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A Comparative Analysis of the Categorization of Multidimensional Stimuli: II. Strategic Information Search in Humans (*Homo sapiens*) but Not in Pigeons (*Columba livia*)

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Pigeons and undergraduates learned conditional discriminations involving multiple spatially separated stimulus dimensions. Under some conditions, the dimensions were made available sequentially. In 3 experiments, the dimensions were all perfectly valid predictors of the response that would be reinforced and mutually redundant; in 2 others, they varied in validity. In tests with stimuli in which 1 of the 3 dimensions took an anomalous value, most but not all individuals of both species categorized them in terms of single dimensions. When information was delivered as a function of the passage of time, some students, but no pigeons, waited for the most useful information, especially when the cues differed in objective validity. When the subjects could control information delivery, both species obtained information selectively. When cue validities varied, almost all students tended to choose the most valid cues, and when all cues were valid, some chose the cues by which they classified test stimuli. Only a few pigeons chose the most useful information in either situation. Despite their tendency to unidimensional categorization, the pigeons showed no evidence of rule-governed behavior, but students followed a simple “take-the-best” rule.

Keywords: pigeon, undergraduate, categorization, one-reason decision making, information search

Wills, et al. (in press) have noted that an accurate understanding of the cognitive differences between humans and other animals is an essential preliminary to any discussion of the features of the protohuman ecological niche that may have resulted in the unique enlargement of the human brain. An important difference between human and animal cognition appears to be that humans are much more able than other animals to govern their behavior by rules. Some psychologists, notably Skinner (1969, chap. 6), have sought to reserve the term *rule-governed* for behavior that is under the control of explicit verbal statements, and this usage is widespread in the field of behavior analysis (e.g., Hayes & Hayes, 1992; Place, 1988). On this view, it becomes trivially true that only human behavior (and perhaps the behavior of language-trained individuals of other taxa) can be rule-governed. However many cognitive psychologists have found it useful to have a less language-centered definition of “rule governed.” For example, theorists of categorization have often assumed that the use of a single dimension to sort multidimensional stimuli is diagnostic for the use of analytic processing, as compared with a nonanalytic process that would result in classification on the basis of overall similarity (e.g., Smith & Kemler Nelson, 1984). This specific characterization of rule use may well be wrong (as Lea & Wills, 2008, have argued), and we continue to challenge it in the present article. However, as a type of definition, it remains interesting because it makes it meaningful to ask what, if anything, it could mean for nonverbal animals to use a rule and whether they ever do so. This question has begun to be investigated recently (e.g., Murphy, Mondragon, & Murphy, 2008; Wills et al., in press). The present article continues the investigations begun by Wills et al. (in press) and, like that article, focuses on the question of the use of rules in categorization.

Categorization is a frequent, naturally arising, cognitive task for both humans and other animals. Behaviorally speaking, it occurs whenever an organism is required to make one of a limited number of responses (e.g., accept vs. reject) to a series of instances of a large set of stimuli that differ on multiple dimensions. Such tasks

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are referred to as “concept formation,” “categorization,” or “category discrimination,” depending on the context and the details of the procedure. Examples from the natural life of nonhuman animals include distinguishing an important individual (often the mother) from other conspecifics, despite the fact that the individual is seen from many different perspectives; distinguishing conspecifics from members of other species, despite the differences between conspecifics; or distinguishing a familiar place from other places, despite the fact that its appearances changes with weather, time of day, and season. All the aforementioned tasks are category discriminations that it would be adaptive for animals to be able to make, and field studies and laboratory experiments have shown that animals can indeed make all of them (see, e.g., Hare & Atkins, 2001, and Ryan, 1982, for individual discrimination; Hansen, Johannessen, & Slagsvold, 2008, and Coulon, Deputte, Heyman, Delatouche, & Richard, 2007, for species discrimination; and Biro, Guilford, & Dawkins, 2003, and Cole & Honig, 1994, for place discrimination).

Gigerenzer and his colleagues (e.g., Gigerenzer & Goldstein, 1996) have argued strongly that when people are faced with the task of categorizing objects that differ on multiple dimensions, it is maladaptively slow and inefficient to do so on the basis of a weighted sum of the values on all the available dimensions, even when this is in theory the most accurate strategy. Instead, people should and do rely on a strategy of “one-reason decision-making”: identifying one dimension that does a good enough job of categorizing the objects, and ignoring everything else. This strategy is often referred to as “take the best” or “one-reason decision making,” and it has been extensively investigated in human categorization experiments (e.g., Bröder & Schiffer, 2003; Martignon & Hoffrage, 2002; Newell & Shanks, 2003). Gigerenzer’s general approach is of obvious relevance to animal decision making, where the idea that animals use simple heuristics rather than complex optimizing algorithms is even more intuitively appealing than it is with humans; for example, Bateson and Healy (2005) have applied it to mate choice problems.

It has often been observed that humans under conditions favoring extensive cognitive processing do tend to categorize multidimensional stimuli according to single dimensions (e.g., Medin, Wattenmaker, & Hampson, 1987). Under time pressure or other conditions inhibiting cognitive processing, however, humans in these experiments were more likely to categorize according to overall similarity or family resemblance (e.g., Regehr & Brooks, 1995; Smith & Kemler Nelson, 1984). This is why overall similarity sorting has come to be seen as the likely outcome of an associative learning process, with unidimensional sorting being seen as the result of formulating a verbalizable rule (e.g., Ashby, Alfonso-Reese, Turken, & Waldron, 1998; Pothos, 2005). If this were a reliable general way of recognizing rule-governed categorization, it would be expected that nonhuman animals would be more likely than humans to show overall similarity sorting, if they could be exposed to a situation that was appropriately analogous to a human categorization task. However, in a recent review, Lea and Wills (2008) showed that animals often respond to multidimensional stimuli according to a single dimension, whereas humans under conditions favoring rule formation sometimes use multiple dimensions. They therefore argued that unidimensional sorting is not a reliable indicator of rule-governed categorization, and it follows that it is not a straightforward matter to predict how, if at all, the behavior of humans and other animals will differ on a given task. The difficulty is compounded by the fact that the conventional ways of experimenting with humans and other animals differ, and there are often procedural variations that could explain any apparent species differences.

The experiments in the present article were designed to compare human and animal performance on categorization tasks where we have a clear prediction that humans will use unidimensional rules. The animal subjects used in the experiments were pigeons, chosen because there is a substantial existing literature showing that they can learn categorization tasks (reviewed, e.g., by Huber, 2001), but they are sufficiently far enough from humans phylogenetically to make it unlikely that they share with us many cognitive capacities (in particular, any capacity for rule use) except those that are part of a common vertebrate inheritance. The tasks used in the experiments of the present article involved making the dimensions of a stimulus available sequentially and allowing a categorization response to be made before all information had been received. They were designed to emulate a class of tasks discussed extensively by Gigerenzer and his colleagues (e.g., Gigerenzer & Goldstein, 1996), of which the most familiar example is trying to decide which of two cities in a foreign country is the larger, on the basis of a potentially large number of cues. In many of Gigerenzer’s experiments, the cue values have to be obtained from memory; our procedure was more explicit in that the information had to be obtained from the external environment, so that its availability could be controlled by the experimenter. In addition, the procedures required for training and testing pigeons are quite different from those that have been used to test Gigerenzer’s ideas with humans, so that a direct comparison with published human results would not be possible. Once a successful procedure for pigeons had been developed, therefore, humans were tested in a procedure that resembled the pigeon tests as closely as possible. Of course, procedures can never be identical for species as different as pigeons and humans; indeed, even if they could, we could not be sure that their effects were the same (Bitterman, 1960). However, we have found in previous studies of comparative cognition that making procedures for human and nonhuman experiments as similar as possible can reduce apparent species differences in the results (Goto, Wills, & Lea, 2004; Wills et al., in press).

Experiment 1A

In the first phase of Experiment 1A, we trained pigeons to discriminate between the two prototype stimuli shown in Figure 1, using a go-left/go-right conditional discrimination. These stimuli differ in four dimensions that were spatially separated so that the dimensions could be presented one at a time. In training, all four dimensions were redundant, so that any one of them could be used as a cue for successful discrimination. Training was followed by a test phase using the “one-away” stimuli shown in Figure 1, in which one of the dimensions was exchanged in value between the two stimuli; response to such stimuli allows a sensitive test of which dimensions are controlling behavior in a multidimensional discrimination (e.g., Medin et al., 1987; Milton & Wills, 2004; Regehr & Brooks, 1995). In a series of recent experiments, we used such stimuli to investigate the differences between humans’ and pigeons’ learning of multidimensional tasks (Wills et al., in press).

