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PATTERN RECOGNITION INVARIANCE IN PIGEONS (*COLUMBA LIVIA*): OUTLINE, COLOR AND CONTRAST

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ABSTRACT: Pigeons that had extensive training with an oddity-from-sample discrimination procedure using visual patterns, and that could transfer their performance to novel patterns, were tested for three kinds of pattern recognition invariance. In one invariance experiment the sample stimuli were silhouette shapes and the comparison stimuli were outline figures. In another experiment the samples were white shapes on a dark background whereas the comparisons were black shapes on a bright background. In a third experiment the sample and comparison shapes were of different color. All the shapes used for invariance testing were novel to the pigeons. Performance during the tests was above 90% correct except in the case of the reversed contrast experiment, where it reached only 77%; dazzling and/or attention problems may have been a disturbing factor. Even in this condition, however, significant transfer was obtained. Generally the pigeons showed that they are capable of invariant shape recognition under all three conditions. Since all critical tests involved shapes that were novel to the subjects the results also confirmed that pigeons can conceptualize a relational oddity/identity rule.

ZUSAMMENFASSUNG: Tauben, die vielseitige Erfahrung mit einer visuellen Wahl-nach-Muster Diskriminationsprozedur hatten und die fähig waren, ihr Wahlverhalten auf neue Formen zu übertragen, wurden mit drei verschiedenen Erkennungsinvarianzaufgaben getestet. In einem Invarianzversuch waren die Musterreize Silhouetten und die Vergleichsmuster Umrisse. In einem anderen Experiment waren die Muster weiße Formen auf schwarzem Hintergrund, während die Vergleichsmuster schwarze Formen auf weißem Hintergrund waren. In einem dritten Experiment waren die Muster- und Vergleichsformen verschiedenerlei Farben. Alle die Formen, die zur Invarianzprüfung benutzt wurden, waren für die Tiere neu. Die Unterscheidungsleistungen lagen bei den Tests über 90% richtige Wahlen außer bei dem Kontrastumkehrungsexperiment, wo sie nur 77% richtige erreichten. Blendungs- oder Aufmerksamkeitsprobleme mögen in diesem Fall beeinträchtigend gewesen sein. Aber selbst bei dieser Bedingung war der Leistungstransfer signifikant. Insgesamt zeigten die Tauben, daß sie unter allen drei Bedingungen der invarianten visuellen Formerkennung fähig sind. Da alle kritischen Tests den Tauben unbekannte Formen beinhalteten, bestätigen die Ergebnisse auch, daß sie fähig sind, eine relationale Gleich/Verschieden-Regel zu konzeptualisieren.

On different occasions one and the same object can cast very different images upon the retinae of an observer. The distance and orientation, the prevailing lighting, the viewing conditions generally can drastically modify the image that an object projects on the photo-receptor array. Since object recognition is an essential function of most visual systems central neural processing has to somehow cope with these retinal image vagaries. Such compensation for image variation is said to ensure the invariance of object recognition. Mechanisms that implement invariance may, by extension also play a role in cases where the actual visual properties of objects change inherently (trees in the course of spring for example) or when similar though not identical objects are recognized as belonging to a category (different leaves as oak-leaves for example). In fact, investigations on invariance mostly proceed by examining how well subjects recognize the similarity of patterns actually differing by selected properties.

The invariance competences of humans have been extensively studied from this point of view. Theoretical considerations in connection with artificial vision engineering have suggested that invariance capabilities as a rule require considerable information processing (Hord, 1982). Little is known about the invariance capacities of animals. Even though the behavior of many higher vertebrates in their natural environments suggests that they have comprehensive invariance competences, there have been few studies that show this formally. The abilities of pigeons are of interest in this respect, since as a microcephalic species they must be suspected to be short of sufficient processing capacities to deal with all invariance varieties. Following basic evolutionary arguments it is assumed that small brained organisms have been selected so that whatever capacities they possess have been allocated to ecologically meaningful functions. Extensive studies on visual perception in birds done in our laboratory have been successfully guided by these considerations (Delius and Emmerton, 1978; 1979). Visual pattern recognition invariance results relating to orientation variations (Hollard and Delius, 1982; Delius, 1986; Delius and Hollard, 1987; Lombardi, 1989) and with respect to size variations (Lombardi and Delius, 1989) have already been reported. Here we describe experiments whose primary purpose was to obtain baseline information on the color, outline and contrast invariance capacities of pigeons.

A simultaneous oddity-from-sample conditioning paradigm was used. To simplify technical matters the recognition of two-dimensional patterns rather than three-dimensional objects was studied. During training trials subjects were first shown a sample shape and then presented with two alternative comparison shapes, from which they had to choose the one that was different from the sample and avoid the one that was indentical with the sample. Correct choices were rewarded with food. Subsequent transfer trials involved shapes that were novel to the

subjects. Previously it had been demonstrated by us that given propitious training conditions (involving principally the use of many exemplar stimuli), pigeons solved this task by applying a relational oddity/ identity concept (Lombardi, Fachinelli and Delius, 1984; Lombardi, Delius and Hollard, 1986). The present experiments as a matter of fact involved several further tests of this ability, a point to which we shall return later. In the invariance test trials that were essential to this study both comparison shapes differed from the sample by a particular feature (color, outline or contrast). The pigeons' problem consisted in nevertheless recognizing the oddity/identity relations between sample and comparison shapes.

