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Rule Learning, Memorization Strategies, Switching Attention Between Local and Global Levels of Perception, and Optimality in Avian Visual Categorization

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We begin with an uncontroversial statement: There is much diversity of opinion about the differences between human and nonhuman animal cognitive abilities. Diversity of opinion is found in the scientific community, where some researchers hold fast to associative learning accounts of animal performances and others welcome more cognitive accounts (Smith, Shields, & Washburn, 2003). Diversity of opinion is also found among the public. Some pet owners, on the one hand, seem to attribute to their pets cognitive abilities scarcely less complex than those of humans; on the other hand, others believe, perhaps for theological reasons deriving from Cartesian mind/body dualism, that a nonhuman animal cannot have a mental life, because to assume otherwise might jeopardize the exclusivity of the human soul. These differences of opinion obviously affect experimental research on animal cognition and issues related to the ethical treatment of animals and corresponding political issues (Plous, 1998; Shimp, Herbranson, & Fremouw, 2001).

In this chapter, we examine four specific beliefs about which we see major differences of opinion. First, only humans can deal with abstractions; nonhuman animals cannot. Second, only humans can flexibly adopt different memorization strategies depending on what momentarily is in their best interest; nonhuman animals cannot. Third, only humans can flexibly perceive complex stimuli differently depending on what is in their best interest; nonhuman animals cannot. Fourth, only humans can closely approximate optimal categorization performances in arbitrary tasks; nonhuman animals cannot.

Our first goal in this chapter is to describe recent research that shows how avian visual categorization transcends these specific cognitive limitations that are sometimes attributed to nonhuman animals. Our second goal is to view this research on avian categorization from the larger perspective of two philosophical positions that inform discussions of knowledge, language, concepts, perception, and other themes relevant to research on categorization. We suggest that each philosophy carries with it tangible implications for what is sensible research on cognition. A discussion of related issues is provided in Shimp (2004b), from which parts of the present chapter are drawn. First, we review some of our recent work on avian visual cognition.

EMPIRICAL RESEARCH ON AVIAN VISUAL CATEGORIZATION

Abstract Rule Learning in the Face of Ambiguity, the Flexibility of Attention, and Optimality in Categorizing Multidimensional Stimuli

A perceptual categorization procedure developed by Ashby, Maddox, their colleagues, and others is proving to be especially helpful in revealing the