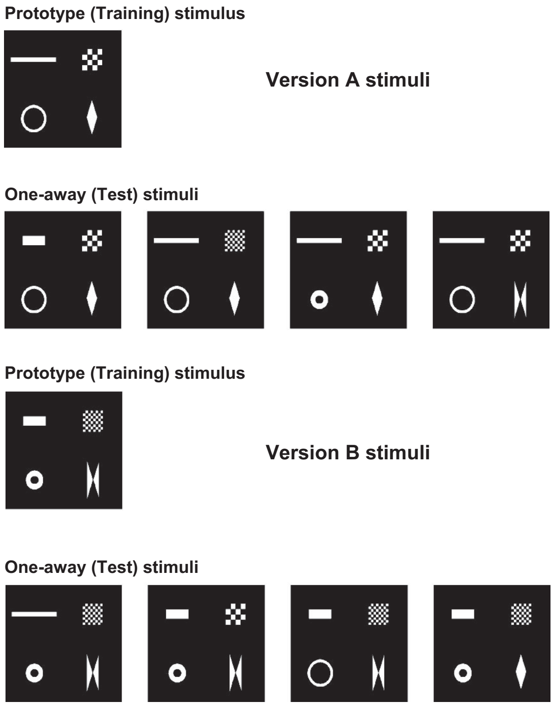

Figure 1. The stimuli used in Experiments 1A, 1B, and 2. Clockwise from top left, the four dimensions of the stimuli are referred to as “bar,” “checks,” “lozenge,” and “doughnut,” each of which was used in two different forms. Each dimension was always presented in the same location within the stimulus. During training, only the prototype forms were used, but under wait-to-reveal conditions, not all elements were exposed at the beginning of the trial. During testing, both prototype and one-away forms of the stimuli were used.

To allow the investigation of one-reason decision making, we used two different kinds of training trials. On full display trials, the entire stimulus was presented at the beginning of each trial. On wait-to-reveal trials, the stimulus was built up gradually over the course of a trial, with elements being added one at a time. The subject could make a choice response at any time, but once it did so, no further stimulus elements were added. The wait-to-reveal condition, therefore, allowed the subject to control how much information it received before it made a categorization response. Because pigeons’ choices tend to be captured by any option that gives immediate reward, even when long-term reinforcement rates would be higher if a delayed-reward option is taken (e.g., Ainslie, 1974), the schedule used ensured that making an early choice response had no effect on the immediacy of reinforcement. To increase the speed of learning, we used training and testing procedures with positionally differential outcomes of the sort introduced by Sheldon (1967) and by Overmier, Bull, and Trapold (1971).

Method

Subjects

The subjects were 6 domestic pigeons, *Columba livia*, obtained from local fanciers. Four of the pigeons had served in a previous experiment on category discrimination, with different stimuli and apparatus from those used in the present experiment. The pigeons were housed in an indoor aviary and were transferred to individual cages on days when they were to be tested; after testing, they were weighed and given any supplementary feeding needed to maintain their weight at around 90% of free feeding levels. On nontesting days, the pigeons remained in the aviary and were given a limited food supply there.

Stimuli

The stimuli used were based, with slight modifications, on those used by Wills et al. (in press, Experiments 1A and 1B). To ensure that all the stimulus dimensions were of roughly equal salience, we avoided highly salient dimensions such as hue and brightness. All the stimuli were filled white geometrical forms shown on a black background, and all stimulus elements consisted of the same number of white pixels, within a tolerance of 2%. They were all derived from the two prototype stimuli shown in Figure 1. These were 2 × 2 square arrays of four elements. Each element was located within a 100-pixel square. The four elements, or dimensions, are referred to as bar, checks, lozenge, and doughnut; and each was used in two forms. Each dimension was presented in the same location within the stimulus array throughout the experiment. These prototype forms were modified in various ways in different phases of the experiment, as described later in the *Procedure* section. In particular, in the test condition, single elements were exchanged between the two versions of the stimuli, generating the eight “one-away” test stimuli also shown in Figure 1.

Apparatus

The experiment used six operant conditioning chambers, measuring 710 × 505 × 435 mm. One long wall of each box included a 38-cm (15-in.) touch monitor, which consisted of a touchscreen mounted in front of a TFT computer display screen. For four of the boxes, the touchscreen was an infrared type (CarrollTouch); for the remaining two, it was resistive (ELO Accutouch, Model 1547L). In all other respects, the boxes were identical. The screen resolution was set to 1,024 × 768 pixels. The bottom edge of the screen was 120 mm above the grid floor of the chamber. Two 2.8-W white houselights were mounted in the top corners of the operant panel above and at either side of the screen. Two apertures, each measuring 60 × 50 mm and giving access to grain hoppers when the hopper solenoids were activated, were located directly below the houselights and 40 mm above the grid floor of the chamber. The hoppers were illuminated by a 2.8-W white light when activated and delivered a 2:1 mixture of hemp seed and conditioner to the pigeons. White noise was played into the box from a 50-Ω loudspeaker located centrally below the touchscreen, and the interior of the box could be observed by a video camera mounted on the side of the chamber, 250 mm above the floor. The chambers were housed in a darkened room together with other similar apparatus. Stimulus presentation and reinforcement contingencies for all chambers were controlled, and responses and other data were recorded, by a computer (supplied by Quadvision Ltd., Dorset, United Kingdom) running Visual Basic software using the Whisker control system (Cardinal & Aitken, 2001). The computer was located in an adjacent laboratory area. The pigeons’ behavior could thus be observed from outside the test room using the imaging software ViewCommander (Internet Video and Imaging, Ltd.). Each pigeon was assigned its own test chamber for all stages of the experiment.

Procedure

The pigeons were pretrained to peck a 32-mm-diameter white disk located centrally on the touchscreen, referred to as the *observing key*. Successful pecks caused this disk to be replaced by a similar white disk located close to one or the other feeder, its location varying at random between trials; pecks to these side disks (referred to as *side keys* or *choice keys*) were followed by a 2-s presentation of the corresponding food hopper, which contained a mixture of preferred grains to serve as food reward. Once the pigeons began completing this sequence reliably, regardless of the side on which food was offered, a conditional discrimination training procedure with differential outcomes was introduced. Pecks to the central disk caused it to be replaced by a discriminative stimulus, either one of those illustrated in Figure 1 or a partial version, with only one stimulus element initially (other elements were added later, depending on the subject's behavior). At the same time, both of the side disks were illuminated. For 3 of the pigeons, pecks to the right side key were reinforced in the presence of version A of the stimulus (or any part of it), and pecks to the left side key were reinforced in the presence of version B or any part of it; for the other 3 pigeons, these contingencies were reversed. Reinforcement was always delivered from the food hopper next to the correct choice key. Sessions were normally given daily, 5 days/week, and consisted of 80 trials. Trials were separated by an intertrial interval of 10 to 14 s, and no more than three successive trials involved the stimuli for which pecks to the same choice key would be reinforced. The details of the discrimination procedure varied between phases of the experiment, as follows.

Training phase. During training, each session was one of two types. Full-display sessions consisted of 40 trials with complete versions of each of the two prototype stimuli shown in Figure 1. The stimulus and the two side keys were displayed as soon as the pigeon had pecked the observing key. The schedule of reinforcement in force on the correct side key was a tandem fixed time of 10 s and variable interval of 2 s (*tand* FT 10 s–VI 2 s). That is, during the first 10 s, pecks after the observing response had no scheduled consequences; after the end of that period, the first peck after a variable interval that ranged from 0 to 4 s was reinforced. The trial continued until such a peck was made, so that all trials lasted at least 10 s and ended with a reinforced peck. Pecks to the incorrect side were recorded but had no scheduled consequences. A trial was scored as correct if the first peck on a choice key was made to the correct side. Wait-to-reveal sessions had the same general form, but after a peck on the observing key, only one of the four elements of the stimulus, chosen at random, was presented. Provided that the pigeon did not peck either choice key, additional randomly chosen elements were added at 2.5 s intervals, so that after 7.5 s the entire stimulus was present. However once the pigeon had pecked either choice key, no further elements were added. All other contingencies were identical to those of full-display sessions, so that all trials still lasted at least 10 s and ended with a reinforced side key peck. Training started with two full-display sessions followed by a wait-to-reveal session, and this pattern of sessions continued throughout the training phase. The phase continued for 40 sessions or until the pigeons reached a criterion of 80% correct trials or better in three successive sessions, whichever took longer; in all cases, the last session was given under full-display conditions.

Test phase. The test phase included sessions in which the "one-away" test stimuli illustrated in Figure 1 were used. There were eight possible one-away stimuli. Each test session began with 20 trials using the training stimuli. The remaining 60 trials included 40 with the training stimuli, 2 with each of the one-away stimuli, and 2 with each of the training stimuli under the same contingencies as were used with test stimuli. In one of the trials with each test stimulus, a right choice key peck was reinforced, and in the other a left choice key peck was reinforced, to maintain the same overall reinforcement density as in training conditions. All test sessions were given under full-display conditions. The first session of the test phase was conducted with training stimuli only, also under full-display conditions. A test session followed. A further session with prototype stimuli only was then given, and if necessary it was repeated until the level of performance reached the mean level of the last three full-display sessions of the training phase. The sequence of test and prototype sessions was repeated until three test sessions were completed.

