Riddles of Natural Categorization [and Discussion]

R. J. Herrnstein and D. I. Perrett

Phil. Trans. R. Soc. Lond. B 1985 **308**, 129-144
doi: 10.1098/rstb.1985.0015

Phil. Trans. R. Soc. Lond. B **308**, 129–144 (1985) [129]
Printed in Great Britain

Riddles of natural categorization

By R. J. Herrnstein

Department of Psychology, Harvard University, 33 *Kirkland Street, Cambridge,*
Massachusetts 02138, *U.S.A.*

Pigeons and other animals can categorize photographs or drawings as complex as those encountered in ordinary human experience. The fundamental riddle posed by natural categorization is how organisms devoid of language, and presumably also of the associated higher cognitive capacities, can rapidly extract abstract invariances from some (but not all) stimulus classes containing instances so variable that we cannot physically describe either the class rule or the instances, let alone account for the underlying capacity.

In contrast, with other contingencies of reinforcement, pigeons will not extract abstract rules of categorization; they will instead learn to identify visual stimuli down to small details, and they will retain much of what they learned for a year and more. How animals can shift between abstraction and photographic retention, and whether or not the two modes can be unified under a single theory are questions that help define the boundaries of knowledge about animal intelligence.

When it comes to categorization, nature clearly has a secret. Animals that are celebrated more for their lack of intelligence than the reverse can sort exemplars of such variety that they out-perform the most ambitious computer simulations (or even the most ambitious theories of a simulation). How can animals with such remarkable powers of classification still seem stupid in some sense? That is the main riddle posed by a growing collection of laboratory experiments on visual categorization by pigeons and other animals. An older hypothesis was the animals classify objects in the natural environment by fixing on some specific, single feature, as the tick supposedly does by responding to butyric acid emanating from the flesh of mammals or the male stickleback fish to the red underside of a competing male. The new evidence leaves no doubt that simple stimuli are not a general solution to the riddle of natural categorization. The general solution to the riddle must deal with the enormous physical variety within natural categories and thus may well bear on wider issues relating to natural and artificial intelligence and to the distinctive nature of biological information processing systems. But, at this point, we know more about the dimensions of the riddle than about its solution. This article samples from the findings out of which the riddle arises and then draws such tentative conclusions as are suggested by them.

1. ACQUIRING AND EXTENDING A VISUAL CATEGORY

In one experiment (Herrnstein 1979) pigeons working in a standard chamber were first thoroughly accustomed to pecking at a switch for brief access to feed, then with no additional special training, they were shown 80 photographic slides (35 mm) of natural scenes projected on a small screen next to the response switch. The slides appeared one at a time for varying durations averaging 30 s. Half of the slides contained trees and half did not, but otherwise the slides looked comparable. The tree slides included full views of single and multiple trees, but also various obscure, distant, inconspicuous, and achromatic silhouetted instances. An attempt was made to sample natural settings in New England.

An experimental session consisted of a single complete rotation of a tray containing the 80 slides. In the presence of a tree slide, pecking was intermittently reinforced with brief access to food. Given the schedule of reinforcement and the schedule of slide presentation, a pigeon could earn between 0 and 3 reinforcements by pecking in the presence of a tree slide. In the presence of non-tree slides, pecking earned no reinforcement. Each session showed the same 80 slides in a new random order. (See Herrnstein (1979) for further procedural details).

The discrimination between tree and non-tree slides formed about as rapidly as possible for three of the four pigeons in the experiment, and the fourth was not much slower. In figure 1, the acquisition curves are in terms of mean rank of positive slides, r_p, obtained by ranking the rates of pecking in the presence of all 80 slides, then averaging the ranks earned by just the

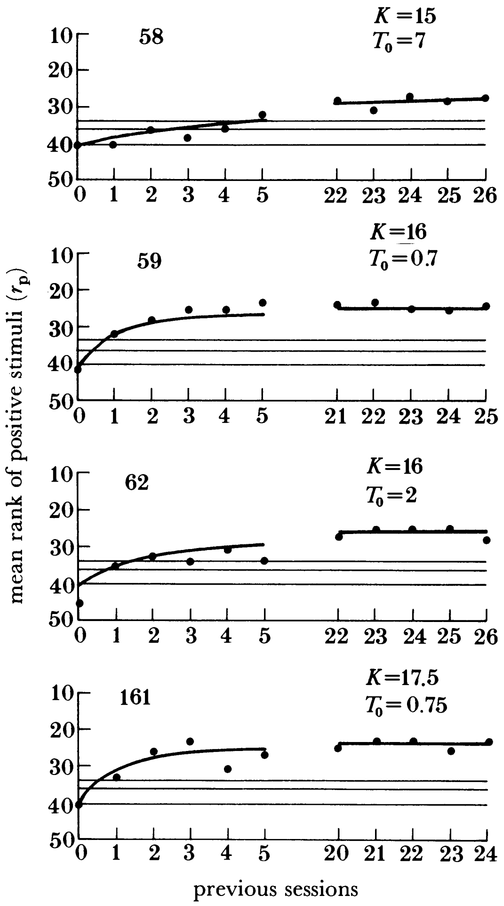

FIGURE 1. Four pigeons were reinforced for pecking in the presence of 35 mm slides of natural scenes containing trees but not in the presence of those lacking trees. Rates of responding to the 80 slides were ranked for each session; the ordinate gives the average rank earned by responding to tree slides (r_p) starting with the first session. The bottom horizontal line is at the expected value of r_p when discrimination is absent; the middle line shows r_p with discrimination at the 0.05 level of significance; the upper line, at the 0.01 level of significance. The function fitted to the points is $r_p = 40.5 - Kt/(t+T_0)$, for which the learning rate parameter is T_0 and the asymptotic level of discrimination parameter is K (from Herrnstein 1979).

tree slides. If responding is unrelated to the contents of the slides, r_p should be around 40.5, as it was at the first session (except for 62, who evidently started with a bias against pecking in the presence of tree slides). The bottom horizontal line in each panel of figure 1 is at 40.5; the two above it are at the 0.05 and 0.01 levels of discrimination. Two of the four pigeons were discriminating at or beyond the 0.01 level by the second session, having seen the slides only once before; a third (62) was discriminating at the 0.05 level by the second session; the fourth (58) took five sessions to reach and remain beyond the 0.05 level of discrimination. Even 58, the slowest pigeon, learned rapidly by the usual standards of discrimination learning in the laboratory.