EXPERIMENT 1: OUTLINES

Humans can easily recognize objects represented in line drawings, and indeed they are often required to do so in the modern cultural environment. There is obviously no comparable demand in the pigeon's environment. In fact, some experimental evidence seems to indicate that pigeons cannot perceive the correspondence between line drawings and the solid objects they represent (Cabe, 1976; Cabe and Healey, 1979; see also Cerella, 1982 for supporting evidence), although they probably interpret full silhouettes and photographs of objects correctly. Cook, Wright and Kendrick (in press), who trained pigeons to distinguish between naturalistic drawings of mammals and birds found no transfer to mere outline drawings, although there was some transfer to silhouette representations. Towe (1954) reported a single test where pigeons that had previously learned to discriminate a silhouette triangle from a silouette square also distinguished between an outline triangle and an outline square.

The present experiment sought to settle the elementary question whether pigeons recognize the shape identity/oddity between silhouette (surface) and outline (perimeter) patterns using more complex and varied shapes. The more general question whether pigeons recognize the equivalence of pictures and objects has been addressed in another study (Delius, 1989; see also Lumsden, 1977).

Method

Animals.   Nine adult homing pigeons *(Columba livia)* of local origin were used. They were housed in individual cages located in a well-ventilated room, kept at 18°C, with a 14-h light, 10-h dark cycle. The birds were maintained at 85% of their normal weights throughout the experiment. They had previously served in other experiments involving oddity concept learning and size invariance tasks (Lombardi, Fachinelli and Delius, 1984; Lombardi and Delius, 1989).

Apparatus. A three-key Skinner box of conventional design was employed. The response keys were 7 cm apart and 20 cm above the floor. The food hopper was located below the central key 7 cm above the floor. The stimuli were back-projected onto the response keys with the aid of an automatic projector. Three electromagnetic shutters placed directly behind the keys controlled the displays on these. The projector was equipped with photocells that sensed the presence or absence of coding perforations in specially made slide frames. The decorative geometric patterns used as stimuli were selected from among a large collection routinely used in our laboratory. They were originally drawn in black ink on white paper. Photographically reduced negatives were affixed to the slide frames. The shapes, one to a key, appeared as white patterns of about 10x10mm on the dark background of the 25mm diameter keys. The pattern shown on the central key served as the sample, those shown on the side keys served as comparison stimuli. On each trial, one of the comparison stimuli was identical or equivalent to the sample, the other was different. Such three-stimulus constellations will be called sets. Given n number of different patterns there are m = 2n (n–1) possible sets when odd pattern to the right and odd pattern to the left constellations are included. In some instances (specified below) a random selection from among such a collection of sets was made to keep their number manageable. Care was taken that if the odd-right version of a combination was used, the odd-left version was also used. A microcomputer controlled all events within the experimental sessions, and the relevant performance data were recorded on a trial by trial basis.

Training Procedure. As explained above all the subjects had had extensive experience with the oddity-from-sample task, so no shaping or pretraining was necessary. The subjects were simply retrained for 4 sessions. Each trial within these sessions began with a pattern, the sample stimulus, being projected on the middle key. As soon as the subject pecked this key 15 times, the two comparison stimuli were additionally and separately projected on the two side keys. One comparison pattern was identical to, and the other was different from the sample displayed on the middle key. When the animal issued 5 consecutive pecks to the key bearing the odd pattern, the stimuli on all three keys were obscured, a reinforcement light came on and grain was offered for 3 sec. When the subject pecked 5 consecutive times on the key bearing the identical pattern, it was punished with a 3-sec time-out during which all the stimuli and the houselight, otherwise on throughout the session, extinguished. Any response pattern other than 5 consecutive pecks on a side key had no scheduled consequences. The time that elapsed between the onset of the comparison stimuli and the first response to a side key was recorded as reaction time. The next trial began 8 sec after the end of reinforcement or blackout. If the subject had responded incorrectly in

the last trial, the new trial was a simple repetition, a correction trial in which the same patterns were presented on the same keys. If the pigeon had responded correctly during the last trial, a new stimulus set was shown in the next trial. Correction trials were discontinued after the penultimate retraining session. At the same time, a partial reinforcement contingency was put into force, such that only 60% of randomly selected trials ended with reinforcement or blackout, the others leading directly into the intertrial interval. These extinction trials (neither food reward nor time out) were inserted to accustom the pigeons to the non-reinforced transfer trials that were essential during the test phase (see below). A session involved the presentation of 40 stimulus sets. These were chosen randomly among the group of sets in use, with the restriction that the position of the odd pattern on the left or right side key was determined by a quasi-random sequence (Fellows, 1967). Only the outcomes of noncorrection trials were used for performance evaluation. Sessons were run daily.