Results and Discussion

Five of the pigeons reached the 80% correct criterion within 40 sessions. The remaining pigeon required a further 12 sessions. Figure 2 shows the mean course of acquisition of the discrimination over the first 13 cycles of 3 sessions in the training phase, in terms of the percentage of trials with a correct first response in both full-display and wait-to-reveal conditions, and the number of elements of the stimulus revealed before the first choice response in wait-to-reveal conditions.

Details of performance in the wait-to-reveal sessions of the training phase were assessed over the last five session cycles for each pigeon. As Figure 2 shows, typically not all elements of the stimulus were revealed before the pigeons made their first choice peck, although the number of elements revealed increased with

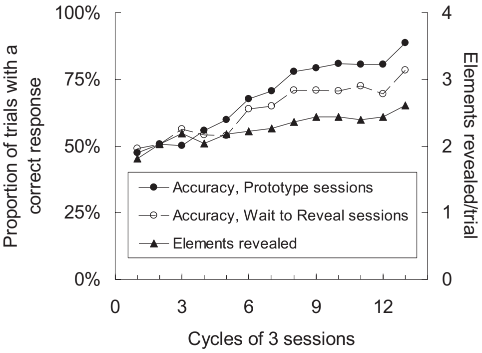

Figure 2. Experiment 1A: Acquisition, percentages correct on prototype and reveal trials, and elements revealed on reveal trials. Data are means across the 6 pigeons, 5 of which reached the 80% criterion of correct discrimination by the end of the 13th session cycle. Confidence intervals of mean percentages correct varied from ±3% to ±5% around the means and of mean numbers of elements revealed from ±0.10 to ±0.25.

training. Figure 3 shows that even after the pigeons had reached criterion accuracy, choice accuracy was correlated with the number of elements revealed, reaching the same level as in full-display sessions only when all four elements were available. This result is consistent with what Gibson, Wasserman, Gosselin, and Schyns (2005) found using the “bubbles” procedure of Gosselin and Schyns (2001): They used stimuli that were covered by a mask perforated by various numbers of openings that they called bubbles, and the more bubbles were made, the more accurately their pigeons performed.

Because the elements were revealed in random order, and typically not all were revealed, it was possible to assess the differential influence of each dimension of the stimulus on choice accuracy. This was done using logistic regression analysis. The side that was correct on a given trial and the session cycle number were included as regressors to allow for side preference and any continuing learning respectively. The analysis was conducted separately for each pigeon; the side on which reward was available and the session number were also included in the regression. Figure 4 summarizes the results of the logistic regressions and shows that the dimensions acquired differential control over behavior to very different extents. The lozenge dimension did not acquire significant control for any pigeon, but all the other dimensions did for at least one pigeon. One pigeon (Wv) showed no significant improvement in its performance as a function of the presence of any dimension; this result would be obtained if the pigeon was using all the dimensions to a similar extent. One pigeon (Cm) showed a negative impact of the lozenge dimension, possibly indicating that this element acted as a distracter.

Figure 5 shows the proportion of wait-to-reveal trials on which each dimension of the stimulus had been made available by the time the pigeon made its first choice peck. In contrast with the highly differential impact of the dimensions seen in Figure 4, for each pigeon these proportions were highly similar for all dimensions, showing that there was no tendency for the pigeons to wait for particular stimulus elements to appear before making their choice response. A related way of considering such selectivity is to ask on what proportion of trials the choice peck followed immediately on a particular dimension being revealed; for no pigeon was this figure higher than 28% for any dimension (with four dimensions, the figure expected by chance is 25%).

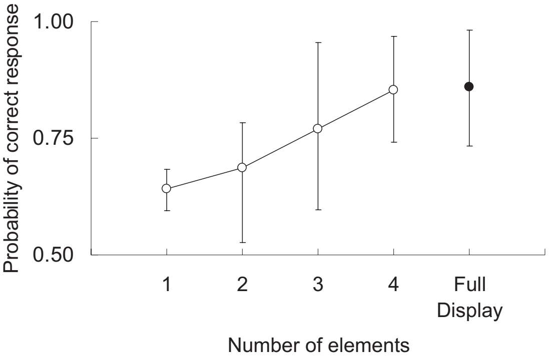

Figure 3. Experiment 1A, wait-to-reveal conditions. Impact of number of elements revealed at the moment of the first choice response on choice accuracy. Data are means and ranges across 6 pigeons taken over the final five sessions of training. Data from the prototype stimulus in the last 10 full-display training sessions are shown for comparison.

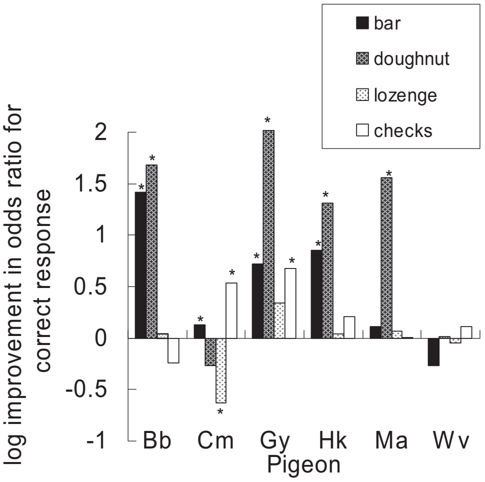

Figure 4. Experiment 1B: Logistic regression coefficients measuring the differential impact of the availability of the stimulus dimensions on choice accuracy during the final five wait-to-reveal training sessions. Bars marked with an asterisk indicate effects significant at $p < .05$.

Table 1 includes the percentages of the test trials with one-away stimuli on which choice behavior was consistent with each of five simple hypotheses—control by each of the four dimensions or control by overall similarity. Three pigeons showed evidence of being under the control of a dominant single dimension (“doughnut” for Hk and Ma, “checks” for Cm). One pigeon (Wv) was best described as being under the control of overall similarity. Results for the remaining two pigeons were ambiguous, with evidence that one dimension (“doughnut” in both cases) played more of a role than the others but that more than one played at least some part.

The results in Table 1 are generally consistent with those for the wait-to-reveal sessions at the end of training as shown in Figure 4, where it can be seen that the presence of doughnut was the best predictor of correct choice for Hk and Ma and the presence of checks was the best predictor for Cm, whereas Wv showed little differential impact of any dimension. However both Hk and Cm showed some evidence of control by a second dimension in the wait-to-reveal condition. Bb and Gy both showed evidence of quite strongly differential control by two or three dimensions in the

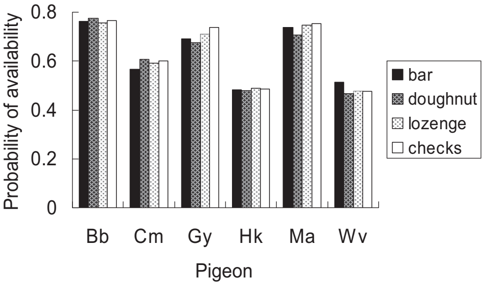

Figure 5. Experiment 1A: Probability of availability of each stimulus dimension at the moment of choice. Data are means across the last five wait-to-reveal sessions during training.

Table 1

Experiments 1A and 1B: Results of Test Trials With One-Away Stimuli: Percentages of the 48 Trials That Were Correctly Predicted by Simple Hypotheses About the Aspects of the Stimuli Controlling Behavior

	% Unidimensional sorting based on:				
Subject	Bar	Doughnut	Lozenge	Checks	% Overall similarity
Pigeons					
Bb	67	79	58	54	79
Cm	67	54	50	79	75
Gy	54	75	67	54	75
Hk	52	94	48	52	75
Ma	58	79	50	54	67
Wv	63	79	63	63	83
Students					
1, 2, 9, 11, 21	100	50	50	50	75
6, 7, 15	50	100	50	50	100
19	44	94	44	56	69
13	50	50	100	50	75
5, 8, 20	50	50	50	100	75
17	50	38	50	88	63
3, 10, 12, 18	75	75	75	75	100
16	69	81	69	69	94
4	63	75	75	63	88
14	56	69	81	56	81

wait-to-reveal condition, and this is consistent with their performance in the one-away tests.

Two different procedures, the wait-to-reveal sessions during training and the one-away test trials, conducted at different times, thus gave converging, if not identical, evidence about the stimulus dimensions that had acquired control over behavior. The data agreed with the conclusion of Lea and Wills's (2008) findings that when multiple stimulus dimensions are available to pigeons, they may nonetheless come under control of only one or a few of those dimensions, although they also show that multidimensional control is not impossible.

The results show that our novel wait-to-reveal procedure was successful in enabling us to see the impact of different quantities and kinds of information on the pigeons' choice. However, nothing in the results suggests that the pigeons used the wait-to-reveal procedure to enhance the speed and accuracy of their choices. It would clearly have been to the advantage of most of the pigeons to wait for the doughnut dimension to be revealed and then respond immediately, because that was the dimension that controlled behavior most effectively. However, Figure 5 shows that, in fact, they were completely indiscriminate in their waiting: For each pigeon, the probabilities that each of the dimensions had been revealed at the time the pigeon made its choice were virtually identical.