Sometimes, in experiments like these, I have seen pigeons discriminating significantly before the first rotation of the slide tray has been completed. Slides never seen before are already getting sorted correctly. Something like this can be seen in this experiment as well, if the results are appropriately analysed. During the early sessions, the individual tree slides accumulated reinforcements in their presence at varying rates because of the intermittency in the reinforcement schedule, the varying presentation periods, and the pigeons' somewhat erratic initial rates of pecking. This variation gives us a chance to test whether any particular exemplar's discriminability was influenced by its reinforcement history. According to traditional interpretations of reinforcement as a means of stamping in stimulus–response connections, it would seem that some such relationship ought to have been found.

Figure 2 shows r_p for tree slides sorted by the criterion of how many reinforcements had ever been received in its presence, for individual subjects. Reinforcements are cumulated from the first session on; figure 2 shows the results for the second to the sixth session for the four pigeons. If the stamping-in theory were right, we would expect rising functions, indicating that a slide's discriminability depended on its reinforcement history. The theory is nicely illustrated by 58,

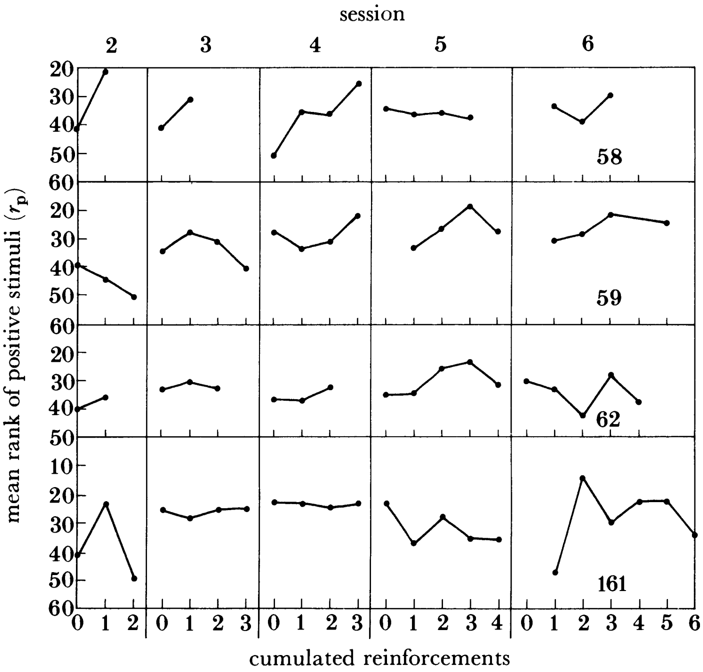

FIGURE 2. Mean rank of responding to positive stimuli classified according to the total number of reinforcements in their presence, for sessions 2–6 and for the four pigeons in the experiment (from Herrnstein 1979).

the slowest learner, for sessions 2–4, namely, before this pigeon started discriminating reliably. The three other pigeons provide little or no support for the theory. Their functions are generally horizontal, which means that even slides with no, or just 1 or 2, reinforcements in their history were being discriminated as well as those with many more reinforcements. For all four pigeons, clear discrimination coincided with evidence against the stamping-in theory. An analysis of cumulated presentation times likewise showed that discriminability was independent of prior history.

In this experiment, the same 80 slides were repeatedly shown, so that the pigeon could have solved the discrimination problem by memorizing whether each exemplar was positive or negative, never noting that one category had treeness in common. The analysis just described, however, makes that interpretation unlikely, if not insupportable, for a positive instance with no reinforcements in its history would, by hypothesis, be indistinguishable from a genuine negative instance. Yet, in most cases, they were not only distinguishable, but as distinguishable as any other positive instance. Later in this experiment, there were tests with additional tree and non-tree slides confirming that the pigeons generalized the principles used for sorting to new exemplars before any reinforcements in their presence. In other experiments (Herrnstein *et al.* 1976), the category of trees versus non-trees (and other categories) has emerged rapidly although a different set of exemplars was presented in every session. The level of discrimination with changing sets of exemplars was barely lower, if at all, than that with fixed exemplars (figure 9 in Herrnstein (1979) presents this comparison).

Generally speaking, we could describe these findings as showing that pigeons learn the relevant category as a whole, rather than just an assortment of slides. But that would be to gloss over several unanswered question. It may be asked whether the pigeon's category is literally isomorphic with the corresponding human category, for example 'tree', or whether it is, instead, some overlapping category or categories that we fail to detect. We can test particular alternative categorical principles, but not exclude the possibility of others unthought of. We cannot even be certain that the pigeons see the slides as representing objects in a three-dimensional space or as flat shapes on a plane. In another terminology, the pigeon *seems* to be displaying object constancy when it recognizes a tree in a new slide but it may only be responding to a two-dimensional form that resembles previously reinforced two-dimensional forms. I have no answer to these questions, only some guesses offered later.

Concentrating on experiments with pigeons looking for trees may foster groundless hypotheses. For example, pigeons may be thought to have a special talent for visual categorization because some breeds are capable of homing, a task calling for considerable sensory powers. Or, trees are found in the pigeons' natural habitat, so this may be supposed to be a category with special salience for them. In fact, neither pigeons nor trees, nor their coincidence, seem to be very special as far as categorical powers are concerned. Alan Kamil and his associates at the University of Massachusetts have found that blue jays are highly skilled at categorizing photographs containing particular kinds of moths, or silhouettes of particular kinds of partially eaten leaves, depending on which kind of caterpillar had eaten it (Real *et al.* 1985; Pietrewicz & Kamil 1977, 1981). Turney (1982) has shown that mynah birds can recognize trees or people in pictures, and signal their identification by vocal utterances – words, in short – instead of pecking at buttons. A parrot has learned to answer, vocally, questions about objects' shapes and colours, even about objects not seen before (Pepperberg 1983). A sizeable literature (reviewed by Herrnstein 1984) has established at least as much categorical capacity in monkeys and apes as in pigeons. Until recently it has simply been assumed that discrimination by subhuman animals is always to be explained in terms of simple generalization from specific exemplars. Despite the universality of that assumption, no species has yet been shown to be that limited in its categorical capacities, as far as I know. Each new effort to push the limits of animals' conceptual abilities seems to have a good chance of finding new abilities. The limits to date are more in the experiments tried with animals than in the animals.

Nor are species limited to the categories of their natural habitats. Peter de Villiers and I found quite good performance by pigeons looking for fish versus non-fish in underwater photographs (Herrnstein & de Villiers 1980). The ancestors of today's pigeons and fish have not shared an environment for tens of millions of years; the latter is not part of the former's natural habitat. Michael Morgan and his associates, then at Cambridge University, first showed pigeons capable of discriminating alphanumeric characters in essentially any typeface (Morgan *et al.* 1976). That finding has now been confirmed and extended by Donald Blough (submitted for publication), who also showed that the errors pigeons make in discriminating letters from each other can be explained by approximately the same underlying feature structure as are human judgments of letter similarity. Delius & Nowak (1982) have demonstrated that pigeons can recognize symmetry *per se* in visual patterns, to some extent independently of the shapes with which they are initially trained. Fish, letters, and symmetry are about as discriminable for pigeons as trees and people, so categorization cannot be limited to the objects of natural habitats.

