3-dimensionality concept" using a large set of object pairs that were displayed side by side in digitized images. The target object was 3-dimensional, and provided both shading and perspective cues for depth. The shading and/or perspective cues were absent or distorted for the distractor object. The pigeons learned to select the 3-dimensional object, and their accuracy remained above chance on transfer tests with completely novel target and distractor objects. At the very least, these results suggest that pigeons can form a concept based on pictorial cues that distinguish 2-dimensional and 3-dimensional objects; whether they actually see the pictures as representations of 3-dimensional objects is more difficult to determine.

The present research addresses a slightly different aspect of pigeons' picture perception, namely, the extent to which their recognition of spatial relationships and objects presented in pictures generalizes across changes in perspective. In natural settings, animals are frequently faced with the problem of recognizing places and objects from different viewpoints, due to their own movement or to the movement of an external object. Quick and accurate object and place recognition despite changes in position of the object or viewer would appear to benefit many adaptive behaviors, such as returning to a nest or feeding site, recognizing a conspecific, or avoiding predators. Thus, an interesting question from the perspective of picture processing is whether animals can readily and accurately recognize spatial relationships and objects in pictures across changes in viewpoint. The two experiments reported here follow from studies on pigeons recently conducted in our laboratory. The first uses a landmark-based search task and investigates pigeons' ability to generalize spatial localization across different views of a complex naturalistic scene. The second concerns pigeons' generalization of object recognition across changes in orientation. In both studies, the basic procedure involved training with a set of views and then testing for transfer to novel views.

EXPERIMENT 1

In several studies we have shown that pigeons can use visual landmarks in images of a scene to accurately locate a small unmarked area in the scene (Lechelt & Spetch, 1997; Spetch & Wilkie, 1994; Spetch, Kelly, & Lechelt, 1998). This demonstrates the processing of visual details in the scene and of spatial relationships, but by itself does not tell us whether the scene is processed as a representation of three-dimensional space. In a recent study (Spetch et al., 1998), we attempted to address this question by training pigeons with images that showed a scene from different viewpoints. The pigeons' task was to find a small unmarked location in the scene. When shown from different viewpoints, the 2-dimensional spatial relationships between visual landmarks and the unmarked spot changed across images, even though the depicted three dimensional relationships in the scene were invariant. Thus, if the images were processed only in terms of two-dimensional relationships, this would be equivalent to training the birds to find a goal that moved about with respect to the landmarks. Not only should such learning be difficult because it would require memorization of different two-dimensional relationships for each trained image, but we would also expect little transfer to novel viewpoints because these would provide new two-dimensional relationships. On the other hand, if the images were processed in terms of the underlying three-dimensional relationships in the depicted scene, then only one set of landmark-goal relationships need be learned, and transfer to novel viewpoints should be possible because the same three-dimensional relationships exist. In Experiment 1 of Spetch et al. (1998), pigeons were trained with six different views of an outdoor scene and then tested for transfer to six novel views. The pigeons used were laboratory Silver King pigeons with no outdoor experience. The pigeons learned the task but showed poor transfer to the novel views. In a second experiment, racing pigeons with prior outdoor experience were trained with 28 different views of a different outdoor scene and then were tested with 18 novel views. The birds again learned the task, albeit slowly, and in this case, good transfer to the novel views was found. This study showed that transfer of landmark-based search can occur under a restricted set of conditions. However, it did not isolate which condition(s) are critical for transfer because several factors changed between the first and second experiments, including the past experience and strain of the pigeons, the nature of the scene and visual landmarks, and the number of training and test views. Any or all of these factors could account for the difference in transfer results.

The present study represents a first attempt to determine whether subject factors (past experience or strain of pigeon) or stimulus factors (type of scene or number of training and test orientations) are more important for the occurrence of good transfer across changes in viewpoint. Accordingly, we trained and tested outdoor-experienced racing pigeons with the stimulus materials and training conditions that had generated poor transfer in laboratory pigeons. If prior outdoor experience and/or strain of pigeon are critical in the emergence of transfer across orientations, then these birds might show superior transfer to novel orientations than had been observed for the laboratory pigeons. On the other hand, if the nature of the stimulus and/or the number of training and test orientations are critical, then racing pigeons might also show poor transfer performance under these conditions.

Method

Subjects. The subjects were 4 adult pigeons obtained from the same local pigeon racer who supplied the pigeons used in Spetch et al. (1998). The pigeons in this and the previous studies were a local strain bred specifically for racing performance. They had previous outdoor experience through their participation in races, but they were naive with respect to experimental procedures and the scene depicted in the images. For at least four weeks prior to, and throughout the experiment, the birds were housed indoors in large individual cages under a 12 hour light/dark cycle (lights on at 6:00 a.m.). All birds were maintained at approximately 85% of their free-feeding weights by Kay Tee pigeon pellets obtained after experimental sessions and mixed grain during experimental sessions. Water and grit were available ad libitum in the home cages.

Apparatus, stimuli, and search space. The apparatus and search space were identical to those used in Experiment 1 of Spetch et al. (1998). The custom-built experimental chamber was 44 cm high, 32 cm deep, and 74 cm wide (inside dimensions), with a large opening in the back wall which provided access to the surface of a Zenith 1492 color monitor with attached infrared touch frame (Carroll Touch, 1492 Smart Frame). Spacers separated the touch frame by approximately 3 cm from the opening, and by approximately 1.6 cm from the monitor. Two Gerbrands grain feeders were mounted on the back wall, one on each side of the monitor, with the feeder openings 8.5 cm from the sides of the monitor opening, and 17 cm from the floor. Lamps located within each feeder illuminated feeder presentations and photocells in each hopper measured head entries to limit eating times. Experimental contingencies and response detection were controlled by a microcomputer located in an adjacent room. The touch frame was programmed to detect individual responses (i.e., detection of a beam break, and subsequent return to an unbroken state before another response would be recorded). The search space was a rectangular area, approximately 26 × 20 cm, on the surface of the color monitor.

The images used for training and for testing were the same as those used in Experiment 1 of Spetch et al. (1998). The procedures for producing and editing the images, and for matching the goal location to touch-screen coordinates, are described in Spetch et al. (1998). The training images displayed six different views of an outdoor scene which contained three landmarks (a chair, potted flowers, and a pile of logs) near the goal, as well as several visually distinct background cues (house, flowers, trees, etc.). These views had been selected to be noticeably different from one another and to differ from one another in the absolute location of the goal on the computer screen. A blue plastic box marked the goal area in images used during preliminary training only. The goal marker was absent in the images used during the later stages of training and during all testing. The test images used during the first test series consisted of six novel views of the same scene. These novel views differed from the training views both in visual appearance and in the location of the goal on the computer screen. During a second test series, the images used for testing were derived from the six training images but had some of the visual information (the nearby landmarks, the background cues, or both) edited out of the scene.

Procedure

– *Preliminary training*. Each bird first received one or two sessions of training to eat from the raised illuminated hopper. All birds then received several sessions of training with a modified autoshaping procedure to establish reliable pecking at the monitor. Initially, a 2-cm blue square was intermittently presented in various screen locations against a green background, with 60-s intertrial intervals (ITI). The blue square remained on until the bird pecked at it, or until 8 s elapsed, and then food was presented. Once reliable pecking was established to the blue square, the six images shown in the top of Figure 1 were introduced (with a rectangular goal marker present as illustrated in the first image). Pecks in a 2-cm area centered at the goal marker were reinforced immediately; otherwise the display terminated with food after 8 s. For the final session of preliminary training, the ITI was decreased to 5 s and the image stayed on until a peck in the goal area was recorded.