Training Stimuli. Each training session involved the presentation of 24 silhouette sets and 16 outline sets, randomly ordered. The former sets were randomly selected from those that could be assembled with the 15 silhouette (filled) training shapes shown in Figure 1. The birds had already had extensive training with these stimuli in the course of the previous experiments. The outline (perimeter) sets were randomly selected from all those that could be assembled from outline versions of 5 shapes that were novel to the birds (Fig. 1). The outline component was

FIGURE 1. Experiment 1: Outlines. Left: all patterns used shown as positives. Right: some examples of the actual stimulus sets derived from the patterns shown left. Dimensions not to scale.

intended to familiarize the pigeons with the altered style of shapes that would be needed during the testing phase.

Testing.   Ten transfer sessions followed. Each session consisted of 24 training trials, 16 with silhouette sets and 8 with outline sets selected from among those used in the previous phase, and 16 transfer trials. Eight of these trials involved sets where the sample was always a silhouette and the comparisons were always outline shapes. The outline shapes were already known to the subjects from the preceding phase. The 5 basic patterns yielded 40 sets. All trials involving these sets were reinforced and served to prevent the birds associating mixed silhouette/outline sets with non-reinforcement. The other 8 transfer trials involved sets analogously assembled from silhouette and outline versions of 5 patterns that were completely novel to the birds (Fig. 1). Each of the 40 sets was used twice during the 10 transfer sessions. These invariance test trials were never reinforced. Non-reinforced transfer trials were not given among the first and last 3 trials of a session, otherwise the various kinds of trials were randomly ordered.

Results

Figure 2 shows the mean percent correct trials computed separately for the various components, plotted session by session. Performance on the silhouette sets was high from the beginning onwards. As explained before the subjects had extensive experience with this basic task. Performance on the outline sets was only slightly worse, even though it was the first time that the pigeons were faced with outline shapes. During the initial 4 sessions, however, the mean response latency was significantly longer during outline trials than during silhouette trials (1.01 sec versus 0.76 sec, Wilcoxon test, $p < 0.01$).
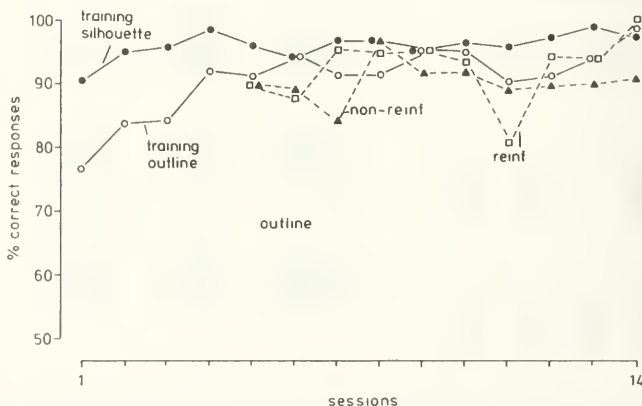

FIGURE 2. Experiment 1: Outlines. Pigeons' performance on the habituation and test sessions. Filled triangles: invariance tests.

The average performance during the reinforced transfer trials involving shapes known to the subjects was 94.1%. The performance on the critical invariance tests (novel shapes, no reinforcement) in which the subjects had to spontaneously recognize the identity/oddity relation between silhouette samples and outline comparison shapes (Fig. 2, filled triangles) was overall 93.8% correct and well above chance for each of the subjects (binomial tests, all p < 0.01) and was not significantly worse than that on the reinforced transfer component. The mean response latencies on the various components of the test block rose from silhouette training (0.76 sec) over outline training (0.98 sec) to novel mixed trials (1.13 sec; Friedman analysis of variance, p < 0.01).

Discussion

Excellent invariance performance was obtained in this experiment. The recognition of outline comparison shapes as being the "same" as or "different" from silhouette samples was close to perfect; this, even though the shapes used for the critical tests were absolutely new to the birds and never reinforced.

As pointed out previously, in a natural environment it is unlikely that recognition of the correspondence between silhouettes and outlines of shapes is often called for. Only under very exceptional rear lighting conditions can some objects be seen only by their outline halos. It is thus remarkable that pigeons should have evinced such a good performance in our tests. However, theoretical considerations about the processes that subserve pattern recognition (e.g Marr, 1982) as well as empirical experience with artificial visual systems (e.g. Braddick and Sleigh, 1983) suggest that extraction of outline information is generally an efficient initial processing step. It reduces the redundancy of pictorial information without appreciable loss of information essential for later recognition step. Several procedures have been developed to implement outline extraction in artificial systems. A conceptually simple one involves spatial filtering with a particular subset of so-called Laplace operators (Braddick and Sleigh, 1983).

Similarly, a certain class of neurons in the visual cortex of mammals seems to be specially engaged in extracting outline information (Creutzfeld and Nothdurft, 1978). It may well be that any visual system that is reasonably efficient in pattern recognition has to incorporate an outline detecting stage. When such a visual system is presented with actual outline patterns (line drawings in the case of humans) these will represent optimal stimuli for this stage, initiating the pattern recognition process. The avian visual system may well conform to this physiological principle even though it is anatomically quite distinct from the mammalian visual system (Emmerton, 1983a; 1983b). Thus the unproblematic recognition of shapes by their outlines found in pigeons and indeed in

humans may not represent an adaptation to a direct environmental demand, so much as an evolutionary by-product of an efficient object recognition strategy.