Experiment 1B

Experiment 1A showed that pigeons could be trained to work in a task in which multiple cues were revealed sequentially and that, in such a procedure, most pigeons would show something close to unidimensional control over behavior. However, it appeared that their choice was not governed by a take-the-best strategy, or indeed any strategy, because they did not wait selectively for the information that they used selectively. Objectively, of course, all dimensions of the stimuli offered equally good information, but the dimensions' differential control over behavior that they acquired meant that the pigeons' failure to use such a strategy made their behavior inefficient.

In several experiments (e.g., Bröder & Schiffer, 2003; Martignon & Hoffrage, 2002; Newell & Bröder, 2008) humans have been shown to follow take-the-best or related strategies in multidimensional discrimination tasks, although they do not do so universally (Newell & Shanks, 2003). However, despite formal similarities, these tasks were procedurally quite unlike those we gave the pigeons in Experiment 1A. Accordingly, in the present experiment, university students were exposed to a task that was as similar as possible to the procedure used in Experiment 1A.

Method

Participants

Twenty-three undergraduates were recruited through the participant panel of the University of Exeter School of Psychology in Exeter, United Kingdom. Participation was incentivized by a small money payment or course credit.

Apparatus and Stimuli

Experimental sessions took place in a small, quiet room. Students sat at a table on which there was a keyboard and computer screen, with a touchscreen as in Experiment 1A. The stimuli were identical to those in Experiment 1A, and the same program was used to control the experimental procedure. Students responded by touching the screen.

Procedure

The session structure was different from that in Experiment 1A. There was a single session divided into training and test phases. The timing of events differed slightly from that in Experiment 1A in that the intertrial interval was reduced to 1 s and was constant and correct responses were followed by the presentation of a large smiley face in the center of the screen for 1 s. The training phase was divided into blocks of 40 trials, in which every third trial was conducted under wait-to-reveal conditions and the remainder under full-display conditions. The timing of the presentation of elements of the stimulus on wait-to-reveal trials and the schedule of reinforcement in force on the choice keys, were exactly as those in Experiment 1A. For half the participants, responses on the right choice key were reinforced in the presence of the Version A prototype stimulus shown in Figure 1 and responses on the left choice key were reinforced in the presence of the Version B prototype; for the remaining participants, these contingencies were reversed. If a student reached a criterion of 80% or more correct on a training block, the test phase started; if this criterion was not reached within three blocks, the student was dropped from the experiment. The test consisted of 60 trials, of which 40 were training trials and the remaining 20 were test trials, 16 of them with one-away stimuli and 4 with prototype stimuli under test contingencies. Each test stimulus was used twice, once with reinforcement contingent on a response to the left choice key and once with reinforcement contingent on a response to the right choice key. All trials in the test phase were run under full-display conditions.

Results and Discussion

Two of the students failed to reach the learning criterion within three blocks of training trials. Among the remainder, who learned successfully, the mean number of elements exposed before the first choice response was 2.24 on the final trial of acquisition (95% confidence interval, 1.72 to 2.76), somewhat less than for the pigeons in Experiment 1A (see Figure 2). This demonstrates that the schedule of reinforcement used in these experiments was successful in restraining the comparatively high impulsiveness commonly shown by pigeons when there is any possibility of immediate reward.

Performance on the wait-to-reveal trials was much more variable than for the pigeons in Experiment 1A. To some extent, this variability is to be expected as there were relatively few such trials (for a student who learned the task within the first block, only 13), so that behavior may not have had time to stabilize fully, and in any case, high sampling variability is to be expected. In addition, however, different styles of responding were apparent. Three of the participants (Nos. 1, 20, and 21) always waited until all four elements had appeared. For these students, the lack of intertrial variability meant that it was not possible to find any evidence about which dimensions of the stimulus were exerting control over behavior. Other students appeared to be waiting more selectively than the pigeons. The small number of wait-to-reveal trials meant that it was not possible to use the logistic regression method (the results of which for the pigeons are shown in Figure 4) to analyze the impact of the presence or absence of the different stimulus dimensions. However, it was possible to consider which dimensions were present at the moment of choice and so obtain data that were parallel to those from the pigeons shown in Figure 5. The proportions of trials on which the dimensions were present at the moment of choice differed much more between dimensions within an individual student's data than in the pigeon data shown in Figure 5, suggesting that at least some of the students were waiting selectively. To see what the students were waiting for, we examined which dimension had just been presented when the choice response was made. For 4 of the students, there was one dimension that was immediately followed by the choice response on over 50% of trials (the bar for Students 2 and 9 and the checks for Students 6 and 7).

Table 1 includes the results of the test trials with one-away stimuli. It can be seen that 14 of the 21 students showed clear evidence of unidimensional sorting strategies, with 5 (Nos. 1, 2, 9, 11, and 21) making all their choices on the basis of the bar dimension; 4 (Nos. 6, 7, 15, and 19) making all or almost all on the basis of the doughnut dimension; 1 (No. 13), on the basis of the lozenge; and 4 (5, 8, 20, and 17), on the basis of the checks. Of the remaining 7 participants, 6 responded in test trials on the basis of overall similarity and the remaining student (No. 14) showed a mixed pattern. Consistent with the conclusions of Lea and Wills (2008) and with other recent experiments in which we have compared the behavior of pigeons and humans toward multidimensional stimuli in closely comparable procedures (Wills et al., in press), the tendency toward unidimensional sorting was not obviously stronger in the students in the present experiment than in the pigeons of Experiment 1A (recall that, in the one-away tests, 3 of the 4 pigeons whose categorization strategy was identifiable showed unidimensional control).

The 2 students (Nos. 2 and 9) who showed highly selective waiting for the bar in the wait-to-reveal training trials were among those who showed unidimensional control by the bar in the one-away test trials. Similarly, the students (Nos. 6 and 7) who showed selective waiting for the checks were among those who showed unidimensional control by the checks. Unlike any of the pigeons in Experiment 1A, therefore, these 4 students had developed something reasonably like a take-the-best strategy, waiting selectively for the information that they were treating as relevant to the task. Four of 23 participants is not a high proportion, and we cannot rule out the possibility that if we had tested a large number of pigeons, we would have found one or two that showed the same kind of strategy. However, the very low variability in the pigeons' self-exposure to the different dimensions (see Figure 5) makes this unlikely; even the students who were less selective in their waiting showed much less uniform behavior than the pigeons.

Experiment 2

Experiment 1A found that pigeons could be trained to work in a situation that somewhat resembled the tasks that have been discussed by Gigerenzer and his colleagues (e.g., Gigerenzer & Goldstein, 1996; Gigerenzer, Todd, & the ABC Research Group, 1999), and Experiment 1B showed that, in the same procedure, some humans (admittedly a minority) would use a version of the take-the-best strategy—whereas none of the pigeons did. The procedures used in Experiments 1A and 1B were designed to be similar to those used in our previous comparative experiments with multidimensional stimuli (e.g., Wills et al., in press), and the results from one-away tests were similar to those obtained before, establishing the consistency of the situation with standard approaches to human and animal categorization. However, the procedures of Experiments 1A and 1B differed in many ways from previous experiments investigating the take-the-best strategy in humans (e.g., Bröder & Schiffer, 2003; Newell & Bröder, 2008). The purpose of Experiment 2 was to develop the procedure of Experiment 1A to see whether pigeons could be trained in something more like the established experimental tasks and, if so, whether, they would then show something more like a take-the-best strategy.

Three of the ways in which the procedure in the wait-to-reveal trials of Experiment 1A differed from typical published experiments with humans were as follows:

(a) Making an early choice did not result in earlier reward. This constraint was introduced deliberately in Experiment 1A to ensure that pigeons' well-established impulsiveness would not prevent them being exposed to the full contingencies of the wait-to-reveal trials. In the first phase of Experiment 2, we explored whether it was necessary.

(b) The pigeons had no control over the timing of the arrival of additional information. In some cases, therefore, elements of the stimulus may have been revealed while the pigeons were not looking at the stimuli or were, for other reasons, unable to respond to them. In the second phase of Experiment 2, therefore, we instituted a procedure called "peck to reveal," in which the pigeons were required to make a response (directed at the stimulus area) to reveal each element of the stimulus. Numerous experiments with the successive encounters choice procedure, introduced as a simulation of natural foraging by Lea (1979), have shown that pigeons will switch selectively from one operant response to another when a signal for a favorable schedule is produced by a response.

(c) The pigeons had no control over the order in which additional information arrived. In the final phase of Experiment 2, therefore, we instituted a procedure called "choose to reveal," in which pecking at particular zones within the stimulus area would reveal particular elements of the stimulus.