– *Search training*. The procedure used for search training was identical to that used in Experiment 1 of Spetch et al. (1998). During initial search training sessions, the goal marker was gradually eliminated so that the pigeons needed to rely on visual cues in the scene to find the goal. This was accomplished by presenting images that were edited so that the marker was covered with patches of grass. Images were created in which the grass covered about 50%, 75%, and finally 100% of the marker (all, except the top left, images in Figure 1 show examples of images with the marker 100% covered). This phase of search training continued until the bird completed (by pecking in the goal area) at least 80 trials in a 60 m session with the goal marker absent. During the next few sessions, the number of pecks in the goal required to terminate the trial and obtain food was increased to 2, and then to 3. Next, a consecutive peck requirement was added such that the last two pecks recorded had to be consecutive pecks in the goal area. Thus, the response requirement during the final stage of training and for all subsequent baseline sessions was a minimum of three pecks in the goal with the last two

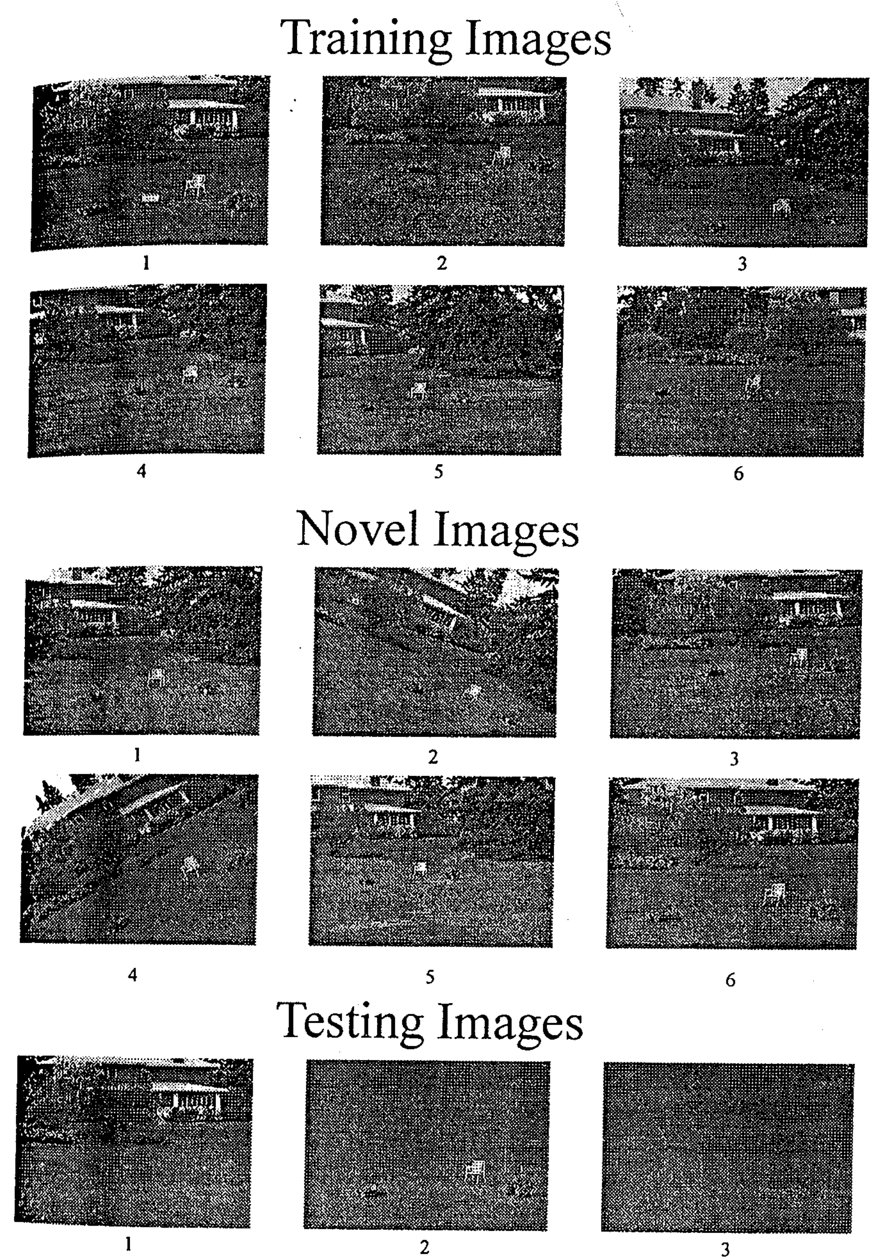

Figure 1. Images used for training and testing in Experiment 1.
The top set of images shows the 6 training views. The rectangular target marker is shown for illustrative purposes in the top left image; except during the preliminary training sessions, this marker was edited out of all images used for training and test sessions. The middle set of images shows the novel views presented during the transfer tests, and the bottom set of images shows the test images that were edited to remove the landmarks (NoLm), the background cues (NoBk), or both (None), respectively.

pecks being consecutive goal pecks. Each increment in the response requirement was implemented only if the bird completed 80 trials in a session. During the last set of search training sessions, the percentage of trials on which reinforcement was available decreased from 100% to 50%. On unreinforced trials, completion of the response requirement terminated the display but no food was presented. Each bird remained on 50% reinforcement for at least 5 sessions and advanced to the test phase only after completing at least 80 trials on each of the last two sessions. Rate of learning varied considerably, with 2 birds requiring less than 100 sessions (76 and 99), and 2 birds requiring over 200 sessions (217 and 224).

- *Testing*. All birds received two test series, separated by a return to baseline training for two or more sessions, depending upon performance. A single baseline training session also followed every third test session within each test series. Each test session consisted of 50% reinforced baseline trials. The remaining trials consisted of unreinforced baseline trials, control trials that were visually identical to baseline trials but were procedurally the same as test trials, and test trials with novel or altered images. On control and test trials, the image terminated without reinforcement 8 s following the second peck recorded anywhere on the screen.

The first series was a transfer test in which six novel views of the scene were presented on test trials (middle images in panel of Figure 1). For the second test series, the images presented on test trials had been edited to remove all three local landmarks ("No Lms"), to remove all of the background information ("No Bk"), or to remove both the landmarks and the background ("None"). Examples of these images are shown in the bottom panel of Figure 1. Tests were conducted with edited images of each of the six training views.

Data recording and analysis. All data presented are from unreinforced control and test trials. Data were recorded and analyzed in the same manner as in Spetch et al. (1998). Each response was recorded as touch-screen coordinates that ranged from 0 to 640 in the horizontal dimension and from 0 to 480 in the vertical dimension. The first three pecks made on every trial, and all pecks that fell within 20 pixels from the far edges of the search space, were excluded from the analysis (see Spetch et al., 1998).

Responses were considered correct if they were within 25 pixels of the center of the goal in both the horizontal and vertical dimensions. Accuracy was calculated as correct responses divided by the total responses. All accuracy scores presented are averaged across all test trials of that type.

The accuracy level expected on the basis of chance is very low. For example, random responding on the screen would generate accuracy levels of less than .01. If pigeons learned to respond only within the range of screen locations in which the goal is sometimes found (a range that spanned 230 by 178 pixels), then the probability of a response falling in the 50 by 50 pixel goal area as a result of random responding in this restricted range is .06.

For all statistical tests, our criterion for significance was $p < .05$.