EXPERIMENT 2: COLORS

The physical color of given objects varies greatly in nature. In accordance with this ecological fact humans by and large have no difficulties in recognizing shapes as being the same regardless of mismatching coloration. In agreement with this, there is much psychophysical and neurophysiological evidence that in the primate brain shape and color information is processed largely independently and that object recognition is primarily mediated by achromatic mechanisms (Livingston and Hubel, 1988). Bird vision may again be functionally similarly organized despite fundamental structural differences (Emmerton, 1983a; 1983b). This leads to the expectancy that the color invariance competences of pigeons should be good. This species is however known to be markedly more responsive to color cues than to shape cues when these compete for attention in the context of discrimination learning (Nelson and Wassermann, 1981; Lombardi and Delius, in preparation; pigeon color vision incidentally is more complex than human color vision: Emmerton, 1983b). Distracting colors could thus after all be expected to disrupt shape oddity recognition. In the critical transfer trials of the following experiment both comparison stimuli were odd with respect to the sample in terms of color but naturally not in terms of shape. The experiment incorporated two consecutive phases: a first one involving one additional distractor color and a second one involving four such colors.

Method

Animals and apparatus. The animals, the general conditions under which the experiment was run and the apparatus were the same as in the previous experiment, except that different stimulus sets were used.

Training. The training of both phases consisted of 6 sessions involving two types of trials. There were 24 white silhouette trials equivalent to those of the training period of Expt. 1, and 16 colored silhouette trials, involving stimulus sets made from 5 patterns already known to the pigeons. For the first phase each of these sets was backed with a piece of red transparent cellophane sheet so that all three shapes of a set appeared as red patterns on a dark background (Fig. 3). For the second phase each of the equivalent sets was backed with either red, blue, green or yellow cellophane. These colored training sets were intercalated at

random among the white training sets. The first three sessions of each training session were run with a correction procedure and continuous reinforcement. The remaining sessions were run without a correction procedure but with the partial reinforcement schedule described above.

Testing.   Each phase ended with 10 transfer sessions, each of the sessions consisting of 4 components. There were 16 white and 8 colored training trials as well as two transfer components, each consisting of 8 trials. The trials of one of these components were reinforced; the trials of the other component, the critical invariance tests, were run under extinction conditions. Each transfer component involved 40 sets assembled from 5 patterns. All 20 patterns, 10 for each experimental phase were novel to the birds (Figure 3). Sets corresponding to each phase were each shown twice in the course of the appropriate 10 sessions. The corresponding trials were randomly intercalated among the training trials, avoiding the first and last 3 trials of a session.
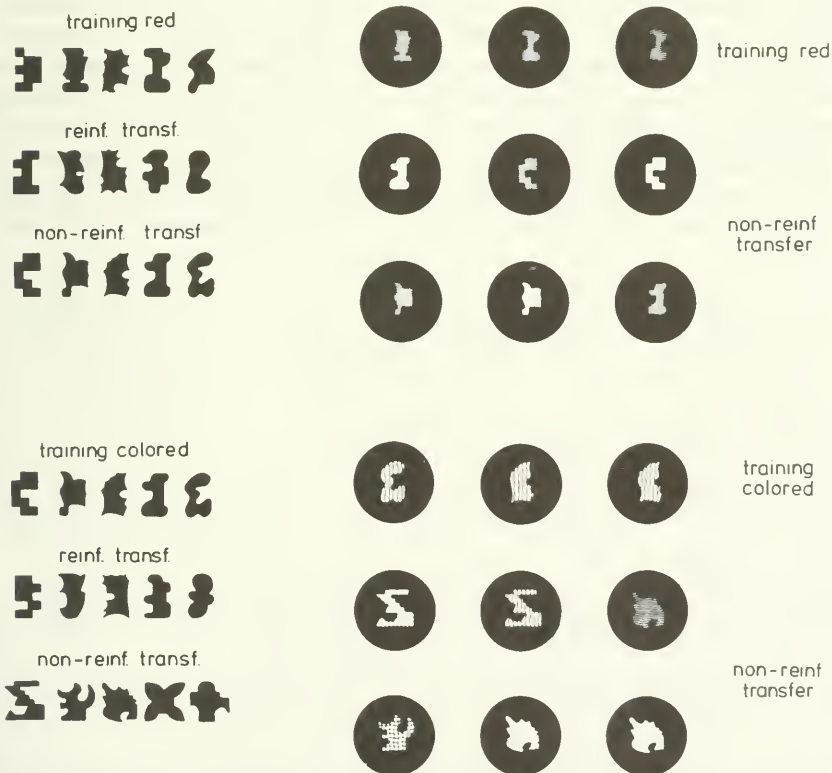

FIGURE 3. Experiment 2: Colors. Left: all patterns (shown as negatives) used in phase I (top) and phase II (bottom). Right: some examples of the actual stimulus sets (shadings indicate different colors, see text) used in the same experiment.