The basic research strategy in categorization experiments on animals has been to establish a discrimination with a set of exemplars and then to see to what extent it generalizes to new exemplars. If it generalizes substantially, the argument goes, then we can infer some principle of extension. The ambiguities arise because there are always multiple principles that could encompass the observed extension, not all of which are equally interesting. A pigeon finding a specific woman in photographs, for example, is a more arresting result than one finding flesh-toned blobs of a particular shape on a plane surface (Herrnstein *et al.* 1976). The latter finding would be thought of as explaining away anything surprising about the former finding. It would be interpreted as evidence against the claim that the pigeon recognized a particular person in favour of the more mundane claim that a set of arbitrary two-dimensional patterns happen to resemble each other. How can we distinguish between claims of these two types when an animal learns to generalize to new exemplars?

When we hold constant a principle of categorization and vary exemplars, we are hoping that the lines of generalization will converge on something useful or illuminating. It is possible, however, to reverse the strategy, to hold the exemplars constant and separately vary the principle. In a new experiment by William Vaughan and me, just that new strategy has been attempted. Our argument is that, to the extent that we can dissociate a principle of categorization from the particular exemplars that convey it, we are adding credence to the notion that more is involved than mere similarity (see Lea (1984) for a fuller statement of this point).

In this experiment, pigeons control the advance switch of a slide projector by pecking a response key whenever they want a new slide. In a single session, they could advance all around an 80-slide carousel plus part of a second time around, but the results I will illustrate are from the first rotation in any session. The 80 slides consisted of 40 with trees and 40 without, inserted into the tray in a different random order for every session. Tree slides signalled one schedule of reinforcement; non-tree slides, another. By advancing the tray, the pigeon would shift from one reinforcement schedule to the other if the slide change was also a change from a tree to a non-tree or vice versa. If the next slide was in the same category, as it would be half the time, the schedule would not shift, but the pigeon could change the slide again almost immediately.

The schedules of reinforcement constituted a modified concurrent variable-interval, variable-interval, a much studied procedure in research on choice (Herrnstein 1970; de Villiers 1977; Herrnstein & Vaughan 1980). The procedure fixes a certain ratio of reinforcement rates for the two alternatives (that is, tree versus non-tree) to which animals tend to match their ratio of times allocated to each, a relationship known as the matching law. During the course of the experiment, we fixed the ratio of reinforcement rates at 1:1, 5:1, 1:3, 3:1, and 1:5 for trees and non-trees, respectively. In addition to the changing reinforcement ratios, five different sets of 80 slides were used, each one containing 40 trees and 40 non-trees.

How the reinforcement ratios and the different slide sets were programmed is shown in figure 3, along with the major results for the four pigeons in the experiment. The dots show relative reinforcement rates for successive experimental sessions starting with the first. For the first 21 sessions, the value hovers around 0.5; the reinforcement rate ratio was 1:1. Then, the ratio goes to 5:1, and the relative reinforcement rate rises to the vicinity of 0.833 until session 52, after which it drops to 0.25 as the reinforcement rate ratio fell to 1:3, and so on.

The first set of slides was used for the first 14 sessions, then at '2', the second set replaced it. Note that the schedule of reinforcement did not change at this point, but remained at 1:1 until session 21. When the schedule changed to 5:1 (at session 22), the second slide set continued to be used. It was replaced at session 40, while the reinforcement schedule stayed at 5:1. In this way, changes in the slide set and the reinforcement schedule alternated. The last change was on session 157, when the fifth slide set was replaced by the first set.

The solid lines in figure 3 trace the pigeons' behaviour as a proportion of time spent in the presence of tree slides. The matching law implies that this proportion should follow the relative reinforcement points, and it approximately does. The small but systematic deviation of the line towards 0.5, a phenomenon called 'undermatching', need not concern us here (but see Baum 1974, 1979; Wearden 1981). More to the point is the evidence that at each reinforcement ratio, the behavioural proportion transferred from one set of slides to another. Occasionally, the change in slide set caused a slight and transient regression of performance toward 0.5, the expected level if discrimination had been obliterated by the slide change. However, even in the worst case, transfer was almost complete and immediate. Figure 3 itself shows that it takes a pigeon a few sessions to reach stable performance when reinforcement schedules are changed; no such new acquisition was observed when the slide sets were replaced. The first four slide set changes (at sessions 15, 40, 81, and 120) show that an existing discrimination in performance transfers along the lines of the tree–non-tree categorization. The fifth slide set change tells us that plus something more.

On session 157, the fifth slide set was replaced by the first set as the pigeons were spending about 0.20 of their time with tree slides. The behavioural proportion transferred with almost no perturbation. Slide set 1, however, was previously seen with a reinforcement ratio of 1:1 and a behavioural proportion close to 0.5. If the pigeons had learned specific exemplars rather than a general category, the change on session 157 should have caused a return to approximately equal time allocated to trees and non-trees, which was the categorical discrimination when slide set 1 had last been seen. The lack of a change in behaviour on session