Results

The top graph in Figure 2 shows accuracy scores on the control trials, averaged across the six training views, and on transfer test trials, averaged across the six novel views. For comparison we also show the results obtained by Spetch et al. (1998), with the middle graph showing the results they obtained with lab pigeons that were trained and tested on the same stimuli used here, and the bottom graph showing the results they obtained with racing pigeons that were trained and tested on a different scene and a larger set of viewpoints. The racing pigeons in the present study showed a significant decrement in accuracy when tested with novel views, $t(3) = 15.77$, and thus appear more similar to the lab pigeons of the previous study than to the racing pigeons of the previous study.

The top panel of Figure 3 shows mean accuracy for each of the individual trained and novel images for the racing pigeons in the present study. For comparison, the middle and bottom graphs, respectively, show mean accuracy for the same individual images for the lab pigeons and for humans tests in Spetch et al. (1998). As can be seen, there was a strong positive correlation between the scores obtained by the two sets of pigeons (r = 0.907). By contrast, the scores obtained by humans were not positively correlated with the scores obtained by either the racing pigeons (r = -0.130) or the lab pigeons (r = -0.109).

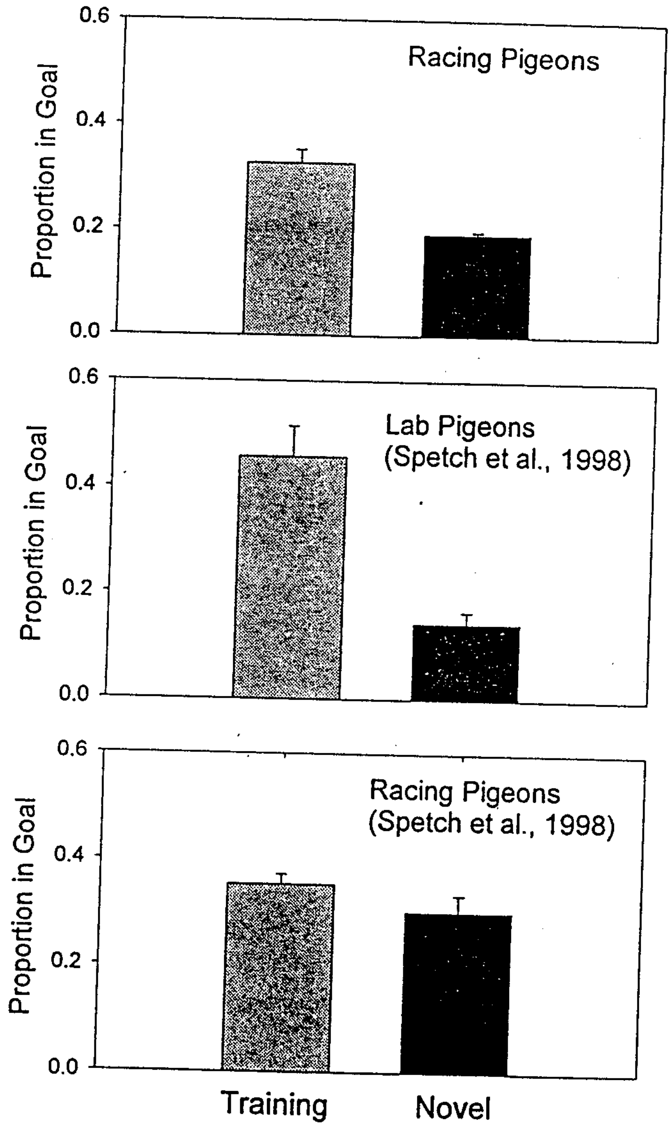

Figure 2. *Mean accuracy during transfer tests, averaged across the six training images and the six novel images, for the racing pigeons of the present experiment, the laboratory pigeons tested by Spetch et al. (1998) with these same images, and the racing pigeons in Spetch et al. (1998) that were tested with a different set of images.*
Error bars represent standard error of the mean.

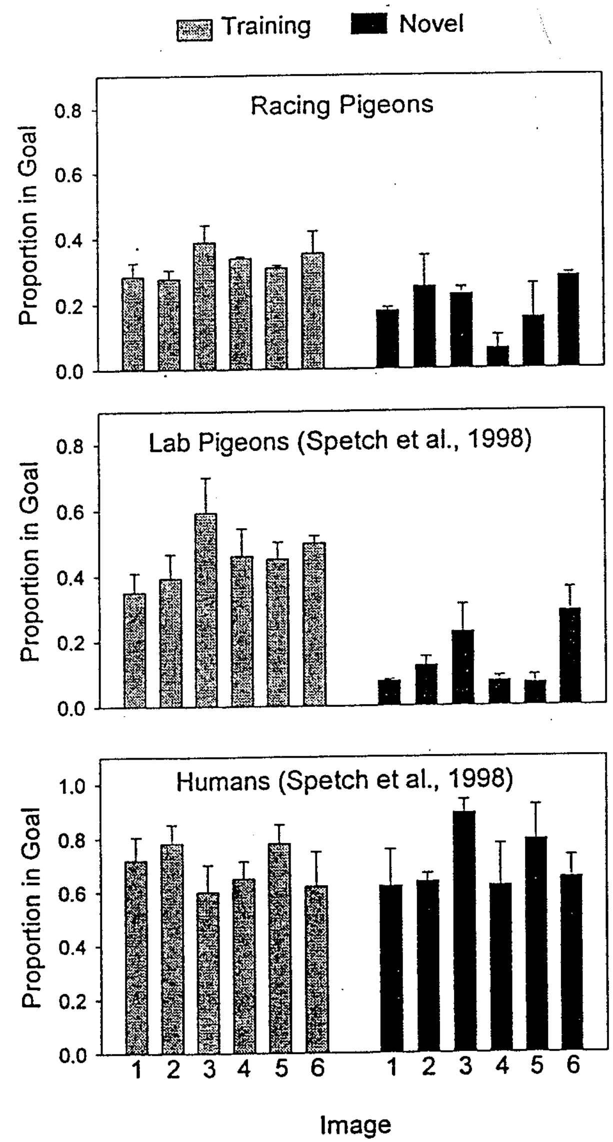

Figure 3. *Mean accuracy for each of the individual training and novel images presented during transfer tests for a) the racing pigeons of the present experiment (top), b) the laboratory pigeons tested by Spetch et al. (1998), and c) the humans tested by Spetch et al. (1988).*
The same set of images was used in each case, and the images correspond to the order shown in Figure 1. Error bars represent standard error of the mean.