During Phase I, half of the transfer stimulus sets had a red sample pattern and white comparison patterns. Each pattern appeared equally often as a red sample, as a white same comparison and as a white odd comparison. In the same way, the other half of the stimulus sets had white sample patterns and red comparisons. In all cases the background to the patterns was dark (Figure 3). Within each group of transfer trials (reinforced and non-reinforced), four trials per session involved sets with red samples, and four sets with red comparisons. During Phase II each component stimulus of any given transfer set was backed with a different colored sheet of cellophane. Each of the 5 colors (red, green, yellow, blue and white) was equally often attached to sample, to odd and to matching patterns.

Results

The average percent correct performance on the various components of both phases of the experiment is shown in Figure 4 (top). Performance on the white training sets during the first phase was nearly perfect. Performance on the red sets was only slightly poorer. The accuracy on the mixed shade transfer sets was also excellent. In particular, the correct choices on the non-reinforced test trials (overall 95.1% correct) were significantly above chance for each subject (binomial tests, all $p <$ 0.01). Differences in performance relating to the red sample/white comparison and the white sample/red comparison sets were not apparent (Wilcoxon test, $p > 0.05$). As in the previous experiment the choice
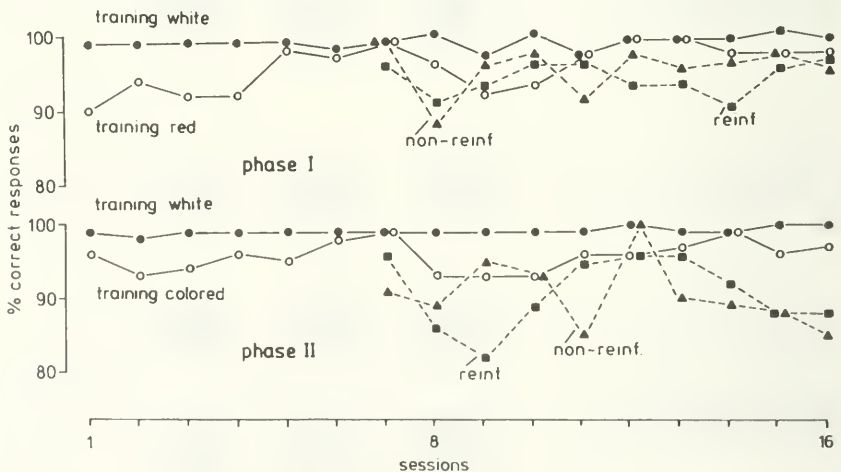

FIGURE 4. Experiment 2: Colors. Pigeons' performance on the habituation and transfer trials of phase I (top) and phase II (bottom). Filled triangles: invariance tests.

latencies rose slightly with presumed task difficulty. The mean reaction times corresponding to white training, red training and mixed non-reinforced test trials were 0.75, 0.86 and 0.90 sec (Friedman analyses of variance, $p < 0.05$).

During the second phase performance on all components was near-ly perfect (Figure 4 bottom). The accuracy on the non-reinforced com-ponent of the transfer block, the true invariance test, was well above chance (binomial tests, each subject, $p < 0.01$; overall 90.4% correct). As before, though, response latencies increased with presumed task diffi-culty. The mean reaction times were 0.70, 0.79 and 1.62 sec for white training, colored training and mixed non-reinforced transfer trials respectively (Friedman analysis of variance, $p < 0.1$).

For phase II the effect of the different colors on performance was separately analysed. As regards the colored set trials of the training block, it was found that sets involving red patterns yielded the best performance (98.2% correct) and sets involving yellow the worst (93.3% correct), the other colors being intermediate (Friedman analysis of variance, $p = 0.05$). The data from the colored training trials during the test phase showed the same trend but the differences were not signifi-cant (the animals made few errors). Since red was the color used in the previous phase, it is possible that the better performance with red sets was due to greater familiarity with this shade. Analysis of the transfer data helped to clarify this issue, since the sets used there also included white as a shade. White was at least as well known to the pigeons as red, since all the pigeons' experience before Expt. 2 was exclusively with white shapes. Within the reinforced transfer component, the sets with the odd comparison colored red yielded the best performance (93.2% correct) and those with yellow and white odd comparison stimuli the worst (76.6 and 64.1% correct) (Friedman analyses of variance, $p < 0.02$). Within the non-reinforced transfer component an equivalent trend was apparent but it did not reach significance ($p > 0.05$). A similar analysis was done for the colors of the sample patterns and the matching comparison patterns, but no significant differences were found.

Discussion

In accordance with the ecologically based expectation and in dis-agreement with the distraction hypotheses the subjects showed excel-lent color invariance. That was so when only 2 (phase I) or as many as 5 (phase II) different distractor colors were involved. Pattern identity/ oddity recognition was invariant with respect to color differences. This fits in with the fact that in nature the color of objects is subject to great variation due to both frequent natural variations of the chromatic com-position of the illuminating light, but also because equivalent objects

often vary considerably in chromatic reflectance characteristics (maize grains for example) while retaining reasonable shape constancy.