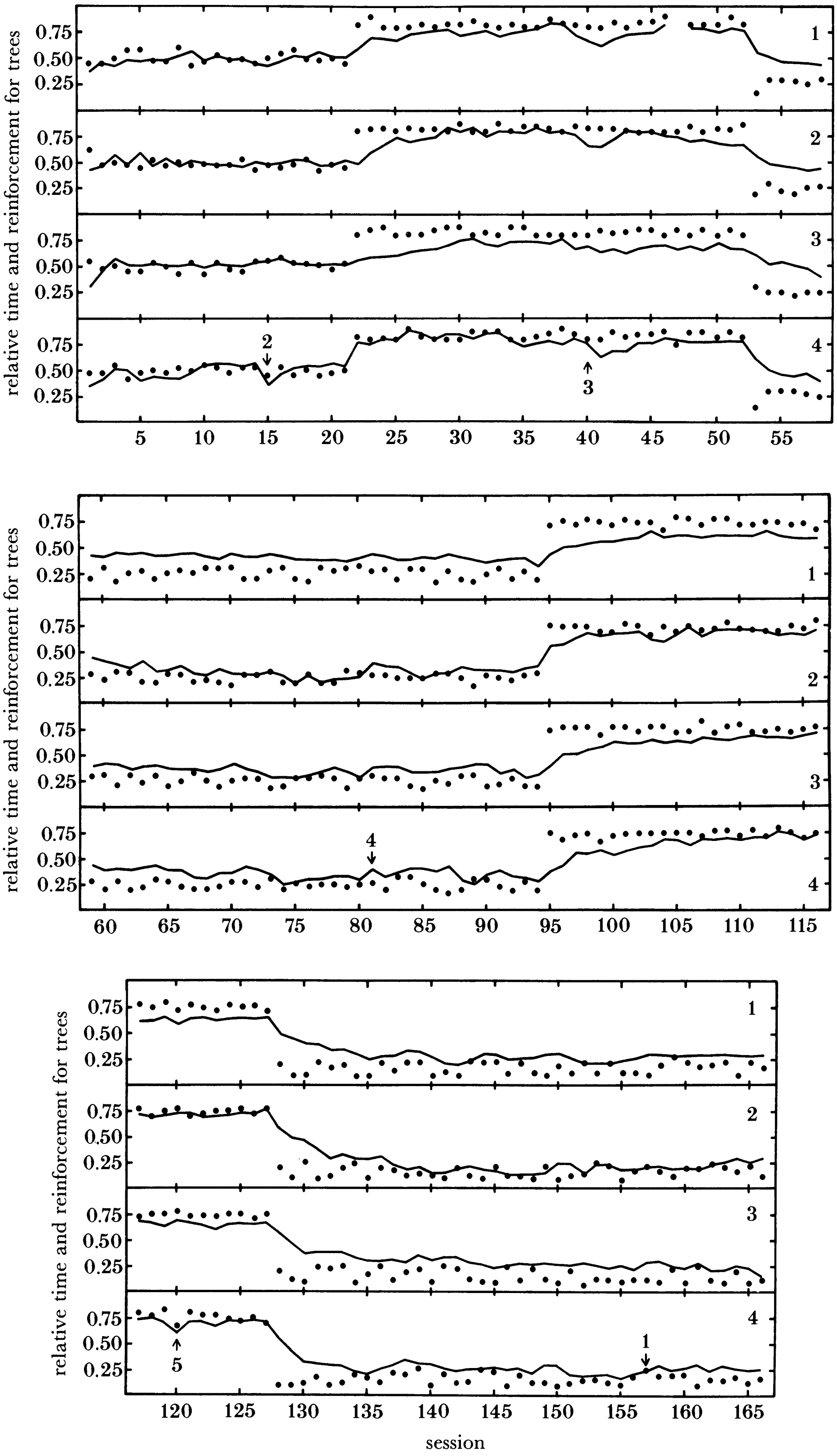

FIGURE 3. Four pigeons worked on a modified concurrent variable-interval, variable-interval schedule: one rate of reinforcement was signalled by slides containing trees and the other by slides not containing them. The pigeon controlled the advance switch of the slide projector. Relative reinforcement rate, which was changed four times during the experiment, is plotted by filled circles; relative time spent in the presence of trees is given by the continuous line. At the numbered arrows (2, 3, 4, 5 and 1), the prevailing set of 80 slides was replaced by another set. At the arrow labelled '1', the fifth slide set was replaced by the one used for the first 14 sessions of the experiment. (This experiment was performed in collaboration with W. Vaughan, Jr.)

157 says that a new discrimination had transferred to an old set of exemplars. While we still cannot say just what the pigeons are using as the criteria for discriminating one class of slides from the other, we may safely say the criteria are more general than a mere aggregation of exemplars. A bit of anthropomorphism may help. At the fifth change in the slide set, the pigeon seemed to be guided by how they were currently responding to 'trees' and 'non-trees', rather than how they had previously learned to respond to this particular slide set. The next section presents evidence that this lack of regression to an earlier performance was not due to the pigeon's inability to remember earlier discriminations.

2. Learning exemplars

Having made the case that animals can form categories that transcend mere exemplars, this section concerns the pigeon's quite striking powers of exemplar learning and retention, as revealed in a new series of experiments by William Vaughan and Sharon Greene (Greene 1984; Vaughan & Greene 1984*a*, *b*).

Instead of requiring pigeons to discriminate between collections of slides differing in some categorical respect, Vaughan and Greene have used collections of slides in which 'correct' and 'incorrect' exemplars are chosen arbitrarily. For example, 80 slides depicting outdoor scenes around the laboratory at Cambridge, Massachusetts, were arbitrarily divided into positive and negative categories and shown to three pigeons in a different random order in every session. The only way performance could improve was by memorizing whether each exemplar was positive or negative, since there was no general rule that divided the two categories. Figure 4, at A, plots the acquisition of the discrimination by increasing values of a statistic, ρ, which expresses the probability that a positive exemplar will be ranked higher than a negative (Herrnstein *et al.* 1976; Herrnstein 1979). When ρ is 0.5, discrimination is absent; when it passes 0.61, discrimination is significant at the 0.05 level. At $\rho = 0.95$, the significance level is well beyond 10^{-10}. Acquisition was not much slower than in figure 1, where tree and non-tree slides were being discriminated, but such a comparison must be qualified by the differences in procedural details, including two rotations of the carousel tray per session for this experiment versus only one for the other.

At B, C, and D in figure 4, new trays of 80 slides were introduced, each time with an arbitrary separation into positive and negative categories. To a human observer, the four sets of slides looked like random assortments of local scenes. The sessions omitted in figure 4 included a variety of tests for possible artefacts (described in Vaughan & Greene 1984*a*), all of which were negative. Each set was rapidly learned to a high level. Then, at E, the eight sessions cycled through the four sets twice (4, 3, 2, 1, 4, 3, 2, 1 in consecutive sessions). The pigeons were evidently able without difficulty to tell whether virtually all of 320 slides fell into one or the other of two arbitrary categories. Retention of these discriminations survived without further training for over a year, though with some erosion.

Vaughan and Greene also showed that the pigeons generalized what they knew about slides to their mirror reversals: putting a slide into the tray backwards did not much disrupt its discriminability. (Up–down inversions, in contrast, were highly disruptive.) But this does not mean that left–right reversal is absent from the pigeon's internal representation of a slide, as Vaughan and Greene proved in a subsequent procedure. If slides repeatedly reversed their status as positive or negative depending on their left–right orientation, the pigeons learned that too.