Method

Subjects and Apparatus

Five of the pigeons used in Experiment 1A were used (the sixth pigeon, Ma, had become ill and was not available). The pigeons were kept under the same conditions as in Experiment 1A. The apparatus was the same as that used in Experiment 1A.

Procedure

The experiment took place in several phases. The general procedure was based on that used in the training phase of Experiment 1A, but different variations were introduced in each phase.

Wait-to-reveal condition with immediate reward for correct choice. The first phase was identical to the training phase of Experiment 1A, except that the schedule on the correct choice key was continuous reinforcement, so that trials terminated as soon as a correct choice was made. The phase continued for a total of 30 sessions. The sequence of full-display and wait-to-reveal sessions was maintained as it was in Experiment 1A, so there were a total of 10 wait-to-reveal sessions.

Peck-to-reveal condition. In the second phase, the pigeons were trained to peck the stimulus area to reveal the elements of the stimulus. As in the wait-to-reveal condition, a peck to the observing key caused it to be replaced by one randomly chosen element of the stimulus. However, further elements were not revealed until the pigeon pecked the stimulus area. The order in which they were revealed was random. The schedule for revealing them was a fixed interval (FI) of 2.5 s, so at least 2.5 s elapsed before an additional element was revealed. In the first 10 sessions of this phase, the choice keys were presented simultaneously with the fourth element. In the remaining 10 sessions, the choice keys were presented simultaneously with the first element, and as in the wait-to-reveal condition used earlier, the first peck to either choice key prevented any further elements being added. As in the preceding phase (and unlike the conditions in Experiment 1A), pecks to the correct choice key were immediately reinforced.

Choose-to-reveal condition. The final phase was preceded by a reinstatement of the conditions of the wait-to-reveal phase until a criterion of 80% correct choice was met, and then there was a reinstatement of the conditions of the training phase Experiment 1A (i.e., with reinforcement for choice pecks delayed), again until criterion was met. Once stable discrimination was re-established, we introduced a procedure that gave the pigeons control over which elements of the stimulus array were presented. When the pigeon pecked the observing key to start the trial, it was presented with an array of four white disks covering the locations where the elements of the stimuli had previously appeared. A single peck on any disk caused it to be replaced by the corresponding stimulus element. The choice keys were presented after one to four elements had been exposed, the number varying randomly from trial to trial but all numbers being used equally often within each session. A single peck to the correct choice key ended the trial, but pecks to the incorrect choice key had no scheduled consequences; in particular, after an incorrect choice key peck, further pecks to the stimulus area could still reveal further elements of the stimulus. Twenty choose-to-reveal sessions were given in this phase.

Results and Discussion

In the wait-to-reveal sessions, all 5 pigeons waited for fewer elements to be revealed than in the same kind of sessions in Experiment 1A. The mean number of elements exposed over the last five sessions of the present experiment was 1.53 (range across individual pigeons = 1.16 to 2.20), as compared with 2.42 (range = 1.94 to 3.06) in the last five wait-to-reveal sessions of Experiment 1A. Clearly, the interval schedule on the choice keys in Experiment 1A was effective in ensuring that the pigeons were exposed to the gradual increase in information available to guide choice.

Figures 6 and 7 show the influence of the availability of each stimulus dimension at the moment of choice on choice accuracy, and the probability that each kind of information was available, in

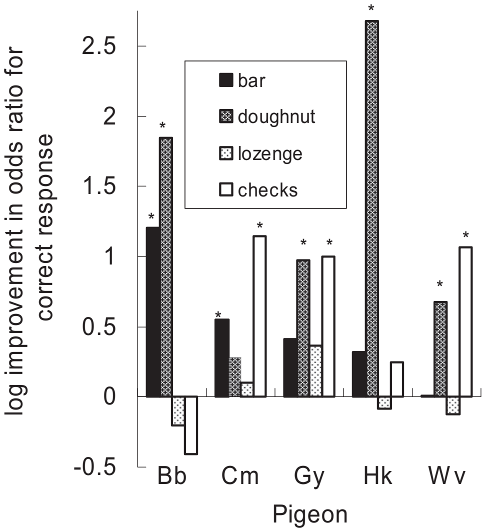

Figure 6. Experiment 2: Logistic regression coefficients measuring the impact of the availability of the stimulus dimensions on choice accuracy during the final five wait-to-reveal training sessions, with immediate reward available for correct choice. Bars marked with an asterisk indicated effects significant at $p < .05$.

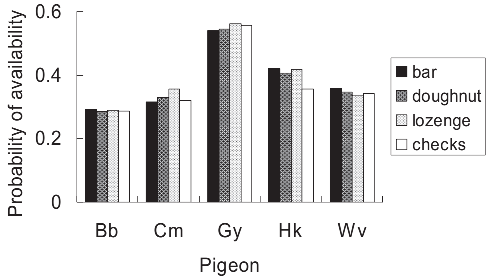

Figure 7. Experiment 2: Probability of availability of each stimulus dimension at the moment of choice. Data are means across the last five wait-to-reveal sessions during training with immediate reward for correct choice responses.

the last five wait-to-reveal sessions, corresponding to Figures 4 and 5 for Experiment 1A. Figure 6 shows that the pattern of control over behavior was similar to that seen in Experiment 1A, although rather more clear. Figure 7 shows that, as in Experiment 1A, there was no evidence of selective waiting for the dimensions that exerted effective control; for the majority of the pigeons, the probability of availability of each dimension was only a little over 0.25, indicating that they tended to make a choice key peck before a second element had been presented. Correspondingly, none of the pigeons showed any tendency to make their first choice peck more often after the presentation of one dimension rather than the others.

Under the peck-to-reveal condition, all the pigeons pecked the choice keys as soon as they were made available on almost every trial. Choice accuracy was affected by what dimension was exposed first, in ways that could be predicted for each pigeon from their behavior in the previous phase, so these data too could be seen as evidence of failure to wait strategically: The pigeons could have kept pecking until the dimension that controlled their behavior most strongly appeared, but they did not. The results are strikingly different from those that have been found by Lea (1979) and many authors since with pigeons in the successive-encounters choice procedure, in which pecks at a single "foraging" key make different schedules of reinforcement available on a separate key. However, in that procedure, the stimuli that differentiate the final schedules are presented on the key associated with them, whereas in the present experiment, the different signals were presented on the key that had to be pecked initially. It is likely that the pigeons were so strongly under the control of the appearance of the choice keys, which, on some trials, led to immediate reinforcement, that they had no tendency to wait at all. As a result, it was impossible to tell whether they would have waited strategically.

The choose-to-reveal condition led to quite different behavior. As in the peck-to-reveal condition, the pigeons almost always pecked one of the choice keys as soon as they were made available; the proportion of trials on which they did not was less than 1%. Accordingly, in later sessions in the choose-to-reveal conditions, the mean proportion of trials on which a dimension was available to a pigeon at the moment of choice was almost exactly equal to the proportion of trials on which the pigeon revealed that dimension. However, the pigeons were selective in which dimensions they pecked. The upper panel of Figure 8 shows the probability that each dimension was pecked first, and it can be seen that there were marked differences both within and between individuals—but was this selectivity functional in any way? The lower panel shows the influence of the availability of each dimension on the accuracy of the pigeons' choice, which was analyzed with logistic regression as in Figure 4 for Experiment 1A. It can be seen that the pigeons did not expose the dimensions of the stimuli equally. Comparison of the two panels shows that 2 of the 5 pigeons (Bb, Gy) selectively exposed the dimensions that most strongly controlled their behavior, whereas the other 3 (Cm, Hk, and Wv) did not. This proportion of pigeons selecting one of four dimensions falls short of significance, although the sample is small. What is not in doubt is that the choose-to-reveal condition, unlike any we had used previously, led the pigeons to self-expose to different dimensions differentially. This is consistent with results on pigeons' acquisition of observing responses, where it is found that the extent to which discriminative stimuli will serve as reinforcers is affected by how easy they are to discriminate (e.g., Dinsmoor, Sears, & Dout, 1976).

Experiment 2 thus gave evidence that pigeons may be capable of choosing to expose themselves selectively to information that is useful to them. However, there was no sign that they would do so except where they were actively selecting information. When information was presented at random, according either to the passage of time (as in the wait-to-reveal condition of the present experiment and Experiment 1A) or as a consequence of pecks at an undifferentiated target (as in the peck-to-reveal condition), there was no evidence of selective waiting for the most useful information. Experiment 3 explored the choose-to-reveal condition further, but it also introduced new features that might make it more likely that pigeons would behave strategically.