Pigeons are known to have strong spontaneous color preferences (Delius, 1968; Sahgal and Iversen, 1975). The expectancy that these would influence the choice behavior during the present experiment was not supported, however. The results of the corresponding analysis are not consistent with a preference for the blue end and an avoidance of the red end of the spectrum reported in the above-mentioned studies. No simple explanation seems to cope with the differential effects that the various distractor colors had on the invariance test performance.

EXPERIMENT 3: REVERSED CONTRAST

The identification of the correspondence/non-correspondence between simple patterns such as letters of opposite contrast mostly presents little difficulty for humans. The task arises very frequently in their culturally determined environment. However, when complex patterns are involved (photographic positives and negatives of portraits for example), humans have considerable problems. Pigeons are undoubtedly rarely confronted in nature with having to recognize the equivalence of shapes in reverse contrast versions. On the other hand, the hypothesis presented earlier that any efficient visual system has to incorporate an outline extraction stage implies proficient reversed contrast invariance. The corresponding filters commonly operate regardless of the contrast sign of edges. Indeed, Towe (1954) has reported briefly that pigeons trained to discriminate a black triangle from a black square on a white background transfered well in a single test to a white triangle and a white square on a black background. The present experiment was designed to check the generality of this finding.

Method

Animals and Apparatus.   They were the same as those employed in the previous experiments. Since a pilot experiment had suggested that pigeons have difficulties with discriminating dark patterns on a white background if the overall luminance is too high, a neutral density filter of approximately 1 log unit attenuation was inserted into the optical path of the projector.

Training.   The training lasted for 27 sessions. Each session included 24 trials involving the usual white shape/dark background sets. The remaining 16 trials involved black shape/light background sets made up from 5 patterns already known to the subjects (as white shapes; Fig. 5). The first 14 sessions were run with a correction procedure, the

remaining, without. The last three sessions were conducted with the usual partial reinforcement schedule.
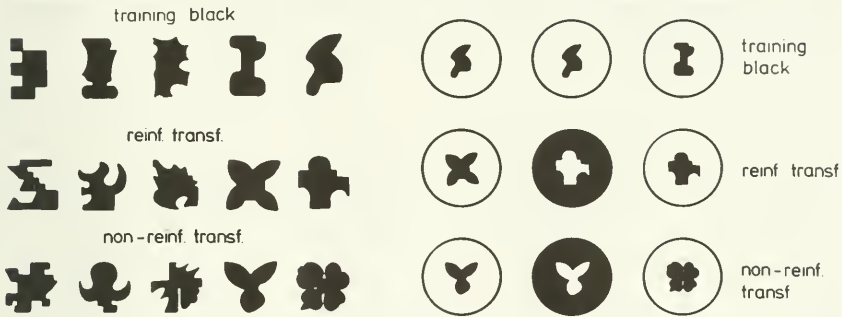

FIGURE 5. Experiment 3: Reversed Contrast. Left: all stimulus patterns. Right: some examples of actual stimulus sets.

Testing. Testing consisted of 10 transfer sessions structured in the same manner as in the previous experiments. In each session there were 16 training trials using white stimulus sets and 8 such trials using black stimulus sets. The remainder of the session consisted of 16 transfer trials (8 reinforced, 8 non-reinforced), using sets that had a white shape as sample, and black shapes as comparisons (Figure 5). The reinforced transfer trials involved 40 sets assembled from 5 shapes known to the pigeons from the test component of the previous experiment. The non-reinforced, invariance test trials involved 40 sets made up from 5 novel patterns, each shown twice within the 10 transfer sessions.

Results

Four pigeons consistently achieved 80% correct responses on the reversed contrast component during the last 10 sessions of the training phase. The other five pigeons that did not achieve that criterion (their performance hovered on the 65% correct mark) did not participate in the transfer sessions.

Figure 6 shows the mean correct responses of the four successful pigeons in the first three and the last three sessions of the training phase, and all transfer sessions. The percent correct choices is shown separately for reinforced and non-reinforced mixed contrast transfer trials. With 77.3% correct choices overall, the performance on the latter, the true tests, was well above the 50% chance level (binomial tests, each animal, $p < 0.01$) but it was markedly worse than on the training and habituation trials. Choice accuracy during the white training, black training and mixed non-reinforced test trials differed significantly (Friedman analysis