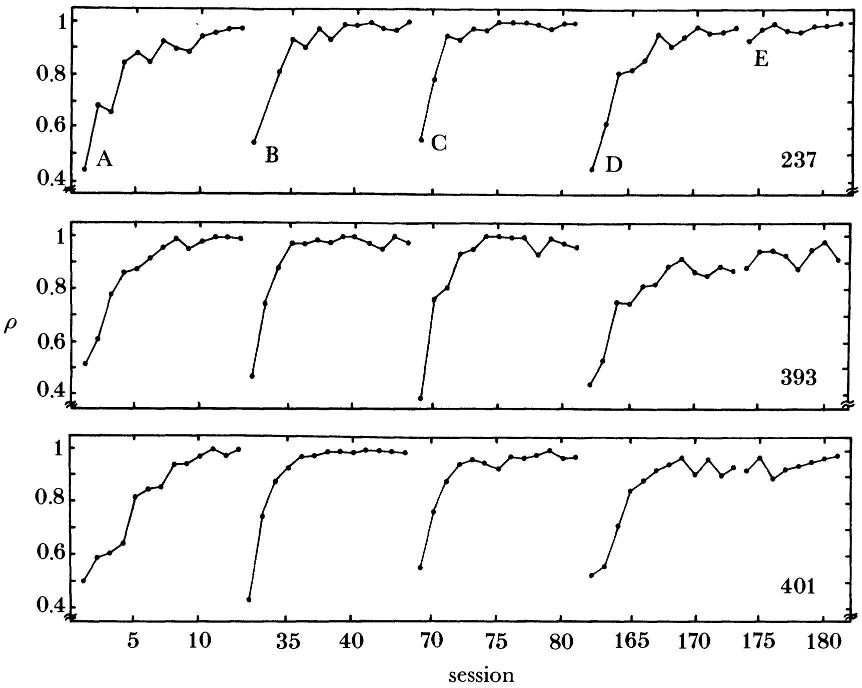

FIGURE 4. Four pigeons learning to sort sets of 80 slides of natural scenes into two arbitrary categories. The measure of discrimination, ρ, estimates the probability of ranking a positive instance over a negative instance (see Herrnstein (1979) for the relation between this measure, r_p, and signal detection analysis). Without discrimination, ρ approximates 0.5; discrimination achieves conventional statistical significance at ρ of about 0.61. At B, C, and D, new sets of 80 slides were introduced. At E, each session used one of the four slide sets, starting with the last and cycling back to the first twice: that is, in the order 4, 3, 2, 1, 4, 3, 2, 1 (from Vaughan & Greene 1984*b*).

They then responded to a slide in one orientation but not to its reversal, just as if the two orientations were two slides. A pigeon *can* distinguish mirror reversals, but it *will* only if the contingency of reinforcement requires it to do so.

The final finding to be reviewed here was a serendipitous discovery by Sharon Greene (Greene 1984). She was interested in testing whether pigeons could master relational concepts, as contrasted with the object concepts described earlier. In one experiment, pigeons looked at blocks of 10 consecutive slides composed of four slides shown twice each and two slides shown only once, irregularly interspersed with each other. Responding was reinforced only in the presence of slides being seen for the first time in a block. The second time, the slide was negative. A given set of 10 slides was used again and again to see if repetition within the identical pairs would become a basis for descrimination. Repetition prescribes a relation between stimuli, rather than a set of characteristics defined over individual exemplars, such as the class of trees or fish. The concept of repetition appeared to be rapidly learned by the pigeons, with responding largely confined to first presentations of a slide within a block.

On closer scrutiny, however, Greene discovered that it was not repetition alone, or for some pigeons, not repetition at all, that was controlling behaviour. To obtain the multiple copies of slides, Greene had photographed scenes several times in rapid succession, taking care to try to keep the camera steady. Then, in the experiment, for pairs of presumably identical slide pairs, one photograph was always the first and the other, the second. The slide pairs looked identical to casual inspection, but if they were not, then the pigeon might have learned to respond to the difference between them. This possibility was tested quite simply by reversing the order of presentation within slide pairs, and the result was a drastic, in some instances total, disruption of discrimination. Impelled by this result, Greene searched her slides and found minute differences in shadows or in the edges of the scene that could have been the basis of discrimination.

In the next phase of the experiment, Greene randomized presentation order within slide pairs. Now, only repetition could provide a reliable signal for non-reinforcement. The pigeons relearned the discrimination, although not to the level obtained when other cues were being used. Pigeons could, in short, learn a relational principle, but apparently found it less congenial than to respond to what, to a human observer, would seem to be obscure features of the slides. Just as for mirror reversal, the relational concept of repetition needed selective reinforcement before it took control of behaviour.

3. Pigeon intelligence

Pigeons can categorize at levels of abstraction that defy both explanation and simulation, but they do not have to. They also have surprisingly strong resources for learning specific exemplars. Vaughan and Greene's data on exemplar retention are reminiscent of the remarkable ability of some animals to recall where they hide bits of food. Vander Wall estimates that a particular species of nutcracker caches tens of thousands of seeds in a season, then recovers well over 50% of them on the basis of the specific cues in the vicinity of the cache (Vander Wall 1982). The homing behaviour of pigeons is yet another case of notable exemplar recognition.

In these respects, pigeons display surprising cognitive capacity. In other respects, they live up to a reputation for dullness. One form of discrimination at which pigeons, and perhaps other animals, are deficient is the relational. Greene's repetition experiment suggests a degree of reluctance to use a relation as a basis for discriminating. Similarly, it has proved to be difficult, though not impossible, to teach pigeons to generalize the concept of sameness or difference (Wright *et al.* 1984; Zentall *et al.* 1984). Pigeons learn only with some trouble that they are being reinforced for responding to a stimulus that matches another stimulus in some respect, or that does not match it. When they do learn to solve such problems, they do so with less generality than they could, as if the abstract relation of identity or difference is contaminated by the specific stimulus features of the stimuli used to illustrate it (Lombardi *et al.* 1984). There is also some question whether they can recognize the relation – identity or difference – as such, above and beyond applying it to a series of test stimuli (Premack 1976, 1978).

In Blough's letter discrimination experiment, the pigeons were required to peck at a particular letter out of three presented. For various procedural reasons, the correct letter was always pitted against two identical incorrect letters: an A versus two Bs or a K versus two Ds, for example. The pigeons could have solved the problem by always pecking the odd letter, but they did not. The relational solution was apparently harder for them than the absolute one: learning to peck the A, then the K, and so on through the alphabet. What could have been reduced to the learning of one relational concept remained for the pigeons the learning of 26 separate letters.

Even in the tree–non-tree kind of discrimination, pigeons may betray a lack of relational insight. A two-way categorization involves just one bit of information: if we can recognize trees, then non-trees are simply the complement. Logic would dictate symmetrical errors, once the biases due to reinforcement are taken into account. Yet, pigeons are more likely to label a non-tree a tree than vice versa, whether trees are the reinforced or the non-reinforced category (Herrnstein 1979). It is as if the pigeon is trying to formulate two sets of rules, one for trees and another for non-trees. The latter is bound to be harder.