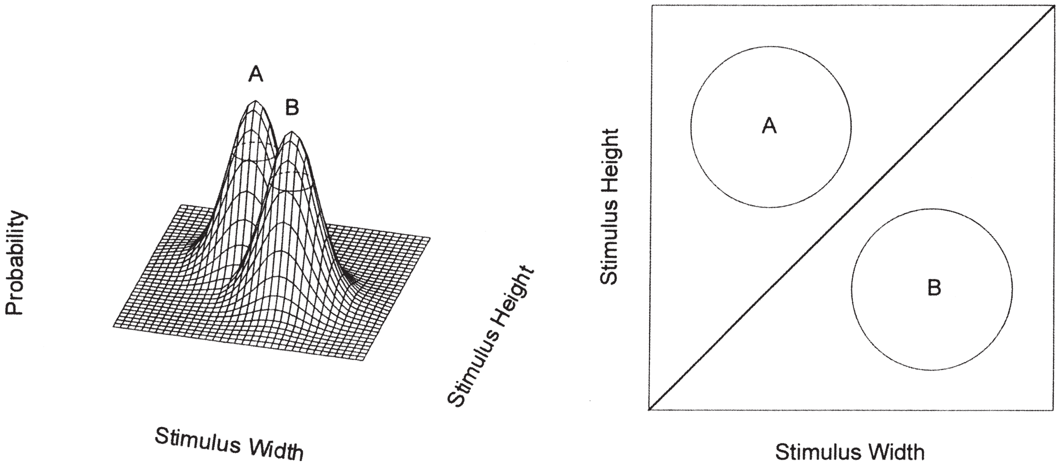

Figure 20.1. *Left*, Bivariate approximately-normal distributions represent likelihoods with which rectangles are sampled from either of two ill-defined (overlapping) categories: A and B. A rectangle is represented in the stimulus space as a point with coordinates equal to the corresponding width and height. A pigeon successively categorizes individual rectangles and is reinforced if a choice corresponds to the category, either A (left key) or B (right key), from which a rectangle was sampled. One arbitrary contour of equal likelihood is shown for each category. Each contour consists of all points corresponding to rectangles equally likely to be sampled from a category. *Right*, Arbitrary contours of equal likelihood for each category and the corresponding linear optimal decision bound, $x = y$, according to which a rectangle should be categorized as an A or as a B, depending on whether the rectangle is taller than wide or wider than tall, respectively. (From "The Randomization Procedure in the Study of Categorization of Multi-Dimensional Stimuli by Pigeons," by W. T. Herbranson, T. Fremouw, and C. P. Shimp, 1991, *Journal of* Q4 *Experimental Psychology: Animal Behavior Processes, 25,* 113–135. Copyright 1999 by the American Psychological Association. Reprinted with permission.)

cognitive and neurobiological mechanisms of categorization (Ashby & Ell, 2001; Ashby & Gott, 1988; Ashby & Maddox, 1998). The task more closely resembles the problems that organisms face in naturalistic settings than do many other categorization tasks, in the sense that it permits a category to have many exemplars and it permits exemplars to be ambiguous as to category membership (Herbranson, Fremouw, & Shimp, 1999, 2002). We have conducted several experiments using this procedure, two of which we review here. One involves static exemplars in the form of rectangles and another involves dynamic exemplars in the form of a moving object.

The general task requires participants to categorize stimuli that vary along two dimensions. For example, a specific task could require a participant to categorize rectangles varying in height and width or color patches varying in hue and brightness, and so on. All possible stimuli can be represented as points on a two-dimensional plane. A *category* is defined in terms of the corresponding sampling distribution that gives the likelihoods of all possible stimuli in that category.

Static Exemplars Figure 20.1 is a graphic representation of such a categorization task. Each of the two bell-shaped curves represents a category. A point on the surface of the mesh plot for a category shows the likelihood that a stimulus with a specific height and width will be sampled from that category. Note that both surfaces are approximately bivariate normal and that the likelihood of a stimulus from either category never quite reaches zero. Therefore, any possible stimulus in principle can be sampled from either category; that is, every stimulus has some degree of ambiguity as to its category membership. However, most stimuli are more likely to be sampled from one category than from the other. The exceptions are those stimuli that fall exactly on the line where the two categories intersect, as illustrated in figure 20.1. The diagonal line represents all stimuli that are equally likely to have been sampled from either category. This line also represents the optimal decision boundary. A participant who categorizes stimuli falling on one side as belonging to category A and stimuli falling on the other side as belonging to the category B will maximize the average number of correct responses.

Herbranson et al. (1999) arranged a task in which pigeons successively viewed on discrete trials a large number of different rectangles, one rectangle per trial. The reader is encouraged to consult the interactive, real-time, Web-based demonstration of this procedure that is available at Malloy et al. (2001). The pigeon's task was to categorize each rectangle: If the pigeon believed a rectangle was an exemplar of one category, then it was to peck the left key, whereas if the pigeon believed a rectangle was an exemplar of the second category, then it was to peck the right key. If the pigeon categorized a rectangle as an exemplar of the category from which it was sampled, then the pigeon received a small amount of grain; if the pigeon made an error, then it had to make a correction response to the correct key before the next trial could begin. The base rates of the two categories were equal; on average, the pigeon was reinforced equally often on the left and right.