of variance, $p < 0.01$). As in previous experiments, the mean reaction times tended to be longer with increasing task difficulty, though the effect was not significant in this case (0.65, 0.88 and 0.94 for training, habituation and non-reinforced test trials respectively; Friedman analysis of variance, $p > 0.05$.)
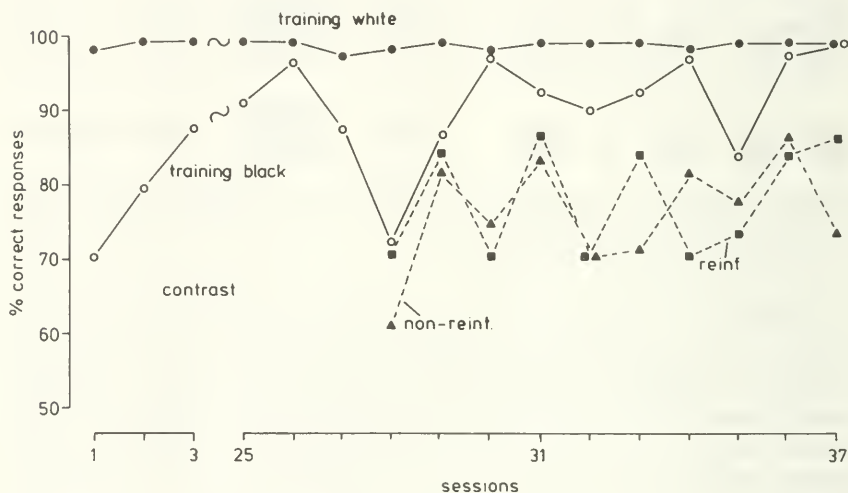

FIGURE 6. Experiment 3: Reversed Contrast. Pigeons' performance on the first three and last three sessions of the training period and all transfer sessions. Filled triangles: invariance tests.

Discussion

Even though the test performance of the 4 subjects that completed the experiment was well above chance, it was comparatively poor. This could be seen as fitting the ecological fact that there is little demand for recognition of objects in reversed contrast versions. It is not certain however that the results necessarily reflect poor pattern recognition invariance in the context of reversed contrast. Five of the 9 pigeons had already experienced considerable difficulty with the reversed contrast training component that did not demand any invariance. An earlier experiment (Lombardi, Delius and Hollard, 1986) had indicated that pigeons can have difficulties with discriminating such dark pattern/white background stimuli due to their higher luminance. Accordingly the present experiment had incorporated a filter to minimize dazzling by such stimuli. It is possible though that the light attenuation was not sufficient.

It could also be that dazzling was not the only reason for poor performance. In a recent, as yet unpublished pattern discrimination experiment pigeons learned with about equal ease to distinguish photographic negative and positive versions of shapes without any brightness adjustments but still had marked problems with transfer between them. In this experiment some incidental evidence indicated that the problem is one of attention. Having extensive training with shapes of one kind of contrast seems to make pigeons reluctant to attend to shapes of the other contrast, perhaps even enticing them to attend preferentially to the irrelevant background of the transfer stimuli. However that may be, Cabe and Healey (1979) contrary to Towe (1954), have also reported that switching from a dark to a light background disrupts the object recognition performance of pigeons. Attempts to investigate why reversed contrast patterns created problems in the present experiment were inhibited by the fact that the pigeons subsequently performed poorly even with normal white shape/dark background training sets. Regardless of what a more successful analysis might have revealed, it is interesting to note that after informal tests human observers also reported that the reversed contrast invariance task was definitely more difficult than either the outline or the color task of the previous experiments.

GENERAL DISCUSSION

The results extend the list of pattern recognition invariance capacities of pigeons. In previous publications we have shown that these animals exhibit an excellent orientation invariance (under certain circumstances even better than humans: Hollard and Delius, 1982; Delius and Hollard, 1987; Lombardi, 1989; see also Emmerton, 1986) and a somewhat more restricted size invariance (Lombardi and Delius, 1989). The considerable invariance competences of pigeons are remarkable in view of their relative microcephaly (their brain is only 2 ml in volume) and the significant information processing known to be associated with invariance implementing algorithms (Hord, 1982).

One of the invariances demonstrated by the present experiments, recognition of shapes regardless of their coloration, matches the ecological situation, since equivalent objects often occur with varying coloration. In humans some of the natural color variations, namely those due to varying chromaticities of illuminants, are taken care of by the phenomenon of color constancy. It reflects a process by which overall chromaticity biases of a scene are centrally compensated before subjective colors are ascribed to individual items. Color constancy has been shown to also operate in goldfish (Ingle, 1985). Our experiments do not yield information on this issue, since what was varied was the pattern's

own colors. Our results do suggest however, that as in primates (Living-ston and Hubel, 1988), shape recognition in pigeons is mediated by achromatic mechanisms. A final decision on this point nevertheless will have to await tests with colored shapes whose background is precisely matched for pigeon-subjective brightness.

The partial reverse contrast invariance that was demonstrated can not be easily related to environmental demands. Objects only very occa-sionally present themselves in reverse contrast as a consequence of special lighting conditions. It may thus not be surprising that the per-formance of our pigeons on this task was relatively weak. On the other hand, as discussed earlier, this weakness can not be easily accommo-dated with the birds' good performances on the outline task. Further work will have to examine whether the poor performance with reverse contrast was due to either the very particular conditions of the experi-ment or a limitation of the pigeons' visual system.