In our laboratory, we tried, without much success, to demonstrate mental rotation by pigeons, using adaptations of procedures developed for human subjects by Roger Shepard and his associates (for example, Shepard & Metzler 1971). Hollard and Delius have, in contrast, reported that pigeons can learn to match a simple geometrical figure to its duplicate or to its mirror reversal, and to generalize the skills across varying rotations in the picture plane of the figures (Hollard & Delius 1982). There are, however, grounds for scepticism about whether the pigeons are, in fact, rotating the figures mentally, rather than, say, rotating their heads or learning to identify distinguishing features of rotated or mirror-reversed figures. The main reason for the scepticism is that the pigeon data lack the reaction time function considered to be the *sine qua non* of mental rotation in humans. For humans, the time to decide whether two figures are merely rotations of each other or rotations plus mirror reversals is a linear function of their angular rotation relative to each other, as it was for the human subjects that Hollard and Delius also tested. For their pigeons, however, response latency was independent of angular rotation, and was, moreover, considerably shorter than the human latencies.

Hollard and Delius suggest that the pigeon has a special evolutionary adaptation for assessing rotational invariances by parallel processing, while human observers are limited to a slower, rotation-dependent serial process. While the suggestion is certainly interesting, it has only the data in their own experiment to support it. Our own failure to find evidence of mental rotation in pigeons, combined with the flat functions in Hollard and Delius's experiment, may indicate a deficiency in the pigeon's ability to rotate, or otherwise transform, internal representations. Hollard and Delius characterize the pigeons' performance as more efficient than the humans' because the latencies were shorter, but the pigeons had substantially more practice with the general task (90 sessions compared with 2 sessions), and their error rates were still somewhat higher.

Perhaps the most illuminating deficiency of discrimination at this point is Cerella's finding that pigeons fail to generalize across varying views of computer-generated line projections of cubes (Cerella 1977). More accurately, having seen a sector of the domain of all possible views of the cube, the pigeons generalized no more than they did in the domain of stimuli made up of the lines of the cube rotated 90° around their midpoints, a transformation that wipes out the three-dimensionality for human observers. The two sorts of stimuli are illustrated in figure 5. To a human observer, the three-dimensional invariance of the set on the left is so powerful that generalization across all views is complete and instantaneous, whereas the set on the right is just so many bunches of lines. For a pigeon, judging from Cerella's results, the set on the left is no more homogeneous than the set on the right, nor any more discriminable from stimuli outside the domain.

If there were just this finding of Cerella's, we might conclude that pigeons cannot see three-dimensional objects in plane projection. Some may believe that that is true, but they would be hard put to explain how pigeons recognize trees, people, fish, and so on, in photographs and generalize so readily to new exemplars. Another possibility is that the problem

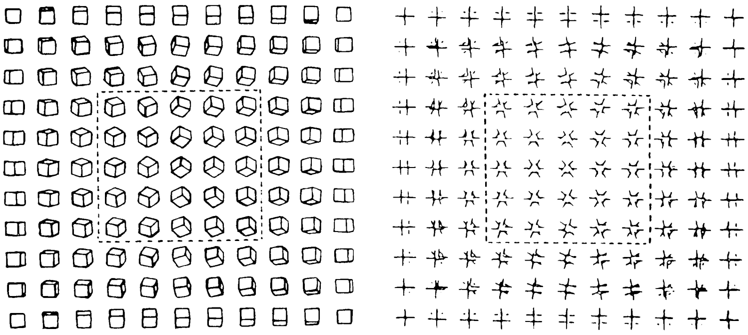

FIGURE 5. Pigeons learned to respond to stimuli drawn from the region inside the dotted squares, but not to generalize beyond this region. They generalized no more broadly with the cubes than with the line patterns (from Cerella 1977).

with the cubes is that they are too impoverished to evoke the perception of three-dimensionality. Photographs of real cubical blocks might, by this hypothesis, have attenuated the striking difference between pigeons and humans. If so, we could say that a pigeon needs more data on a plane than a human being to construct in its mind a three-dimensional isomorph, just as most ordinary people need more data than a structural engineer or an architect trained to read blueprints.

Pigeons have also failed in our laboratory to learn some categories that human observers find easy. Failed experiments are unlikely to be published, though they may contain no less information than just another demonstration of successful categorization. One reason they do not get published is that the experimenter gets discouraged before pinning down the failure to produce discrimination. We gave up trying to teach pigeons to classify photographs of bottles versus non-bottles, chairs versus non-chairs, wheeled vehicles versus anything that was not a wheeled vehicle. We also failed with photographs of the small plastic cups from which the pigeons in the experiment ate their daily rations versus photographs of other scenes around the laboratory. Not every pigeon was a total failure in these experiments; often, a few subjects would learn to recognize a few particular views of target objects. Nevertheless, it was clear that the level of categorization fell far short of that with other objects, such as trees or fish.

It may be helpful to try to sort through the pigeon's failures in categorization. The pigeon's apparent deficiencies with visual classification, taking the human observer as the norm, fall into four general areas, as follows.

(i) Pigeons fail with certain object categories. To date, these cases are all with man-made and three-dimensional objects, for example, bottles, as distinguished from fish (not man-made) or letters (not three-dimensional). If the pattern holds up, it may be because the construction of a mental, three-dimensional invariant places greater cognitive demands than two-dimensional invariants. Man-made objects, reflecting functional and other constraints peculiar to the human context, may simply tax the pigeon's capacities more than objects forged under the same constraints as those of the pigeon's environment. This is different from saying that man-made objects are unfamiliar to the pigeon. Rather, it is to say that the appearances of objects depend in some measure on the processes that give rise to them, and that some of those processes for man-made objects are not ones for which the pigeon's visual system has evolved constancies.

(ii) Along similar lines, pigeons appear to need, not only different, but more information than human observers to construct a three-dimensional image from a plane representation, as in Cerella's cube experiment. Other experiments (Cerella 1980, 1982; discussed in Herrnstein 1984) similarly suggest that line drawings that evoke three-dimensional images for humans fail to do so for pigeons.

(iii) The lesser capacity for constructing three-dimensional percepts may be part of a more general deficiency in mental manipulation. The absence of mental rotation may be an illustration, and so may the breakdown in discrimination for inverted images (Vaughan & Greene 1984*a*). There have been few tests of how readily pigeons compensate mentally for other stimulus transformations, such as changes in size, colour, angle of regard, etc. It may seem reasonable that such compensations must be involved in the experiments showing object constancy in natural settings, but the photographs in those experiments are usually so rich and redundant that substantial deficits could escape detection.

(iv) Relational principles, for example, oddity, identity, complementarity, repetition, characteristically involve not just classes, but classes of classes. To be able to choose the odd stimulus in a trio, for example, requires not only an identification of the three objects, but a formal or logical structure across the objects. Pigeons can solve such two-tiered categorization problems, but they often seem disposed to stay at the pre-logical level. Even when the reinforcement contingencies drive them to the logical level, the performance often shows traces of contamination by the lower level. The logical solution tends not to generalize as far from the specific stimuli used in training as it should. This is sometimes thought of as the pigeon's over-reaction to 'novelty', but it is novelty of a special kind. What the pigeon appears to have difficulty with is the isolation of a relationship among variables, as contrasted with a representation of a set of exemplars.