The top graph in Figure 4 shows mean accuracy scores on control and test trials during the landmark and background removal tests. Accuracy is averaged across the six views used for each image type. A repeated measures ANOVA revealed a significant effect of Image type, $F(3, 9) = 10.53$. For comparison, results for the lab pigeons and the humans tested in Spetch et al. (1998) on the identical tests are shown in the middle and bottom graphs, respectively. It appears that both sets of

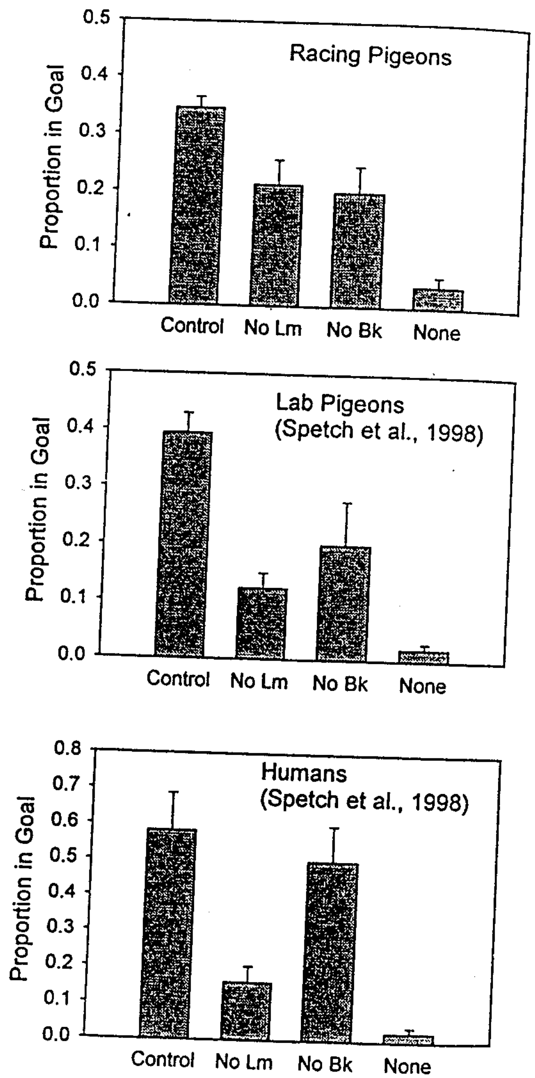

Figure 4. Mean accuracy on control trials with the training images, and on test trials with images that were edited to remove the landmarks (NoLm), the background cues (NoBk), or both (None). Error bars represent standard error of the mean.

pigeons depended to some extent on both the landmarks and the background to respond accurately, whereas humans showed almost exclusive reliance on the landmarks.

Discussion

The results of this experiment failed to support the hypothesis that subject factors (either outdoor experience or strain of pigeons) is a major determinant of whether pigeons process spatial information in pictures in a way that allows transfer to novel viewpoints. Instead, the results of this experiment, which used racing pigeons with prior outdoor experience, are remarkably similar to the previously reported results with lab pigeons. In fact, the very strong positive correlation between the two sets of pigeons in their accuracy on individual images suggests that they processed the information in the pictures in a similar fashion, thus showing good agreement in which viewpoints were easy and which were hard. The decrement in accuracy shown by both sets of pigeons to removal of landmarks or removal of background cues is also consistent with similar spatial information processing, especially given that humans showed disruption only by removal of the landmarks. It appears, then, that the superior transfer to novel images shown by racing pigeons in the Spetch et al. (1998) study was probably due to the use of a different scene that may have provided more salient pictorial cues to depth, and/or the considerably larger set of viewpoints used in training (28) and testing (18).

The finding that transfer of spatial search to novel viewpoints occurs only under certain training or stimulus conditions is perhaps not surprising given the complexity of the task. The novel views not only change the 2-dimensional spatial relationships between the various landmarks in the image, they also alter the appearance of the landmark objects due to the novel orientation from which they are seen. Thus, in order for birds to transfer to novel views they not only would need to recognize and respond appropriately to the spatial relationships at the new orientation, but they would also need to recognize the objects that serve as landmarks despite changes in their appearance from the novel perspective. Difficulties with either of these steps would reduce accuracy on transfer tests. Experiment 2 explores factors that may influence pigeons' ability to recognize objects across changes in their orientation.

EXPERIMENT 2

In Experiment 2, we investigated pigeons' object recognition across changes in viewpoint. Both the task and the stimuli used were less complex than those used in Experiment 1. The task was a simple two-choice discrimination and the stimuli were digitized images of individual objects filmed against a featureless background. These stimuli provided some of the components of a natural scene (e.g., shading cues), but removed much of the complexity thereby allowing us to easily and precisely manipulate characteristics and orientation of the objects presented during training and testing.

The ability to recognize objects seen from different angles is perhaps one of the most fundamental tasks of perception, and it is likely equally critical in the lives of animals as in the lives of humans. Results of studies investigating this ability in pigeons using pictorial stimuli have produced a mixed set of results. Several studies have investigated pigeons' recognition of two-dimensional shapes across rotations in the frontal plane. In some studies, the pigeons were trained with stimuli presented in a particular orientation and then tested for transfer to novel orientations. Although good transfer sometimes occurred to particular orientations (e.g., 180° rotations), transfer was surprisingly poor to some of the novel orientations (e.g., Morgan, Fitch, Holman, & Lea, 1976; Towe, 1954; Vetter & Hearst, 1968). By contrast, Hollard and Delius (1982) and Delius and Hollard (1995) trained pigeons to select an object that matched a sample object and then tested the pigeons with rotations of the comparison objects to produce orientation disparity. With this procedure, the pigeons showed rotational invariance in terms of accuracy and reaction time, both when the incorrect comparisons were mirror images of the objects and when the incorrect comparisons were arbitrary different shapes. It seems likely that rotational invariance as measured by disparity in orientation of simultaneously presented objects is not the same as rotational invariance as measured by tests with novel orientations.

Studies of pigeons' recognition of 3-dimensional objects rotated in depth have also produced variable results. Some studies have found little or no transfer to novel orientations (Cerella, 1977, 1990), some have found rotational invariance for a familiar but not for an unfamiliar object (Watanabe, 1997), and some have found generalization functions in which discriminative performance decreases systematically as an object is rotated further away from the training orientation (Lumsden, 1970, 1977; Lumsden & Pullen, 1970; Reynolds, 1961; Wasserman, Gagliardi, Cook, Kirkpatrick-Steger, Astley, & Biederman, 1996). For example, Lumsden (1970) trained pigeons to discriminate between real 3-dimensional objects that differed in shape. Each object was presented in a single orientation. During subsequent tests, responding to the positive (S+) object decreased systematically as it was rotated further away from the training orientation, with a secondary peak at the mirror-image orientation of the S+.

Wasserman et al. (1996) studied pigeons' generalization to novel depth rotations of line drawings of 3-dimensional objects. In one experiment, pigeons were trained to discriminate line drawings of four distinct objects (i.e., an aeroplane, a chair, a lamp, and a flashlight) presented at a single training orientation. Choice accuracy on tests with novel orientations was well above chance, but decreased as a function of rotation away from the training view. Increasing the training views from one to three increased the degree of generalization to novel rotations.

Taken together, results to date suggest that pigeons can, but do not always, recognize objects in novel orientations. Although rotational invariance can occur, more typically, accuracy decreases as the object is rotated away from the training view.

A great deal of research in humans has been directed toward the question of whether object recognition is object-centered, and hence viewpoint invariant, or viewer centered, and hence viewpoint dependent (e.g., see Biederman & Gerhardstein, 1993; Edelman & Bülthoff, 1992; Jolicoeur & Humphrey, in press; Tarr & Pinker, 1989). Contemporary examples of the viewpoint-independent approach are the recognition-by-components (RBC) theory (Biederman, 1987) and its more recent version, the geon-structural-description (GSD) theory (Biederman & Gerhardstein, 1993, 1995). Both versions hold that objects are represented in memory as structural descriptions of the spatial relations among simple, volumetric, 3-dimensional parts, called geons. Recognition depends equally on the particular geons comprising an object and their spatial arrangements. Thus, viewpoint-depended recognition can be attained provided that (1) an object's image can be decomposed into geons, (2) the arrangement of geons provides a structural description that is distinct from other arrangements, and (3) the structural description of the object is the same across different views. If these conditions are met, recognition should be constant regardless of distance from the training view.