We arranged tasks with two kinds of optimal decision bounds: linear and nonlinear. Among the tasks with linear optimal decision bounds, some required selective attention, whereas others required divided attention. That is, optimal categorization required the bird to attend either to both or to just one of the dimensions of a rectangle, respectively. (The actual psychological dimensions of a rectangle remain to be completely determined, and might be, for example, size and shape; however, for the present purposes it is adequate to write as though they are length and width.) In the selective attention conditions, only one element of a rectangle, either its length or its width, provided information about the category to which it belonged, whereas the other element continued to vary over trials without being diagnostic of the category from which the rectangle was sampled. In these linear conditions, optimal categorization was described by a linear decision rule in the two-dimensional stimulus space (for details, see Herbranson et al., 1999). Pigeons on the whole categorized stimuli more or less in accordance with this linear optimal decision rule. It is as though pigeons learned a simple abstract rule, such as, in one divided attention condition, "go left if width is greater than height, otherwise go right." In this linear task, the diagnosticity of a rectangle was an additive combination of the diagnosticities of the individual elements: length and width.

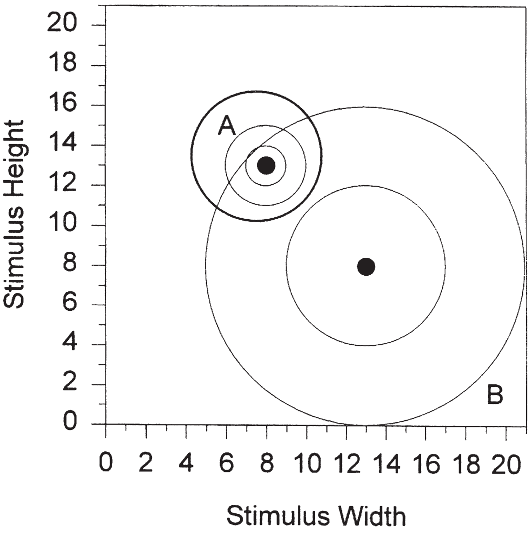

Figure 20.2. A task in which the optimal bound is nonlinear. An optimal response consisted of categorizing a rectangle as belonging to category A or B if its corresponding point in the stimulus space was or was not in the circular region indicated by the *bold circle*, respectively. Two contours of equal likelihood are shown for each category: A and B. For each category, the smaller and larger contours are 1 and 2 *SD*s from the mean (*filled circle*) of the corresponding normal bivariate distribution, respectively. The bold circular line represents the optimal decision bound. (From "The Randomization Procedure in the Study of Categorization of Multi-Dimensional Stimuli by Pigeons," by W. T. Herbranson, T. Fremouw, and C. P. Shimp, 1991, *Journal of Experimental Psychology: Animal Behavior Processes, 25,* 113–135. Copyright 1999 by the American Psychological Association. Reprinted with permission.)

In the nonlinear task, optimal categorization could not be accomplished in terms of a rule according to which the separate diagnosticities of length and width combined additively: Figure 20.2 shows that in this task, the diagnosticities of the elements combined nonlinearly and that optimal decision rule was nonlinear, specifically, circular.

Pigeons nevertheless continued to do a respectable job in approximating the optimal solution. This outcome shows that, in at least this case, pigeons can combine the statistical diagnosticities of different elements of multidimensional stimuli in nonlinear ways, as presumably they must if they are to deal nearly optimally with many real-world categories that involve nonlinear combinations of their elements (Ashby & Maddox, 1998).

In summary, pigeons categorized rectangles in ways that were consistent with their having learned abstract decision rules when elements of complex stimuli combined either linearly or nonlinearly, depending on what a task required them to do. In passing, we note that pigeons therefore can categorize exemplars using either a strategy according to which a multidimensional stimulus is, in the linear case, an additive combination of its elements, corresponding to the case where "the whole is the sum of its parts" or, in the nonlinear case, a strategy according to which "the whole is different from the sum of its parts." The results are therefore compatible with the possibility that a pigeon can categorize complex stimuli either as a simple averaging machine, if that is the more adaptive behavior, or as a Gestalt processor, taking account of interactions among the elements of complex stimuli, if that is the more adaptive behavior. Pigeons also displayed considerable flexibility of attention, in that they could either selectively attend to an individual element of a complex stimulus or divide attention between elements, depending on which was adaptive given the task. Finally, in all cases, there was at least a crude approximation between categorization performance and the optimal decision rule.