This last deficiency may be just another instance of the pigeon's weakness in mental manipulation, but it is an instance with special significance. A facility with relationships among variables, free of contamination by specific values, is what gives both the computer and human language their power. Perceptual constancies allow pigeons and other animals to navigate in a world of objects, but the reluctance, if not the inability, to manipulate mentally the abstract relationships into which objects may be placed may be what prevents animal thought from dealing productively with the world represented internally.

4. A COMMENT ON METHOD

What an animal *can* do may differ from what it *does* do on any occasion, as I noted above. This distinction is a corollary of the environment's control over psychological processes, as illustrated by the power of reinforcement. An animal that fails to perform in a particular way may indeed lack the necessary capacity or it may just be that the particular test has failed to activate it. The animal's psychology is always linked to some context, which is a source of adaptiveness and also a hazard to students of the animal mind. In his wonderfully evocative book, *Animal thinking*, Donald Griffin comments about the oddity problem: 'chimpanzees... have learned to generalize oddity as such... pigeons have much greater difficulty with comparable problems, but do better than cats and raccoons' (1984, p. 140). It is at least equally plausible, in my judgment, that cats and raccoons would do better than pigeons if they had better reasons for doing so than they did in the tests at issue. Even the comparison between chimpanzee and pigeon should be qualified by the limitations of the procedures used. Comparative psychology is a far more elusive subject than, say, comparative anatomy, for its facts are peculiarly dependent on its techniques. It is not impossible to make sound comparisons across species, but it is difficult.

That reservation applies to my comparisons, as well as Griffin's and others. At most, we may conclude that the data suggest that pigeons fail to manipulate internal representations or to use logical structures in situations in which human subjects would not fail to do so. This is different from saying, for example, that people use logical relations and pigeons do not. For one thing, pigeons can be induced to behave logically, and, for another, there is no lack of evidence for human illogicality: halo effects, logical fallacies, 'cognitive illusions', and false inferences have inspired much research on human thinking. If there are different upper bounds for people and pigeons in logical powers or mental manipulativeness, as there no doubt are, finding them would require knowing how to push each species to its limit. Interesting as it may be, performance at the limit would be of questionable relevance to behaviour in natural settings, which is rarely driven to any sort of limit. If making sense of performance in natural settings is one of the riddles of natural categorization, solving it means finding out how the ordinary contingencies of reinforcement interact with a species' perceptual and behavioural predispositions.

Preparation of the article, as well as the conduct of several of the experiments reported here, were supported by grant no. IST-81-0040 from the National Science Foundation to Harvard University. Many thanks are due to the organizers of the conference for which the article was prepared and to W. Vaughan for permission to present previously unpublished results from an experiment we conducted in collaboration.

REFERENCES

Baum, W. M. 1974 On two types of deviation from the matching law: Bias and undermatching. *J. exp. Analys. Behav.* **22**, 231–242.

Baum, W. M. 1979 Matching, undermatching, and overmatching in studies of choice. *J. exp. Analys. Behav.* **32**, 269–281.

Blough, D. S. 1985 Discrimination of letters and random dot patterns by pigeons and humans. (Submitted.)

Cerella, J. 1977 Absence of perspective processing in the pigeon. *Pattern Recog.* **9**, 65–68.

Cerella, J. 1980 The pigeon's analysis of pictures. *Pattern Recog.* **12**, 1–6.

Cerella, J. 1982 Mechanisms of concept formation in the pigeon. In *Analysis of visual behavior* (ed. D. J. Ingle, M. A. Goodale & R. J. W. Mansfield), pp. 241–263. Cambridge, Mass.: M.I.T. Press.

Delius, J. D. & Nowak, B. 1982 Visual symmetry recognition by pigeons. *Psychol. Res.* **44**, 199–212.

de Villiers, P. 1977 Choice in concurrent schedules and a quantitative formulation of the law of effect. In *Handbook of operant behavior* (ed. W. K. Honig & J. E. R. Staddon), pp. 233–287. Englewood Cliffs, N.J.: Prentice-Hall.

Greene, S. L. 1984 Feature memorization in pigeon concept formation. In *Quantitative analyses of behavior, discrimination processes* (ed. M. L. Commons, R. J. Herrnstein & A. R. Wagner), pp. 209–231. Cambridge, Mass.: Ballinger.

Griffin, D. R. 1984 *Animal thinking*. Cambridge, Mass.: Harvard.

Herrnstein, R. J. 1970 On the law of effect. *J. exp. Analys. Behav.* **13**, 243–266.

Herrnstein, R. J. 1979 Acquisition, generalization, and discrimination reversal of a natural concept. *J. exp. Psychol.: Anim. Behav. Process.* **5**, 116–129.

Herrnstein, R. J. 1984 Objects, categories, and discriminative stimuli. In *Animal cognition* (ed. H. L. Roitblat, T. G. Bever & H. S. Terrace), pp. 233–261. Hillsdale, N.J.: Erlbaum.

Herrnstein, R. J., Loveland, D. H. & Cable, C. 1976 Natural concepts in pigeons. *J. exp. Psychol.: Anim. Behav. Process.* **2**, 285–311.

Herrnstein, R. J. & de Villiers, P. A. 1980 Fish as a natural category for people and pigeons. In *The psychology of learning and motivation* (ed. G. H. Bower), vol. 14, pp. 60–97. New York: Academic Press.

Herrnstein, R. J. & Vaughan, W., Jr 1980 Melioration and behavioral allocation. In *Limits to action* (ed. J. E. R. Staddon), pp. 143–176, London: Academic Press.

Hollard, V. D. & Delius, J. D. 1982 Rotational invariance in visual pattern recognition by pigeons and humans. *Science, Wash.* **218**, 804–806.

Lea, S. E. G. 1984 In what sense do pigeons learn concepts? In *Animal cognition* (ed. H. L. Roitblat, T. G. Bever & H. S. Terrace), pp. 263–277. Hillsdale, N.J.: Erlbaum.

Lombardi, C. M., Fachinelli, C. C. & Delius, J. D. 1984 Oddity of visual patterns conceptualized by pigeons. *Anim. Learn. Behav.* (In the press.)

Morgan, M. J., Fitch, M. D., Holman, J. G. & Lea, S. E. G. 1976 Pigeons learn the concept of an 'A'. *Perception* **5**, 57–66.

Pepperberg, I. M. 1983 Cognition in the African Grey parrot: Preliminary evidence for auditory/vocal comprehension of the class concept. *Anim. Learn. Behav.* **11**, 179–185.