Outline invariance is even less likely than reversed contrast invari-ance to be ecologically relevant for pigeons. In this kind of task however our pigeons showed excellent performance. To the present results those of another, smaller scale, experiment reported by Lombardi, Delius and Hollard (1986) can be added. There two pigeons showed analogous and significant transfer in tests where they had to detect the similarity/ oddity relationship between light silhouette shapes on dark background with dark outline shapes on a light background. This competence is likely to be a by-product of information processing strategies that are efficient for pattern recognition, and include a stage that derives information equivalent to a line drawing. However that may be, as far as the evidence goes, pigeons appear to command similar invariance capabilities as humans even though they have a visual system of a very different phyletic provenance. Convergent evolution seems to have been at work.

It could be argued that the invariance capabilities we have studied are nothing else than evidence of classical stimulus generalization (Ril-ling, 1977). Although in a general way it may be reasonable to class invariance as a generalization phenomenon, Lombardi and Delius (in press) have adduced arguments why such allocation may be mislead-ing if it is also meant as an explanation. Briefly, the pigeons in our experi-ments applied the invariance routine to novel stimuli with which they had no conditioning experience. Stimulus generalization gradients are however conventionally viewed as being coupled to previously condi-tioned stimuli. Stimulus generalization theory furthermore does not specifically address the situation whereas in our experiments, the dis-crimination of stimuli differing in one dimension (shape in our case) is still performed by the subjects as the stimuli are modified along other dimensions (color, outline, contrast in our case). To cope with the find-ings described here stimulus generalization theory at the very least, would seem to require major modifications. It is regrettably true though

that it is not easy at present to offer a new theoretical framework that could take its place.

Indirectly this also bears on the question of whether the invariance capabilities demonstrated with the oddity-from-sample paradigm would also automatically emerge with other discrimination paradigms. Lombardi and Deluis (in press) have argued and Lohmann, Delius, Hollard and Friesel (1988) have demonstrated specifically with respect to orientation invariance that this is not necessarily so. Invariance of shape recognition is known to be a facultative option in humans, and the situation cannot a priori be expected to be different in pigeons. In fact, Pepperberg (1987) has shown that at least one individual of another avian species (African grey parrot) can on the one hand specify in what respect a pair of objects is similar, but on the other hand is simultaneously capable of indicating in what respect they differ. The oddity-from-sample paradigm as used by us tends to force pigeons to disregard variations along the invariance dimensions when choosing among alternative stimuli along the discrimination dimension. Many other discrimination paradigms do not incorporate such biasing. But even in our experiments the pigeons may not have been insensitive to the variations on the invariance dimensions. The time they took to decide about the oddity of shapes was consistently lengthened in all experiments when the relevant stimuli differed with regard to the invariance features. Unfortunately, however, we cannot completely exclude the possibility that this effect was due to stimulus novelty since the corresponding tests always involved shapes that were novel to the subjects.

The present results have one further implication. In every experiment the critical test stimuli used were novel to the pigeons. Nonetheless, without any additional learning (as the test sets were presented under extinction conditions), the birds chose correctly among them according to the oddity-from-sample principle they had previously learned to use. There can thus be little doubt that pigeons can apply a relational, conceptual rule in the matching/oddity paradigm (Lombardi, Fachinelli and Delius, 1984; Edwards, Miller and Zentall, 1985; Pisacreta, Lefave, Lesneski and Potter, 1985; Lombardi, Delius and Hollard, 1986; Wright, Cook, Rivera and Delius, 1988) rather than only stimulus or configuration specific rules as several other authors maintain (Carter and Werner, 1978; Mackintosh, 1983; D'Amato, Salmon, Loukas and Tomie, 1985). The present results considerably discredit the suggestion that our pigeons somehow solved the oddity task when faced with novel shapes on the basis of simple chance similarities between the stimuli constituting the training sets and those constituting the testing sets. The profusion of training and testing stimuli we used makes this a highly improbable proposition. An alternative suggestion is that all the pigeons learned and applied was a rule of choosing the odd luminous flux in the experiment by Lombardi et al. (1986). This suggestion can now easily be

rejected. All 3 present experiments involved luminous flux modifications of the comparison shapes during the test components that make that rule inapplicable. Nonetheless the pigeons continued to transfer well to stimulus constellations constructed from shapes novel to them.

In a way we have the reverse problem on our hands and that is to explain why the oddity transfer performance in two of the present experiments was so good. In the original study of Lombardi et al. (1984) the pigeons' transfer performance on unreinforced novel test sets had not exceeded 83.2% correct choices. In this study the analogous transfer test with the best results yielded as many as 95.1% correct responses, even though the test in question was complicated by a distracting color cue. The obvious explanation for this improvement in our opinion is the considerable additional experience that the animals had had with the oddity-from-sample task. Since the original tests they had dealt with several dozen additional stimuli and had completed many tests with novel patterns (Lombardi and Delius, 1989; Lombardi, 1989). Lombardi et al. (1984) and Wright et al. (1988) had already argued that a large number of training exemplars and a thorough novelty immunization were likely to be important factors for the dominance of concept-governed behavior in pigeons. We cannot exclude, and in fact suspect that other, more subtle factors may also be important. A candidate factor that interests us at present is the differing degrees of spontaneous attention that stimuli of various qualities appear to command from pigeons.

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