Dynamic Exemplars The task described earlier can be used not only with rectangles but with nearly any kind of two-dimensional stimuli. A dimension of the natural world that is missing from stimuli in nearly all research on categorization, including research on what has come to be called "naturalistic visual concepts" (Herrnstein & Loveland, 1964) is time. Thus, to make our stimuli in this sense more naturalistically valid, we conducted an experiment in which the two dimensions were speed and direction of a moving object; the pigeon's task was to categorize the moving object into one or another category based not on the visual features of a static object, but on its dynamic features (Herbranson et al., 2002). We hasten to acknowledge that we do not believe that our stimuli were truly "naturalistic," even with the added dimension of time; the object that moved, for example, was merely a white circle, which had no particular ecological significance. We again encourage the reader to consult the interactive demonstration of this task for details (Malloy et al., 2001).

On each trial, a white circle appeared on a computer monitor in front of the pigeon, and after the circle moved for a brief period of time at a fixed speed in a fixed direction, the pigeon was asked to categorize the movement. If the stimulus (a speed/direction pair) had been sampled from one bivariate distribution, then a peck to one side location was reinforced; if it had been sampled from the second distribution, then a peck to the other side location was reinforced. As in the case of static stimuli described above, the two distributions overlapped, so that any stimulus could diagnose either category, but most stimuli were more likely to be sampled from one category than from the other, so that optimal performance was above the chance level of 50% correct but below 100% correct. As in the experiment with static stimuli, the task was changed over conditions so that in some conditions optimal performance could be achieved only if the pigeon divided attention between dimensions and integrated the information from each in a suitable manner. In other conditions, optimal performance required the pigeon to selectively attend to only speed or direction and to ignore the other, irrelevant dimension.

Results were similar to those when pigeons categorized static rectangles. Figure 20.3 summarizes how well the slopes and y-intercepts of the decision rules estimated from the birds' performances corresponded to the respective values in the linear optimal decision rule (for details of parameter estimation, see Herbranson et al., 2002). As can be seen, the correspondence was very close: In this sense, pigeons very closely approximated optimal performance. Thus, pigeons categorized moving objects as though they had learned an abstract rule approximating the optimal decision rule. Because the optimal decision rules varied across conditions in terms of whether attention was required to be allocated to either dimension alone or to both together, we can conclude that pigeons can display considerable flexibility in their attentional strategies; we may speculate that, to a considerable degree, pigeons use attention in ways that depend on