By contrast, multiple-view theories (Bülthoff & Edelman, 1992; Humphrey & Kahn, 1992; Tarr, 1995; Tarr & Bülthoff, 1995; Tarr & Pinker, 1989) assume that objects are encoded within a viewpoint-dependent frame of reference, and are represented as a collection of familiar views that reflect the precise metric (appearance) properties of each experienced viewpoint. Unless the object contains diagnostic features that are not shared by other objects, recognition should vary systematically with distance to the nearest represented viewpoint, because novel percepts must be transformed to match the frame of reference for the nearest stored view. Consequently, recognition speed and/or accuracy should decrease as a function of rotation away from the encoded view(s). More recently, Tarr and Bülthoff (1995; see also Hayward & Tarr, 1997) stated that viewpoint-dependent normalization mechanisms should be expected to dominate recognition when discriminating between visually similar objects, whereas viewpoint–independent mechanisms should predominate when discriminating between visually-dissimilar objects.

Although the issue of whether basic object-recognition processes in humans are object or viewer centered remains controversial, some consistent findings have emerged from studies of humans' recognition of rotated objects. In particular, the composition of the object is critical, with viewpoint invariance most likely to be found if the target object contains a "diagnostic feature" that is not shared by the distractor objects. In fact, both of the aforementioned approaches assume that recognition will be viewpoint invariant if an object can be recognized on the basis of diagnostic features. An interesting question is whether presence of diagnostic features is equally important for pigeons' recognition of depth-rotated objects.

Several of the studies previously described have used objects that contain diagnostic features and have failed to find viewpoint-invariant object recognition in pigeons. Nevertheless, such features may improve generalization of object recognition to novel rotations. The present study is the second of two series of studies designed to directly address the role of stimulus characteristics, and in particular diagnostic features, on pigeons' recognition of rotated 3-dimensional objects. Our first studies (Spetch, Friedman, & Reid, submitted) suggested that pigeons' ability to recognize objects in novel orientations may not benefit from the

presence of a single diagnostic feature to the same extent as humans. In those studies, pigeons and humans were trained to discriminate between two artificially-created objects shown in two different orientations, and then were tested with four novel orientations. The stimuli and experimental conditions were designed to replicate those used in a recent study with humans by Tarr, Bülthoff, Zabinski, and Blanz (1997). The objects were wire frames with different global shapes and in different conditions, either 0, 1, 3, or 5 distinctive parts were added to the objects. In the condition with one added part, the distinctive part differed across objects and could serve as a diagnostic feature. In this case, discrimination between the objects would be possible without attention to the global object shape. Tarr et al. found a large difference between conditions, with the 1-geon condition yielding much less viewpoint dependence than the other three conditions. The humans in Spetch et al. (submitted) also appeared able to use the distinctive part as a diagnostic feature and showed viewpoint invariance in their recognition accuracy in the 1-part condition. Pigeons, however, showed viewpoint dependence in all conditions.

The present study was a systematic variation of the Spetch et al. (submitted) study and was designed to further assess whether pigeons' ability to recognize objects in novel orientations benefits from the presence of a distinctively shaped part that could serve as a diagnostic feature. In the present study, rather than using computer-drawn grey-scale objects, we used digitized images of real objects that were videotaped in various rotations. Although these objects were unfamiliar arbitrary shapes, they provided natural shading cues and thus might appear more realistic than computer drawn objects. The design of this study also differed from the one conducted by Spetch et al. (submitted) in several ways. First, the previous study used a within-subjects design in which all subjects were trained and tested within each object-part condition, whereas we used a between-group design in which some pigeons were trained with objects containing distinctive parts, and others were trained with objects containing identical parts. It seemed possible that sensitivity to the presence of diagnostic features might be greater in a between-subjects design in which only one object discrimination is learned. Second, whereas pigeons in the Spetch et al. study were trained to discriminate one target (S+) object from one distractor (S-) object in each condition, pigeons in the present study were trained to discriminate between one S+ and three S- objects; this might enhance attention to the distinctive features present in the S+ object. And finally, we trained the pigeons with a larger set of orientations (6 rather than 2). Any of these changes might enhance the pigeons' ability to use diagnostic features to recognize objects in novel orientations.

In the present study, one group of pigeons was trained to discriminate objects composed of identical parts and the other was trained to discriminate objects composed of distinctly different parts. Both groups were then tested for transfer to six novel orientations, five of which differed from the nearest training view by only 22°, and one of which differed from the nearest training view by 67°. Based on the literature on object recognition in humans, pigeons in the different-parts group should show less viewpoint-dependence than pigeons in the same-parts group.

Method

Subjects. The subjects were nine Silver King pigeons. Four birds served in the same-parts group and five birds served in the different-parts group. All birds had previous experience with operant chambers equipped with touch-frames but none had previously served in an object discrimination task. All birds were maintained as in Experiment 1.

Apparatus. The apparatus was the same as that described in Experiment 1.

Stimuli. The stimulus set consisted of five different objects created from red Lego™ pieces attached together to form a geometric pattern. Four of the objects were created from the same set of pieces, arranged to form four different global shapes. One of these objects was used as the S+ for the same-parts group and the other three served as the S- objects for both groups. The fifth object was composed of a different set of four pieces and served at the S+ for the different-parts group. The objects and orientations used during training and testing are shown in Figures 5 and 6, respectively. Column 1 shows the S+ for the same-parts group at each rotation, column 2 shows the S+ for the different-parts group at each rotation, and column 3 shows samples of the three objects used as the S- objects for both groups, with each object shown at two of the six rotations used. Images of the objects were created by videotaping each object at each orientation, and then capturing still frames as gif images using a frame grabber system (Creative Labs Video Blaster). These images were then edited using Photofinish software (Zsoft) to create stimulus displays in which a positive and a negative objects were presented side by side. Each object was centered in a rectangular area of approximately 11 cm wide by 16 cm high. The objects were approximately 5.5 cm along the long axis and 4.2 cm along the short axis. Each object was presented equally often on the left and the right during all training and testing conditions.

Procedure. Sessions were conducted at approximately the same time each day, 5, or 6 days per week. Sessions lasted until all scheduled trials were completed or for a maximum of 1 hour. The monitor screen was cleaned at the end of each day and between sessions as needed.

Pretraining. All birds had previous experience in spatial search tasks conducted on the touch screen and hence were trained at pecking the monitor screen, but none had previously participated in a two-choice discrimination task. Each bird was initially given one or two sessions with an autoshaping procedure in order to establish pecking to the stimulus display used in this study. Each autoshaping trial began with the presentation of a stimulus pair, consisting of an S+ and an S- object. The stimulus pair remained illuminated for 8 s or until a peck was recorded within the rectangular area containing the S+ object; the completion of either event resulted in access to a food hopper. Each of the training stimulus pairs (described in the following section) was presented equally often in a randomly-determined order within each autoshaping session. Trials were separated by a 40-s ITI.