Pietrewicz, A. T. & Kamil, A. C. 1977 Visual detection of cryptic prey by bluejays (*Cyanocitta cristata*). *Science, Wash.* **195**, 580–582.

Pietrewicz, A. T. & Kamil, A. C. 1981 Search images and the detection of cryptic prey: An operant approach. In *Foraging behavior: ecological, ethological and psychological approaches* (ed. A. C. Kamil & T. D. Sargent), pp. 311–331. New York: Garland Press.

Premack, D. 1976 *Intelligence in ape and Man.* Hillsdale, N. J.: Erlbaum.

Premack, D. 1978 On the abstractness of human concepts: why it would be difficult to talk to a pigeon. In *Cognitive processes in animal behavior* (ed. S. H. Hulse, H. Fowler & W. K. Honig), pp. 423–453. Hillsdale, N. J.: Erlbaum.

Real, P. G., Iannazzi, R., Kamil, A. C. & Heinrich, B. 1985 Discrimination and generalization of leaf damage by blue jays (*Cyanocitta cristata*). (Submitted.)

Shepard, R. N. & Metzler, J. 1971 Mental rotation of three-dimensional objects. *Science, Wash.* **171**, 701–703.

Turney, T. H. 1982 The association of visual concepts and imitative vocalizations in the mynah (*Gracula religiosa*). *Bull. Psychon. Soc.* **19**, 56–62.

Vander Wall, S. B. 1982 An experimental analysis of cache recovery in Clark's nutcracker. *Anim. Behav.* **30**, 84–94.

Vaughan, W., Jr & Greene, S. L. 1984*a* Acquisition of absolute discrimination in pigeons. In *Quantitative analyses of behavior, discrimination processes* (ed. M. L. Commons, R. J. Herrnstein & A. R. Wagner), pp. 231–239. Cambridge, Mass.: Ballinger.

Vaughan, W., Jr & Greene, S. L. 1984*b* Pigeon visual memory capacity. *J. exp. Psychol.: Anim. Behav. Process.* **10**, 256–271.

Wearden, J. H. 1981 Bias and undermatching: Implications for Herrnstein's equation. *Behav. Analys. Lett.* **1**, 177–185.

Wright, A. A., Santiago, H. C., Urcuioli, P. J. & Sands, S. F. 1983 Monkey and pigeon acquisition of same/different concept using pictorial stimuli. In *Quantitative analyses of behavior, discrimination processes* (ed. M. L. Commons, R. J. Herrnstein & A. R. Wagner), pp. 295–319. Cambridge, Mass.: Ballinger.

Zentall, T., Edwards, C. A. & Hogan, D. E. 1983 Pigeons' use of identity. In *Quantitative analyses of behavior, discrimination processes* (ed. M. L. Commons, R. J. Herrnstein & A. R. Wagner), pp. 273–295. Cambridge, Mass.: Ballinger.

Discussion

D. I. Perrett (*University of St Andrews, U.K.*). My question arises from work (done at St Andrews) on perceptual categorization of faces by macaque monkeys. In the temporal cortex we have found substantial numbers of cells that respond only to the sight of faces. These selective responses generalize over changes in view of faces that are observed with differing backgrounds, distance, orientation and lighting. For some cells selectivity to the general characteristics of faces and even to the identity of particular faces is found to be based on sensitivity to distinctive features of that face and for other cells selectivity is based on the combination or configuration of features. At the cellular level categorization was thus found to be based on key features or their configuration.

At the behavioural level we have trained monkeys to discriminate real faces and picture faces (of monkeys, humans and animals) from objects or pictures not containing faces (unpublished studies). Two monkeys trained in this task correctly categorized 90% of novel pictures on the first trial of their presentation. Generalization tests involving jumbled faces and different regions of the face presented in isolation, revealed that the monkeys based discrimination performance on the presence of key features (such as an eye), since individual facial features and jumbles were treated as faces. It was only after explicit training of discrimination between normal faces and jumbled face features that we were able to show that the monkeys could utilize the configurational cues present in faces. Indeed in this latter task monkeys behaved similarly to humans and showed an increased reaction time to categorize faces as normal when the faces were inverted.

My question is, therefore, what is the visual basis of the pigeon's performance? To be more precise, do generalization tests of the above type reveal that pigeons are attending to characteristic features or configurational cues, or both?

R. J. Herrnstein. For the kinds of photographic stimuli described in my article, there has been no systematic attempt to contrast control by features versus control by general configuration. The impediments to research on the issue are both technical and conceptual. Consider, for example, a discrimination between photos containing trees and those not containing them. Many photographs contain partial views of trees, because of obstructing objects or the edges of the picture. The pigeons generally respond to these as trees, just as a human observer would. But we cannot interpret this response to a partial tree, by either pigeons or people, as evidence against a configurational category, for a partly obstructed tree in a natural setting is in some sense just as good an instance of a tree as an unobstructed one.

It may seem that what is needed are pictures of natural scenes with unnaturally fragmented trees in them. Imagine, for example, a scene in which the parts of a tree have been randomly dispersed in all directions. Would the pigeon respond to this as a tree? The experiment has not been done, and, with the simple slide projectors we work with, it would be quite a hard experiment to do. With computer-driven visual displays, such experiments may be just a few years away.

In my opinion, such experiments are well worth doing even though they may tell us less than some may think about whether the categorization is featural or configurational. Suppose the pigeon fails to generalize to the 'exploded' tree. This would not disprove the feature theory nor prove the configurational theory, for it is always possible that the pigeon would generalize to some other fragmentation of the tree, or that it would have generalized if original training had included more almost totally obstructed trees. Now suppose the pigeon generalizes. This does not prove the feature theory nor disprove the configurational. As Perrett's comments illustrate, animals may respond to features under one set of reinforcing conditions and shift to more global characteristics if the conditions change.

Cerella (1982) showed that pigeons, after training with normal instances, generalized to scrambled instances of the cartoon character, 'Charlie Brown'. But, from other experiments, we may safely assume that the pigeons could have been trained to discriminate between scrambled and normal 'Charlie Browns'. Cerella's finding may seem to imply featural categorization; by the same token, the hypothetical latter finding would imply that categorization is configurational. If this seeems paradoxical, it is because it tacitly assumes that the process of categorization is inflexible, rather than adapted to the contingencies of reinforcement that call it forth. As my paper suggested, what an animal does in a particular setting is not likely to be the proper measure of what it is capable of doing generally.

Reference

Cerella, J. 1982 Mechanisms of concept formation in the pigeon. In *Analysis of visual behavior* (ed. D. J. Ingle, M. A. Goodale & R. J. W. Mansfield), pp. 241–263. Cambridge, Mass.: M.I.T. Press.