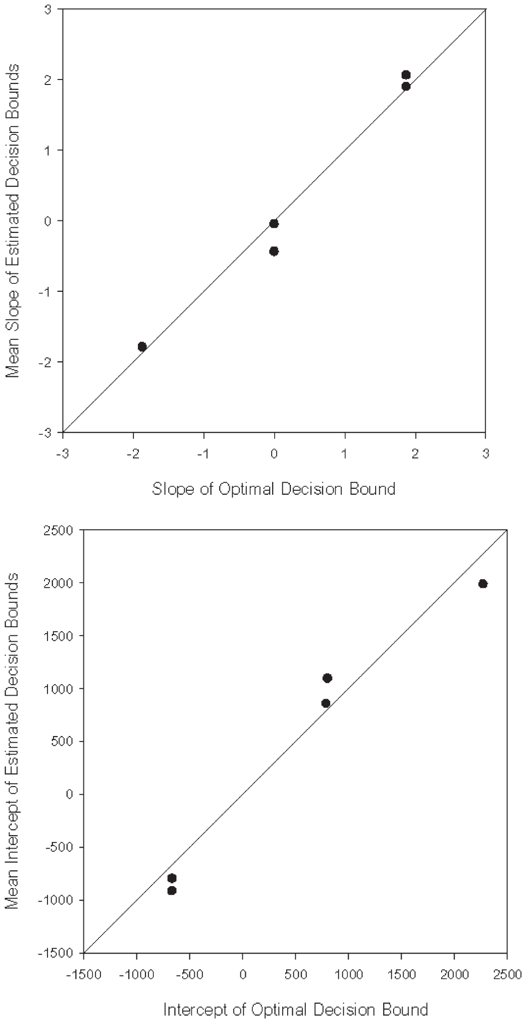

Figure 20.3. The average of the slopes of the individually estimated decision rules as a function of the optimal slope (*left*), and the average of the y intercepts of the individually estimated decision rules as a function of the optimal y intercept (*right*). (From "Categorizing a Moving Target in Terms of its Speed and Direction," by W. T. Herbranson, T. Fremouw, & C. P. Shimp, 2002, *Journal of the Experimental Analysis of Behavior (Special Issue on Categorization), 78,* 249–270. Copyright 2002 by the Society for the Experimental Analysis of Behavior. Reprint with permission.)

what in any particular task is optimal—that is, on what produces higher reinforcement payoffs. This cognitive flexibility was displayed in the face of the statistical ambiguity produced by the overlap between the sampling distributions corresponding to the two categories.

Flexibility in the Use of Attention in the Local/Global Task

When we perceive the visual world, we can pay greater attention to either the forest or the trees. Stated in terms of contemporary cognitive vocabulary, recent history may momentarily prime us to be more inclined to pay attention to either local or global levels of perceptual analysis; what we have come to expect to see can facilitate our seeing a target at that expected level (Lamb & Robertson, 1988; Navon, 1977). The idea of mental continuity, combined with the Gestalt principle of figure-ground reversals, motivated us to determine if pigeons, like humans, could evidence shifts of attention between local and global levels of analysis. In order to do so, we presented pigeons with complex stimuli entailing both a global and a local level (Navon, 1977, 1981); we "primed" either the local or global level, and we rewarded the pigeons for responding to specific targets that could occur at either level. The reader is encouraged to consult an interactive, real-time, Web-based demonstration of this procedure (available at http://www.pigeon.psy.tufts.edu/avc/shimp/).

On each trial, pigeons were shown a compound stimulus composed of a large character created from a number of smaller characters (figure 20.4A). Each stimulus contained a target character at either the global or local level and a distractor character at the other level. The task required the pigeon to indicate which target character was present by pecking a key to the left or to the right. For example, target letters H and S, regardless of the level at which they occurred, required a response to the left or right, respectively. A global target letter H, requiring a response to the left key, could be formed of local letters T or E; a global letter S, requiring a response to the right key, could also be formed of local letters T or E. A local target letter H, requiring a left response, could form either a global T or E; a local target letter S, requiring a right response, could similarly form either a global T or E. Thus, the complex stimuli were hierarchically organized; the pigeon had to search for a target that could be present at either the local or global level.

We used two different methods to train the pigeon to expect a target at a particular level, that is, *A: Example of Primes and Stimuli*

Global Targets with Left Key Correct

Global Targets with Right Key Correct

Local Targets with Left Key Correct

Local Targets with Right Key Correct

B: Example of Stimuli with Novel Distractors

Global Targets with Novel Local Distractor
(Local T Changed to X)

Local Targets with Novel Global Distractors
(Global T Changed to a Random Pattern)

Figure 20.4. *A,* One set of stimuli used in Fremouw et al. (1998, 2002). Each hierarchical stimulus had a target stimulus (in this set either an H or an S) at either the local or global level, and an irrelevant distractor stimulus (in this set either a T or an E) at the other level. When the base-rate procedure was used to prime a level, the four stars at the corner of each stimulus did not appear: they were used only in the trial-by-trial priming cue procedure, where they served as the priming cue. The stars were presented about 1 s prior to the presentation of a hierarchical stimulus, and the first peck to the stars after 1 s elapsed presented the local/global stimulus. The local characters were white and the stars either red or green on a black/gray background. *B,* An example of stimuli with novel distractors used in Fremouw et al. (1998). In the two examples on the left, the original local distractor T has been replaced with the novel local distractor X. In the two examples on the right, the original global distractor T has been replaced with a novel random pattern global distractor.