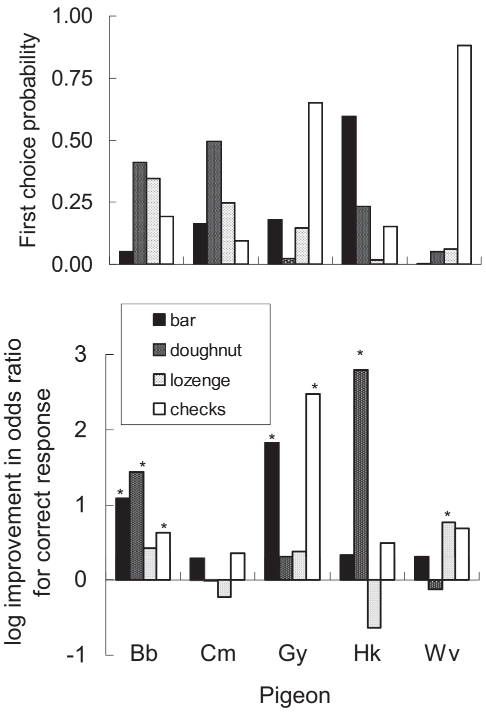

Figure 8. Experiment 2: First-choice probabilities and differential control over behavior for the four stimulus dimensions in the final five sessions of the choose-to-reveal condition.

Experiment 3A

Experiments 1A and 1B identified a possible difference between pigeons and students in their tendency to expose themselves selectively to information that they used in making a multidimensional discrimination. None of the pigeons in Experiment 1A waited selectively for the cues that controlled their behavior to appear, but some of the students in Experiment 1B did. Experiment 2 showed that some (although not all) pigeons would select information that was useful to them, but we found no evidence that they would either wait or work for further information rather than making a choice response as soon as that was available.

In all these experiments, it was only the subjects' own approach to the discrimination task that made one stimulus dimension more useful than another. Objectively, all the dimensions gave 100% valid information about which choice response would be reinforced. This is the usual arrangement in experiments investigating categorization strategies (e.g., Milton, Longmore, & Wills, 2008; Wills et al., in press). However, a better analogue to the tasks discussed by Gigerenzer and Goldstein (1996) and Gigerenzer et al. (1999), and indeed a more ecologically valid task, would be a situation in which different dimensions are of objectively different value. Experiments 3A and 3B explored such a situation, with pigeons and humans, respectively.

Although the pigeons in Experiment 1A did not wait selectively, they did learn to wait progressively longer on wait-to-reveal trials as training continued, and (presumably as a result) their choice accuracy improved, as Figure 3 shows. In contrast, in most phases of Experiment 2, the pigeons (the same pigeons as in Experiment 1A) pecked the choice keys immediately they became available. The difference between the experiments was that correct choice responses were reinforced immediately in Experiment 2. It is not surprising, given what is known about the extreme influence of even occasional immediate reward on pigeons' preference (e.g., Ainslie, 1974; Davison, 1972; Morris, 1986), that the possibility of immediate reward for choice swamped the effect of any improved accuracy that more information would have made possible. Accordingly, in Experiments 3A and 3B, we reverted to using delayed reinforcement for choice responses, as in Experiments 1A and 1B.

However, Experiment 2 did suggest that the choose-to-reveal procedure might give evidence of greater selectivity in pigeons' use of information. Accordingly, Experiment 3A incorporated both a wait-to-reveal and a choose-to-reveal phase.

Method

Subjects and Apparatus

The subjects were 6 experimentally naïve domestic pigeons (*Columba livia*) obtained from local fanciers. They were maintained under the same conditions as the pigeons in Experiments 1A and 2. The same apparatus and general procedure were used in Experiments 1A and 2. Five of the pigeons were tested in boxes with infrared touchscreens; 1 pigeon (Mb) was tested in a box with a resistive touchscreen. To ensure that they were capable of performing a discrimination with the contingencies to be used in the experiment, we pretrained the pigeons to an 80% correct criterion on a conditional go-left/go-right discrimination between red and green colored disks, using the same differential outcomes procedure as in the full-display conditions of Experiments 1A and 2.

Stimuli and Experimental Design

The stimuli used are shown in Figure 9. They were based on those used in the previous experiments; however, because there was little evidence that the lozenge dimension ever acquired control over pigeons' behavior, it was not used, and the remaining three elements were arranged in an upright triangle. All eight possible stimuli were used for all pigeons. Partial stimuli in which only one or two elements appeared (in their usual locations) were also used under some conditions.

For each pigeon, the stimuli were grouped into two sets of four. In the presence of the stimuli from one set, responses on the right choice key were reinforced; in the presence of the remaining stimuli, responses on the left choice key were reinforced. For each pigeon, the stimulus sets and the frequencies with which stimuli were presented were arranged so that the three stimulus dimensions had different correlations with the side key where pecks would be reinforced. For one of the dimensions, all stimuli that included one of the values of the dimension were followed by reinforcement of a left choice key peck and all stimuli that include the other value of the dimension were followed by reinforcement of a right choice key peck (perfect validity). For a second dimension, 75% of stimuli that included one of the values of the dimension were followed by reinforcement of a left choice key peck, and 25% of such stimuli were followed by reinforcement of a right choice key peck; the opposite contingencies were in force of the other value of the dimension (partial validity). For the remaining dimension, 50% of stimuli that included either value of the dimension were followed by reinforcement of a left choice key peck, and 50% by reinforcement of a right choice key peck (zero validity). Table 2 shows which dimensions had which validities and which dimension values were associated with reinforcement of pecks to each side key. Given the number of subjects, not every combination of cue validities could be used, but as Table 2 shows, the design ensured that each pigeon was paired with another that had exactly the opposite contingencies.

The differential validities of the three dimensions were achieved by presenting four of the stimuli three times as often as the other four. For example, pigeons Su and Mb, for which the bar dimension was perfectly valid and the doughnut dimension was partially valid, had three times as many trials with stimuli that had the long bar combined with the thin doughnut, or the short bar combined with the fat doughnut (the left four stimuli in Figure 9), as with stimuli that had the long bar combined with the fat doughnut or the short bar combined with the thin doughnut (the right four stimuli in Figure 9).

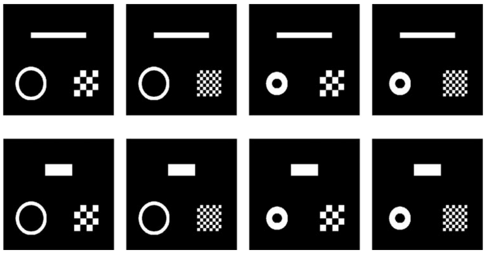

Figure 9. Stimuli used in Experiments 3A and 3B.

Table 2
Experiment 3A: Association of Stimulus Dimensions and Values on Those Dimensions With Reinforcement of Choice-Key Pecks

Pigeon	Validities of dimensions			Values correlated with reinforcement of left choice-key pecks
	Bar	Doughnut	Checks	
Su	Perfect	Partial	Zero	Short bar, fat doughnut
Mb	Perfect	Partial	Zero	Long bar, thin doughnut
Sn	Zero	Perfect	Partial	Fat doughnut, small checks
Tt	Zero	Perfect	Partial	Thin doughnut, large checks
Fr	Partial	Zero	Perfect	Small checks, short bar
Rg	Partial	Zero	Perfect	Large checks, long bar

Procedure

The pigeons were trained in a conditional discrimination, using positionally differential outcomes as in Experiments 1A and 2. The procedure had the following differences from that used in Experiments 1A and 2. Sessions consisted of 96 trials. All eight stimuli shown in Figure 9 were used in each session. Four of them were used 18 times each, and four of them were used 6 times each; the more frequently used stimuli were different for each of the three pairs of pigeons to achieve the cue validities shown in Table 2. The experiment took place in two phases, as follows.

Wait to reveal. The first phase involved two types of session, full display and wait to reveal. The first two sessions used the full-display procedure, the third used the wait-to-reveal procedure, and so on. Under full-display conditions, the entire stimulus was displayed as soon as the pigeon pecked the observing key. A *tand* FT 10-s–VI 5-s schedule was in force on the designated correct choice key. Under wait-to-reveal conditions, only one element appeared when the observing key was pecked, and further elements appeared at 3.5-s intervals unless a choice key was pecked. The same *tand* FT 10-s–VI 5-s schedule was in force on the correct choice key as under full-display conditions, but the first peck to either choice key prevented the presentation of further elements of the stimulus. This phase continued for 55 sessions, which included 18 wait-to-reveal sessions.

Choose to reveal. In the second phase, all sessions involved a choose-to-reveal procedure based on that of Experiment 2. When the pigeon pecked the observing key, the stimulus for the trial appeared with all three elements replaced by white disks. Pecking any of those disks caused it to be replaced by the corresponding stimulus element. Pecks at the choice key prevented any further elements being revealed, but the *tand* FT 10-s–VI 5-s schedule on the correct choice key was maintained. Each pigeon was exposed to 20 sessions of this condition.

Results and Discussion

Learning was slower than in Experiment 1A. Mean performance at the end of training in the first phase (55 sessions) was assessed across the final 15 sessions, which included 5 wait-to-reveal sessions. The mean probability of a correct first-choice response was 71% under full-display conditions (range across pigeons = 51%–92%) and 65% (range = 51%–76%) under wait-to-reveal conditions. In Experiment 1A, all pigeons reached a criterion of 80% correct in fewer sessions than this. This difference is not surprising because in Experiment 1A all stimulus dimensions gave perfectly valid information, so whatever aspect of the stimulus acquired control over behavior could in principle lead to correct performance, whereas in the present experiment, to achieve even 80% correct, the pigeons had to come under control of the one particular dimension that was perfectly valid for them.