Discrimination training. The stimulus pairs used in training were composed of the S+ object and one of the three S- objects, presented in one of six orientations: 0°, 45°, 90°, 135°, 180°, and 225°. For each picture pair, the two objects were presented in the same orientation. For each combination of S- object and orientation, the S+ was shown once on the right and once on the left, making 36 picture pairs for each group. Each of these picture pairs was presented equally often in each session but the order of presentation was randomly determined. Each trial began with the presentation of a stimulus pair that remained on until the pigeon pecked at one of the two objects. Pecks to the S+

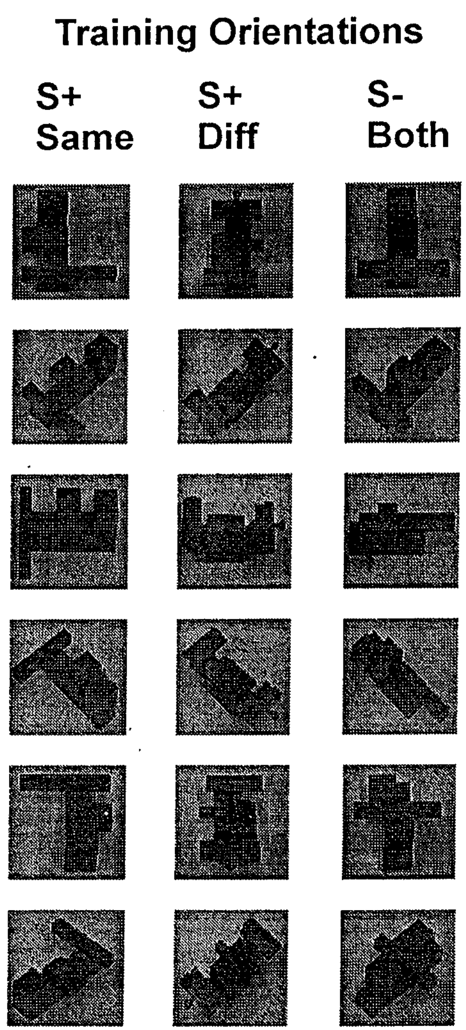

Figure 5. Illustration of the stimuli used during training in Experiment 2.
Column 1 represents the S+ of the same-parts group in each of the 6 training orientations. Column 2 represents the S+ of the different-parts group presented in each of the 6 training orientations. Column 3 represents the 3 S-s presented in two training orientations each. The resolution of the images presented to the pigeons was superior to that reproduced here.

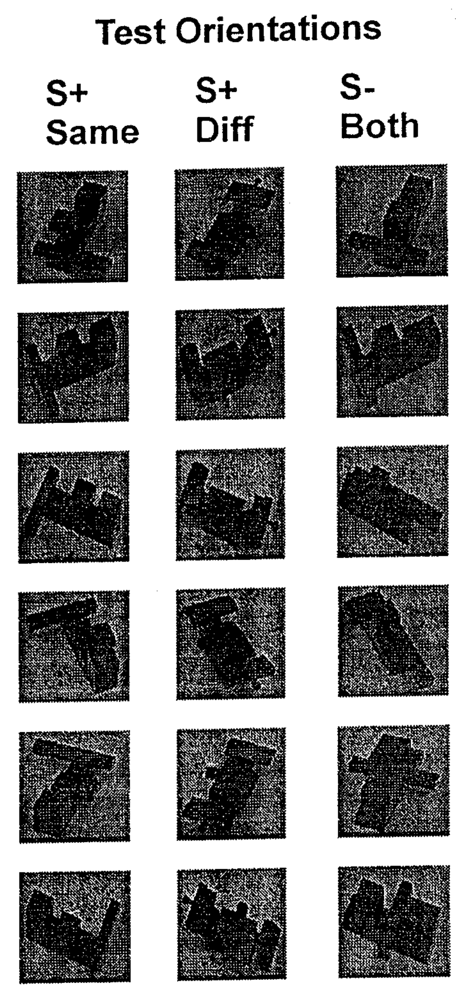

Figure 6. Illustration of the novel orientations used during testing in Experiment 2.
Column 1 represents the S+ of the same-parts group in each of the 6 testing orientations. Column 2 represents the S+ of the different-parts group presented in each of the 6 testing orientations. Column 3 represents the 3 S-objects presented in two testing orientations each. The resolution of the images presented to the pigeons was superior to that reproduced here.

object were rewarded with a 2-s access to a randomly selected food hopper. Pecks to the S- object terminated the trial without reward and initiated a correction procedure in which the same stimulus pair was re-presented until the pigeon made a correct choice. Correction trials were not used in the determination of accuracy. The intertrial interval (ITI) was 2 s during which the monitor was blank. Each pigeon was trained until it reached an average of 80% correct responding over four sessions. The birds in the same-parts group took an average of 37 sessions to reach criterion and the birds in the different-parts group took an average of 16 sessions to reach criterion. The birds then received 5 sessions of training with a 50% reinforcement schedule prior to transfer testing. During these sessions, correct pecks ended with food with a probability of 0.5 and otherwise ended with no food.

Transfer tests. Each transfer test session included a mixture of reinforced baseline trials with training picture pairs, as well as unreinforced probe trials. On probe trials, the trial ended without reinforcement as soon as the pigeon pecked at either object, but the correction procedure was not instituted following incorrect choices. Half of the probe trials served as controls and presented the training picture pairs. The other half of the probe trials presented novel picture pairs. Two transfer test series were conducted, each consisting of three sessions.

Test series one: Transfer to novel depth rotations. Recognition of the objects was tested at six novel orientations: 22°, 67°, 112°, 157°, 202°, or 292°. The first five of these were only 22° from one of the training values, whereas the last one was 67° from the nearest training value. As in training, the two objects were shown in matching orientation.

Test series two: Disparity in orientation of the two objects. This test series examined the effect of presenting the two objects in disparate orientations. Hollard and Delius (1982) and Delius and Hollard (1995) found no effect of disparity in orientation between two simultaneously-presented objects in a matching-to-sample procedure with pigeons. Our test investigates whether disparity between the orientation of simultaneously presented objects influences pigeons' ability to discriminate the target object from the distractor within a simple discrimination procedure. In this test, a selected set of training orientations (0°, 45°, and 90°) were presented on probe trials. On control trials, both objects were shown in the same orientation. On test trials, the objects were shown with a 45° disparity in the orientation of the two objects (i.e., one at 0° and one at 45°, or one at 45° and one at 90°), or with a 90° disparity in the orientation of the two objects (one at 0° and one at 90°).

Results

The top graph in Figure 7 shows pigeons' performance on the probe tests with the training orientations and the novel orientations for each group. The different-parts group was clearly more accurate than the same-parts group, but both groups showed a reduction in accuracy with novel orientations compared to training orientations. A mixed-model ANOVA, with Groups as a between-subject factor and Orientation type (trained vs. novel) as a within-subjects factor confirmed that there was a significant main effect of Group, $F(1, 7) = 26.04$, and Orientation type, $F(1, 7) = 20.72$, but no interaction between Group and Orientation type, $F(1, 7) = 0.18$. Although both groups showed a reduction in accuracy with novel orientations, average accuracy with novel orientations was nevertheless well above chance level (50%) for both groups, $t(3) = 8.35$ and $t(4) = 31.11$ for the same-parts and different-parts groups, respectively.

To determine whether accuracy varied depending on the degree of rotation from the nearest training orientation, we further analyzed the accuracy data in terms of whether the image presented on probe trials was rotated by 0°, 22°, or 67° from the nearest training value. The 0° rotation was the average of the six control orientations, and the 22° rotation score was the average of the first five novel orientations (i.e., 22°, 67°, 112°, 157°, and 202°). The 67° rotation score was the 292° orientation. The middle graph in Figure 7 shows accuracy as a function of rotation. A two-way mixed-model ANOVA revealed a highly significant effect of Group, $F(1, 7) = 50.94$, and of rotation, $F(2, 14) = 26.06$, but the Group × Rotation interaction did not approach significance, $F(2, 15) = 0.26$. Polynomial contrasts revealed a significant linear trend for the Rotation factor, $F(1, 7) = 31.61$. Thus, both groups showed a decrement in accuracy that varied linearly with the degree of rotation from the nearest training value. Although the different-parts group was more accurate than the same-parts group, they showed an equivalent disruption in accuracy as a function of rotation.