to prime a level: a base-rate procedure and a trial-by-trial cuing procedure. In the base-rate procedure, we presented successive blocks of trials, within each of which, most targets occurred at one level: the primed level. Within a given block, targets at the primed level occurred a random 85% of the time, whereas targets at the nonprimed level occurred the other 15% of the time (Fremouw, Herbranson, & Shimp, 1998). We alternated blocks of trials with either global or local levels primed. In the trial-by-trial cuing procedure, on each trial, we presented a brief priming cue prior to the presentation of the hierarchical stimulus. The priming cue consisted of four stars, either all green or all red, that formed the corners of a box slightly larger that the stimuli (figure 20.4A). The color of the stars predicted, with 85% accuracy, the level at which the target would occur. Targets occurred at the global level a random 85% of the time and at the local level the other 15% of the time if the stars were red, and vice versa if the stars were green. Local and global targets occurred with equal probabilities (Fremouw, Herbranson, & Shimp, 2002).

We asked if a pigeon saw a target at the primed level faster than at the nonprimed level. We therefore calculated the median response time to local and global targets when the targets occurred at the primed level and at the nonprimed level. Figure 20.5 summarizes the response time data from the two experiments; clearly, priming occurred with both the blocking method and the trial-by-trial cuing method. These results suggest that pigeons can flexibly switch attention between local and global levels of analysis.

We evaluated an alternative interpretation that each stimulus had some specific feature that could be used to distinguish it from the other stimuli that was independent of the local or global perceptual level. That is, perhaps birds can use some feature independent of local and global perceptual levels. To determine if this were so, we conducted transfer tests in which the original targets remained the same, but the original distractors were replaced. For example, the stimulus with a global target H composed of the local distractor T was changed so that it was composed of the local distractor X and the stimulus with a global distractor T composed of local target H was changed so that the global distractor was a random pattern composed of the local target H (figure 20.4B). If birds used some specific feature across perceptual levels, then a change to one of those levels should significantly reduce performance. There were no significant differences in median response time or percent correct responding between the original stimuli and the transfer stimuli, suggesting that the pigeons did not rely on a specific feature or set of features common to both perceptual levels (Fremouw et al., 1998). It appears that pigeons are indeed able to shift attention between local and global levels of perceptual analysis.