Because the eight stimuli used in training involved all combinations of dimension values, it is possible to evaluate the control over behavior exerted by each stimulus dimension during training, using data from the full-display sessions rather than relying on regression analyses of data from the wait-to-reveal sessions. Figure 10 shows the probabilities of making a correct choice response on trials when the partially valid and perfectly valid cues gave conflicting information and on trials when they gave consistent information, in the last 10 full-display sessions. For 4 of the 6 pigeons (Sn, Tt, Rg, and Fr), the probability of a correct response was above 0.5 for both cue combinations, implying that the perfectly valid dimension exerted strong control over behavior. However the probability of a correct response was slightly higher when the cues were consistent, implying that the partially valid cue exerted some additional but weaker control. This effect is especially noticeable for pigeon Sn. For the remaining pigeons, Mb and Su, the probability of a correct response was below 0.5 when the cues gave conflicting information. This means that the situation was reversed, with stronger control by the partially valid dimension. Pigeon Su showed only weak control by the partially valid dimension and essentially no control by the perfectly valid dimension. For both these pigeons, the perfectly valid dimension was the bar dimension and the partially valid dimension the doughnut, but the sample size is too small to tell whether this is more than a coincidence; it should be noted, however, that the bar did seem to exert some control in the cases (i.e., Fr and Rg) in which it was the partially valid cue. Experiments 1A and 2 showed that, when several cues are equally valid, pigeons show spontaneous individual differences in which of them comes to control behavior; the

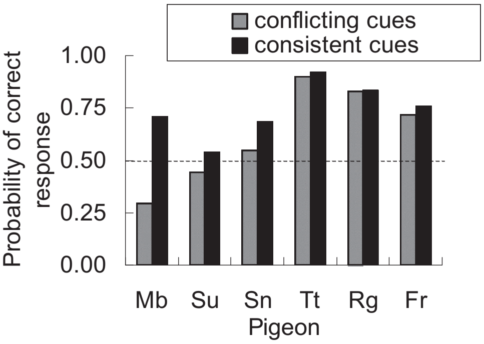

Figure 10. Experiment 3A: Probability of making a correct first choice key peck given different combinations of cue dimension values. On cue conflict trials, the information from the partially and perfectly valid dimensions disagreed; on consistent trials, they agreed. Data are means over the last 10 full-display sessions. For pigeons Mb and Su, the perfectly valid stimulus dimension was the bar and the partially valid dimension was the doughnut; for pigeons Sn and Tt, the perfectly valid dimension was the doughnut and the partially valid dimension was the checks; and for pigeons, Rg and Fr, the perfectly valid dimension was the checks and the partially valid dimension was the bar.

present results suggest that such differences in salience can override even quite marked differences in the validity of cues.

Figure 11 shows the probability that each dimension was present at the moment of choice in the last five wait-to-reveal sessions for each pigeon. Despite the clear differential control by dimensions shown in Figure 10, there was once again no evidence of differential waiting for more useful information.

In the choose-to-reveal condition, the pigeons' behavior resembled that seen in the corresponding condition of Experiment 2. They came strongly under control of the presentation of the choice keys, and on almost all trials they pecked one as soon as they were presented; the proportion of trials on which they exposed a further element after presentation of the choice keys was a little higher than in Experiment 2 but did not exceed 10% for any pigeon and tended to be lower in later sessions of the condition.

Figure 12 shows which elements the pigeons exposed first under choose-to-reveal conditions. As in Experiment 2, the pigeons were highly selective in which element they exposed first. Pigeons Sn, Su, and Fr reliably exposed first the dimension that was perfectly valid for them (doughnut, bar, and checks, respectively; however, Su did not apparently discriminate the bar dimension). Pigeons Rg and Mb reliably exposed first the dimension that was partially valid for them (bar and doughnut, respectively), and in Mb's case, this was the dimension that most strongly controlled behavior. Pigeon Tt reliably exposed first the dimension that had zero validity for that pigeon (the bar). As in the corresponding condition in Experiment 2 (see Figure 8), the association between selective exposure and control over behavior is greater than would be expected by chance but falls short of significance.

The experiment thus confirmed the conclusions of Experiments 1A and 2, under conditions where the importance of different dimensions was under control of the experimenter rather than being a consequence of the pigeons' idiosyncratic attentional strategies. Under wait-to-reveal conditions, the pigeons' behavior more often than not came under the control of the perfectly valid dimension, but there were exceptions. There was no evidence of selective waiting for the most useful information to appear. Under choose-to-reveal conditions, the pigeons were strongly selective in which dimensions of the stimulus they exposed first, but although the majority of pigeons selected the dimensions that controlled their behavior, the trend for them to do so fell short of significance. Furthermore, they rarely continued to expose more information once the choice keys were available, regardless of what information they had available.

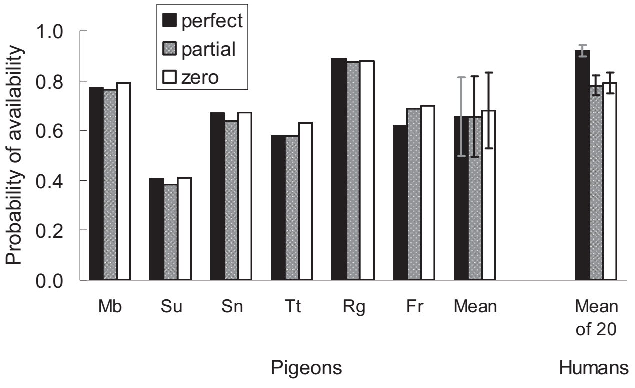

Figure 11. Experiments 3A and 3B: Probability of availability of stimulus dimensions of different validity at the moment of choice under wait-to-reveal conditions. Data are shown for individual pigeons, from the last five wait-to-reveal sessions, and as a mean over all the students, from the trial block in which criterion was reached. The 95% confidence intervals are shown for the mean values from each species.

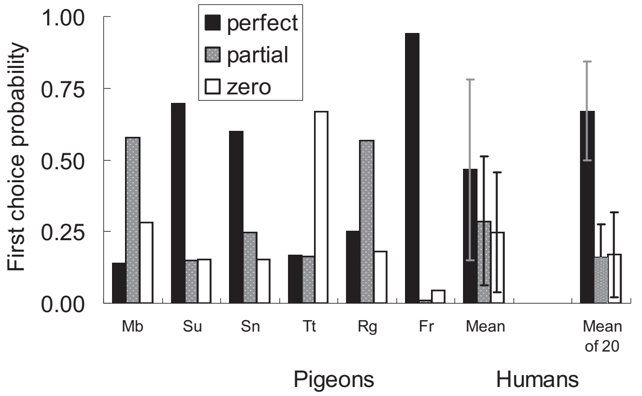

Figure 12. Experiments 3A and 3B: First-choice probabilities for the three stimulus dimensions in the choose-to-reveal condition. Data for pigeons are means over the last five sessions of the condition, and data for students are means over all choose-to-reveal trials. The 95% confidence intervals are shown for the mean values from each species.

Experiment 3B

Experiments 1A and 1B demonstrated a possible difference between pigeons and students in their strategy toward information that was made available in stages: Some humans but no pigeons showed selective waiting for information that they were using. The aim of Experiment 3B was to investigate whether this difference would be seen under conditions where cue validities were not all equally and perfectly valid. Experiment 3B therefore replicated the procedures of Experiment 3A as closely as possible with humans.

Method

Subjects, Apparatus, Stimuli, and Experimental Design

Thirty undergraduate students were recruited on the same basis as those in Experiment 1B. The apparatus was the same as in Experiment 1B and the stimuli were the same as in Experiment 3A. The students were divided into three groups of 10. Each group had the same assignment of dimensions to perfect, partial, and zero validity as one of the pairs of pigeons in Experiment 3A.

Procedure

The experiment took place in a single session of up to 192 trials. Three types of trial were used: full display, wait to reveal, and choose to reveal, as in Experiment 3A. As in the relation between Experiments 1A and 1B, sessions of Experiment 3A were replaced by single trials in Experiment 3B. Trials were divided into blocks of 48 trials. In the first block, every third trial was under wait-to-reveal conditions, the remainder being under full-display conditions. If the student achieved 80% correct in any of the first three blocks, the next block was given under choose-to-reveal conditions. If the student did not reach criterion by the third block of the full-display and wait-to-reveal trials, the experiment was terminated. Up to three blocks of choose-to-reveal trials were given. The experiment terminated when the total number of blocks reached four or if the student reached a criterion of 80% correct in a choose-to-reveal block, whichever happened first. Data are reported only for students who reached criterion and only from the blocks in which criterion was reached.