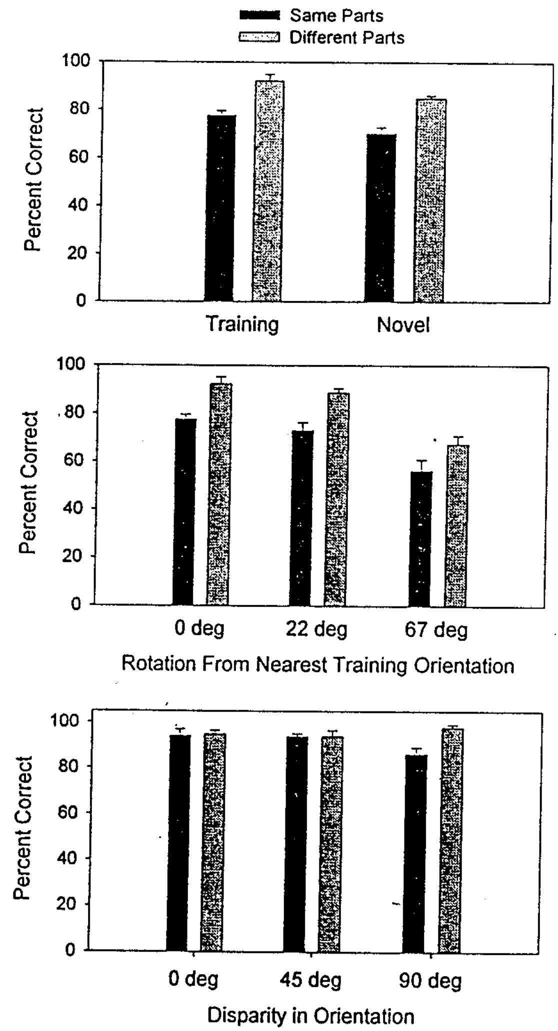

Figure 7. Top: Percentage of correct responses on test trials with training and novel orientations for the different-parts and the same-parts groups in test series 1 of Experiment 2. Middle: Percentage of correct responses on test trials as a function of degree of rotation from the nearest training view for the different-parts and the same-parts groups in test series 1 of Experiment 2. Bottom: Percentage of correct responses as a function of degree of disparity in orientation between the two simultaneously presented objects for the different-parts and the same-parts groups in test series 2 of Experiment 2.

The bottom graph in Figure 7 shows accuracy as a function of disparity in orientation between the two comparison objects (0°, 45°, or 90°). As can be seen, the effect of disparity appeared to vary slightly across groups, with the same-parts group showing a slight decrease in accuracy as a function of disparity and the different-parts group showing no effect of disparity. An ANOVA revealed no significant effect of Group, $F(1, 7) = 3.36$ or of disparity, $F(2, 14) = 0.94$, but the Group × Disparity interaction was significant, $F(2, 14) = 5.94$. However, subsequent one-way ANOVAs within each group failed to reveal a significant effect of disparity within either the same-parts group, $F(2, 6) = 3.54$, or the different-parts group, $F(2, 8) = 1.98$. Thus, the significant interaction term appeared due to the opposite direction of the functions, with the same-parts group showing slightly reduced accuracy as orientation disparity increased and the different-parts group showing slightly increased accuracy at greater orientation disparity.

Discussion

Pigeons in both the same-parts and different-parts groups transferred the discrimination to novel depth-rotations. That is, both groups performed significantly above chance on unreinforced tests with the objects presented in novel orientations. Pigeons in the different-parts group showed higher overall levels of discrimination accuracy than pigeons in the same-parts group, but they displayed equivalent disruption in response to the novel orientations. Specifically, accuracy decreased systematically as a function of rotation from the nearest training value, whether the objects were composed of the same or of different parts.

The higher accuracy for birds in the different-parts group than for birds in the same-parts group indicates that the distinctive parts facilitated the discrimination between the objects. In this context, it is particularly interesting that the presence of distinctive parts did not produce viewpoint invariance. Apparently, the birds could use the distinctive features to more accurately discriminate the positive from the negative object, but these distinctive parts failed to enhance their recognition of these objects when shown in novel depth rotations.

The finding that generalization to novel views was not enhanced by distinctive features is consistent with other recent results obtained in our laboratory (Spetch et al., submitted). The present study differed from the previous one in the nature of the stimulus (digitized images of objects rather than computer drawn objects) and in the number of training orientations. Thus, the lack of an effect of distinctive parts on generalization to novel rotations appears to have considerable generality.

The finding that accuracy decreased when objects were presented in novel orientations is consistent with multiple-view models of object recognition (Bülthoff & Edelman, 1992; Humphrey & Kahn, 1992; Tarr, 1995; Tarr & Bülthoff, 1995; Tarr & Pinker, 1989). According to such models, viewpoint-dependent recognition is the result of the visual system having to transform the unfamiliar orientation of an object to a familiar one represented in memory. This transformation process results in a cost either in accuracy or reaction time. The finding that accuracy decreased as a function of degree of rotation from the nearest stored view is consistent with the assumption that some sort of normalization process is needed to transform novel percepts to the nearest stored orientation. This result is also consistent with findings by Wasserman et al. (1996) in which pigeons that were trained on only one view and then tested with multiple novel views showed decrements in performance as a function of distance from the familiar view.

Accuracy was not affected by the disparity in orientation between the target and distractor object, a finding that is consistent with results obtained by Hollard and Delius (1982) and Delius and Hollard (1995) using a matching-to-sample task. Thus, rotational invariance as assessed by disparity between simultaneously presented objects appears to be a general phenomenon in pigeons. However, invariance with respect to disparity is clearly different than invariance in recognition of novel object rotations.

GENERAL DISCUSSION

Our tentative conclusions based on the present set of results and those of previous studies are that pigeons can: 1) extract detailed information from pictures, 2) discriminate between objects on the basis of complex information such as spatial relationships, pictorial depth cues, and global shapes, and 3) generalize well to novel viewpoints under at least some circumstances. Nevertheless, the processes pigeons use for these accomplishments might not be the same as those used by humans.

Several aspects of the present results suggest that, at least under some circumstances, pigeons may process pictorial information in a fundamental different way than humans do. First, the results of Experiment 1 showed a striking correspondence between the pattern of transfer and test results for the outdoor-experienced racing pigeons in the present study and the laboratory-reared Silver King pigeons of the previous study (Spetch et al., 1998). Not only did both sets of pigeons show poor transfer to novel views, they also showed a very high positive correlation between their accuracy on individual training and transfer images, suggesting good agreement between the two sets of pigeons on the difficulty level of each image. This is particularly interesting given the lack of correlation between pigeons and humans (in fact the correlation was slightly negative). Thus it appears that the pigeons and humans may have attended to different information in the pictures, and/or encoded the information in a different way. Additional evidence for a difference in attention or encoding by pigeons and humans comes from the landmark and background removal tests. Whereas pigeons in both the present and previous studies were disrupted by removal of either the nearby landmarks or the background, humans showed a substantial disruption for landmark removal but not for background removal.

So why were the racing pigeons in Spetch et al. (1998) able to transfer well to novel views? We suspect that the most likely reason is the large number of training views (28) used in that study. Given that recognition of objects at novel orientations is enhanced if more views are provided in training (e.g., Wasserman et al., 1996), recognition of the landmark objects in the novel views was likely facilitated by having seen the landmarks from a larger set of orientations during training. In addition, the large set of views presumably provided a much stronger basis for extraction of the spatial relationships. Finally, training with a large set would discourage any attempt to solve the task by treating each image as an independent scene and memorizing the spatial relationship between the landmarks and goal separately for each scene. Training with a large set of exemplars also enhances concept learning and transfer to novel exemplars (e.g., Cook, Wright, & Kendrick, 1990). Perhaps because adult humans have extensive experience in viewing pictures as representations of the real world, a large set of training views is not necessary to produce accurate transfer to novel views. Thus, the difference between humans and pigeons could reflect experiential factors rather than a fundamental difference between avian and human visual cognition.

In Experiment 2, pigeons showed good generalization to novel rotations of a 3-dimensional object after training with several views of the object. Nevertheless, their generalization was not perfect in that they showed a systematic decrease in accuracy for novel rotations, and particularly for the rotation that was farthest from the nearest training view. Surprisingly, in this study and in a previous one (Spetch et al., submitted), the presence of diagnostic features that distinguished the positive object from the negative objects, did not enhance the degree of transfer to novel views. Although baseline accuracy was higher when the objects contained diagnostic features (indicating that such features were noticed), the degree of viewpoint dependence (i.e., the decrement with novel views) was equivalent whether or not the objects contained diagnostic features. This result contrasts with that typically found for humans (Spetch et al., submitted; Tarr et al., 1997).

Given our argument that animals must be able to quickly and accurately recognize objects and places despite changes in their orientation, one has to wonder why orientation invariance in pigeons rarely occurs and may require specialized training procedures, such as the very large set of views used in Experiment 2 of Spetch et al. (1998). We suspect that the reason is that static pictorial stimuli are impoverished in numerous ways relative to the visual information available to pigeons in the real world. For example, in the real world, movement of the external stimuli or the viewer may play a critical role in both depth perception and object or scene recognition (see Cook & Katz, 1999). Interestingly, one of the strongest demonstrations that pigeons reacted to a pictorial display as a representation of the real world was with the use of video images, and movement was shown to be a critical determinant (Shimizu, 1998). Self movement through an environment produces motion parallax, which may provide the most salient cues to depth for defining and segregating objects. In addition, natural experiences likely provide a very large and continuous set of views of a scene or object. In fact, animals often approach and systematically explore novel objects, places or spatial relationships (e.g., Heinrich, 1995; Poucet, Chapuis, Durup, & Thinus-Blanc, 1986), and this investigatory behavior presumably provides an extensive record of what the object or place looks like from different distances or angles. Even in cases for which it would be adaptive to show accurate recognition after only a single brief exposure

(e.g., recognition of a predator), movement of the object (e.g., predator) or observer may nevertheless provide quite a range of views, and other cues in addition to visual ones may contribute to the recognition. Thus, recognition of scenes or objects presented in pictures may typically be viewpoint-dependent except when several views have been experienced. Natural experience with a real world object may often provide the necessary multiple view training. Consistent with this possibility, Watanabe (1997) found rotational invariance for images of a familiar object but not for images of an unfamiliar one. Additional studies varying familiarity and viewing experiences would be beneficial.

If one accepts that static pictures provide very impoverished stimuli relative to those that may operate in the real world, then one may question the appropriateness of their use for studying cognitive processes in animals. We suggest that in most cases, the use of pictorial stimuli is nevertheless appropriate and can yield valuable information about general processes. For example, in studies of landmark use for spatial search, we have found that results obtained with pictorial stimuli on the touch screen generalize well to real environments and vice versa (e.g., see Spetch, Cheng, & Mondloch, 1992; Spetch & Wilkie, 1994; Spetch, 1995; Spetch, Cheng & MacDonald, 1996; Spetch, Cheng, MacDonald, Linkenhoker, Kelly, & Doerkson, 1997). Cognitive processes such as concept learning (e.g., Wasserman, Kiedinger, & Bhatt, 1988) are likely well tapped through the use of pictorial stimuli. Pictorial stimuli should even be useful for assessing perceptual processes in animals, provided that one does not conclude that they are tapping the limits of such perceptual abilities. Thus, static pictorial stimuli are extremely valuable tools for the study of cognitive processes in animals, but interpretations of the results should not assume that they serve as complete representations of the real world. However, recent advances in technology, such as the creation of virtual reality programs, offer promising means to enrich pictorial stimuli to provide both self-induced and object-induced motion cues. Thus, the future holds exciting possibilities for the investigation of visual perception and cognition in animals.

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RÉSUMÉ

La capacité à reconnaître des objets ou des lieux sous différents points de vue est à la base de nombreux comportements adaptatifs, mais est-ce que les animaux peuvent reconnaître des objets ou des lieux sur des images statiques indépendamment du point de vue représenté ? Lors d'une première expérience, des pigeons ayant eu une expérience préalable avec le monde extérieur ont été entraînés à localiser une cible non marquée sur six vues différentes d'une scène présentée sur un écran tactile. La position relative de la cible restait constante par rapport à des repères dans la scène, mais les vecteurs 2-D repère-cible changeaient d'une vue à l'autre. Les pigeons ont appris la tâche, mais ont montré un faible taux de transfert lorsque de nouvelles vues étaient présentées. Leur performance ressemblait à celle qui avait antérieurement été obtenue chez des pigeons élevés en laboratoire en présence des mêmes images, mais différait de celle observée chez des pigeons ayant une expérience du monde extérieur, mais entraînés à la tâche en utilisant une scène différente et davantage de vues. Ainsi, les facteurs liés au stimulus et/ou à l'entraînement déterminent davantage le degré de transfert aux vues nouvelles que l'expérience que les pigeons peuvent avoir du monde extérieur. Une seconde expérience a étudié la reconnaissance des objets chez les pigeons, en fonction des changements de point de vue. Un groupe de pigeons discriminait des objets composés de parties identiques, et un autre groupe discriminait des objets composés de parties différentes. Les scores de base étaient plus élevés pour le groupe de pigeons qui voyaient des objets faits de parties différentes, mais les taux de transferts à de nouvelles vues des objets étaient similaires pour les deux groupes. Les deux groupes généralisaient leurs performances aux différentes vues, mais les scores diminuaient en fonction de l'angle de rotation par rapport aux vues d'entraînement. Nous discutons les implications de ces résultats en ce qui concerne l'utilisation d'images pour étudier les processus cognitifs chez l'animal.

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What do birds see in moving video images?

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Abstract

Ecological and physiological evidence suggests that motion should be very important in the vision of birds, as it is in human vision. However, because of technical difficulties, and uncertainty about the suitability of current video and computer technology for presenting moving stimuli to birds, there has been relatively little research on avian perceptual and cognitive processing of motion. The present article first reviews what we know about birds' processing of moving video images. Although the bird's eye view differs from the human view, static video images are effective stimuli for birds, and pigeons can respond to apparent motion as though it was real motion. Using video images, birds have been shown to discriminate still from moving images, between moving shapes, and between categories of movement. There is some but not complete evidence of transfer between moving video images and the real objects they represent. Movement may aid the process of feature integration, and it gives rise to some but not all of the cognitive effects that it leads to in humans – for example birds do seem to track a temporarily invisible moving object correctly, but they do not respond distinctively to causal movements. Secondly, the paper reviews some questions that are

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