Results and Discussion

The task proved to be difficult for the students. Ten of the 30 students failed to meet the criterion of correct discrimination. Several of these came under complete control of the partially valid dimension in the full-display/wait-to-reveal trial blocks; because this could at best lead to 75% correct performance, they could not reach the criterion. All 20 of the students whose data are analyzed further therefore must have come under the control of the perfectly valid dimension, and this was confirmed by examination of response tendencies to the eight different stimuli in the full-display trials during the last block when such trials were used. The high degree of accuracy achieved, and the small number of trials relative to the pigeons, meant that it was not possible to detect whether there was also some control by the partially valid dimension.

By the block in which they reached criterion, most students waited for most of the stimulus elements to appear on most of the wait-to-reveal trials. However, they did not wait unselectively. Figure 11 includes the mean percentage of trials on which the perfectly valid dimension was available and shows that the students had some tendency to wait for the perfectly valid cue; for 17 of the 20 students, the percentage of trials on which the perfectly valid cue was available was higher than for either of the other two cues. The agreement between the 20 students in the ordering of the probability of availability was significant (Kendall's $W = .46$), $\chi^2(2) = 18.56$, $p < .0005$. The mean probabilities of availability for the bar, doughnut, and checks dimensions were effectively equal (85%, 82%, and 84%; Kendall's $W = .01$), $\chi^2(2) = 0.18$, *ns*. Thus, although the students' willingness to wait made them appear only modestly selective, their selectivity was unambiguous, and it was always in the direction of waiting for the most useful information. This is in sharp contrast with the pigeons in Experiment 3A, whose data are also shown in Figure 11, with no evidence of selective waiting at all. This confirms the contrast with pigeons' behavior under wait-to-reveal conditions that was tentatively suggested from a comparison of the results of Experiments 1A and 1B.

All the students who reached criterion under full-display/wait-to-reveal conditions continued to perform at above-criterion levels under choose-to-reveal conditions. The mean probabilities of choosing the dimensions first are shown in Figure 12 to allow comparison with the corresponding data from the pigeons in Experiment 3A. Fifteen of the 20 students tended to expose the perfectly valid dimension before the others; the agreement between students as to the ordering of first-choice probabilities was significant (Kendall's $W = .40$), $\chi^2(2) = 16.02$, $p < .0005$. The mean probabilities of choosing the bar, doughnut, and checks dimensions first were 42%, 19%, and 32%, respectively, and these also differed significantly (Kendall's $W = .20$), $\chi^2(2) = 7.82$, $p < .02$; all 5 students who did not expose the perfectly valid cue first tended to expose the bar first, as part of a stereotyped sequence in which they exposed all the elements in a consistent order before making a choice response. Thus, all students who used a strategy that was capable of being selective did so in a way that favored the exposure of the most useful information. This is the same kind of selectivity as was shown by some of the pigeons in Experiment 3A, but it is much more clearly demonstrated despite the low number of trials available. It should be noted that data from all the pigeons tested have been included in the analysis, whereas the procedure used with humans eliminated the worst learners; however, even among the pigeons that learned the task well, not all exposed information in an order that was functionally efficient.

General Discussion

Several general conclusions can be drawn from these experiments.

1. As argued by Lea and Wills (2008), in conditions in which there are multiple redundant stimulus dimensions, any of which might be used to make a discrimination between two stimuli, pigeons are not necessarily more likely than humans to discriminate on the basis of overall similarity rather than a single dimension. This conclusion emerges primarily from a comparison between Experiments 1A and 1B, because in Experiments 3A and 3B the stimulus dimensions were not equally valid. Experiments 1A and 1B hence add to the evidence provided by Wills et al. (in press). Given these results and those of recent human studies (e.g., Milton et al., 2008), it seems increasingly implausible to maintain that there is any simple correspondence between nonanalytic processing and overall similarity classification or between analytic processing and dimensional classification, as has sometimes previously been claimed (e.g., Ward, 1983).

2. When information is made available sequentially, pigeons are more likely to expose themselves to it selectively when they receive it as a consequence of their own responding than when they receive it passively as a consequence of the passage of time. This conclusion emerges from a comparison between Experiments 1A and 2 and also from a comparison between the wait-to-reveal and choose-to-reveal conditions of Experiment 3A.

3. Regardless of how information is delivered, humans are more likely than pigeons to expose themselves to the most useful information selectively. This conclusion emerged tentatively from a comparison between the wait-to-reveal conditions in Experiments 1A and 1B and those in Experiments 3A and 3B, in which humans showed evidence of selective waiting but pigeons did not; but it is also true of the comparison between the choose-to-reveal conditions in Experiments 3A and 3B, for although both humans and pigeons showed some selectivity in that condition, it was more marked in the humans. Subjects who either wait for or choose the dimension that, objectively or subjectively, gives them the best

> information about the location of reward, are showing a simple form of the "take-the-best" heuristic. At least some students did do this in the wait-to-reveal conditions in Experiment 1B, whereas no pigeons did in Experiment 1A; but in those experiments, there was no objectively best dimension to wait for. In Experiments 3A and 3B, in which the objective value of the dimensions differed, the pigeons still showed no sign of selective waiting under wait-to-reveal conditions, whereas the students showed a small but consistent effect. However in the choose-to-reveal condition, students were unmistakably selecting the most useful information to reveal, whereas the evidence that pigeons were doing so was weak.

These conclusions throw light on the distinction between sorting by similarity and sorting by rule, which has often been linked to the distinction between unidimensional and overall similarity categorization (e.g., Ashby et al., 1998; Pothos, 2005). If we were to accept the identification of unidimensional sorting with rule use, we would have to say that the pigeons in Experiment 1A were using rules just as much as the students in Experiment 1B. That seems, prima facie, unlikely. We could rule it out completely by following Skinner (1969, chap. 6) and asserting that rules must necessarily be capable of being verbalized. To do so, however, would be to render trivial the question of what it would mean for a nonverbal animal to use a rule. Lea and Wills (2008) have argued that rule use should, at a minimum, entail that principles governing behavior in one situation are also available to govern it in another. This is a more general form of Skinner's verbalizability criterion: It recognizes that verbalizing a rule when asked about it after an experimental session is just one example of using a single principle in multiple situations. In the verbalization case, the principle that was being used to categorize stimuli within the test session is available to govern behavior in another situation, a verbal exchange with the experimenter, but there seems no particular reason to require that one of the situations should involve verbal behavior.

By the criterion that a rule being used should be available to govern behavior in multiple situations, the pigeons in Experiments 1A and 3A failed to show evidence of rule use. Furthermore, the situation was one in which it would have been adaptive to use a rule, and in which humans do show evidence of using one. Although the pigeons' behavior was selectively controlled by particular dimensions of our multidimensional stimuli (whether by accident of their own attention, as in Experiment 1A, or as a result of the differential validity of the dimensions, as in Experiment 3A), this selective principle was not available to control their waiting behavior, although it would have been to their advantage if it had been. Furthermore, the evidence that it was available to govern their selective exposure of the stimulus elements, in the choose-to-reveal conditions of Experiments 2 and 3A, is equivocal at best.

It is hardly a surprising conclusion that humans use rules under conditions where pigeons do not. However, for several reasons, convincing evidence for such a conclusion is sparse. First, in general, it is rare for experiments with pigeons and humans to be conducted with closely similar procedures. Second, in the specific case of categorization, the identification of unidimensional sorting with rule use has confused the issue.

If the pigeons were not sorting (more or less) unidimensionally because they were using rules, why did they not use more of the information available? The present experiments do not throw much light on this subject, but comparisons with previous experiments may be more illuminating. The stimuli we used were quite similar to those of Lea, Wills, and Ryan (2006). The experimental analysis reported in that article concluded that the most likely reason for birds (chickens) failing to use all the stimulus dimensions available was a limitation of attentional capacity. That is at least a plausible account of the pigeon data from the present experiment and would be a sufficient explanation for the capturing of 1 pigeon (Mb) by the "wrong" dimension in Experiment 3A, which was only partially valid as a predictor of the correct response location. It is well established that birds can remember the significance of large numbers of different visual stimuli (Cook, Levison, Gillett, & Blaisdell, 2005; Vaughan & Greene, 1984), but it is beginning to appear as though they cannot use much of this information simultaneously. However, it would be wrong to conclude that such limitation of attention is restricted to pigeons, because several of the students in Experiment 3B were also captured by the partially valid dimension.

The strong influence of immediate reward on pigeons' choice behavior (Ainslie, 1974; Davison, 1972; Morris, 1986) posed some difficulties in the present experiments, and it may well be that the ability to wait patiently is a difference between human cognition and that of all other animals (Stevens & Stephens, 2008). However, it should be possible to overcome these difficulties by adjusting details of the procedure. If that can be done, exposing information gradually, particularly when it is done as a consequence of a subject's responding, seems to be a powerful way of investigating both the information that subjects use in making discrimination and the extent to which they can be said to be doing so by means of rules.

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