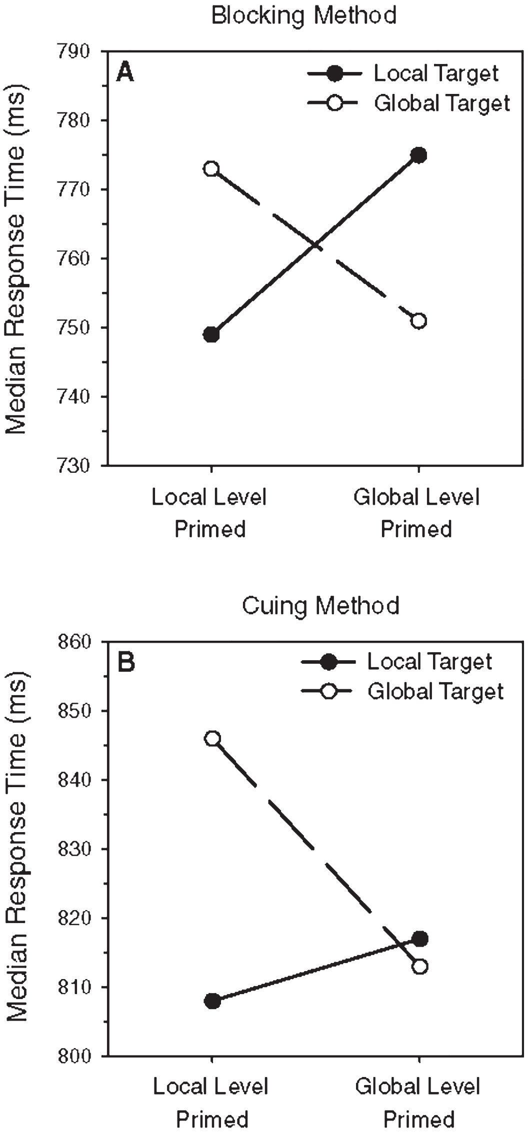

Figure 20.5. *A*, The overall mean median response time to global and local targets as a function of primed level when the blocking procedure was used to prime a level (Fremouw et al., 1998). Response time was significantly faster to local targets than to global targets during the blocks of trials in which targets appeared more frequently at the local level (local level primed). Response time was also significantly faster to global targets than to local targets when the global level was primed. In addition, response time to local targets was faster when the local level was primed than when the global level was primed, and response time to global targets was faster when the global level was primed than when the local level was primed (all *p*s < .05). *B*, The overall mean median response time to global and local targets as a function of primed level when the trial by trial priming cue procedure was used to prime a level (Fremouw et al., 2002). Response time was faster to global targets when the global level was primed than when the local level was primed. Response time was also faster to local targets than to global targets when the local level was primed (all *p*s < .05).

Both methods demonstrate shifts of attention between local and global levels of perceptual analysis in pigeons, but they do so over very different time frames. In the case of base-rate blocking, attention may build up slowly as the base rates are learned; once attention to a particular level has increased, it may simply remain "active" at that level until the base rate changes. That is, if the preponderance of targets is at the global level, then attention to the global level may slowly increase over the course of minutes or hours and then simply remain at the global level as long as the base rate remains the same. In the case of trial-by-trial cuing, the dynamics of attention must be much faster. The level at which the next target is likely to occur is not known until approximately 1 s before it occurs. Thus, attention must be dynamically readjusting on the scale of a second rather than on the scale of minutes or longer. That is not to say that attention cannot also operate on a similarly brief time scale in the base-rate blocking experiment; it simply does not have to do so.

The mechanisms responsible for local/global shifts of attention in humans and nonhuman animals are not yet fully understood and may depend on the specifics of the priming task. For example, Plaisted (1997) suggested that attention in experiments using the blocking procedure may depend on the fact that targets with higher base rates occur more frequently and thus may have more highly activated residual memories. The higher the activated state of the residual memory, the quicker it is that a target could activate the system to some threshold level that activates a response. It is unclear how such a purely time-based, decay-of-target-memory process could account for the attention switching that occurred in our cuing task. In that task, the base rates were the same for both local and global targets. A different kind of memory model might therefore be required to account for the attention switching in the cuing task.

For example, seeing the red stars might activate a memory of the red stars and that memory might be associated with the memories of the four stimuli that have targets at the global level. Activating the memory for red stars might therefore activate those associated global memories, and the higher level of activation for those four global memories might facilitate faster processing of a subsequent stimulus with a target at the global level. In addition, there are other models proposed in the contemporary human literature, including spatial frequency modulation (Lamb, Yund, & Pond, 1999; Shulman & Wilson, 1987) and activation of level-specific neural mechanisms (Lamb, London, Pond, & Whitt, 1998). We expect that the mechanisms underlying local/global attention will be found to involve the dynamic interaction of several processes, including basic memory processes, occurring along the full visual processing stream from the retina to associative cortex.

Recent neurophysiological findings from bats offer some intriguing possibilities for how feedback between cortex and lower sensory nuclei might play a role in attention phenomena on both slower time scales, such as in the blocking task, and on faster time scales, such as in the cuing task. Suga and his colleagues (Ma & Suga, 2003; Suga, Gao, Zhang, Ma, & Olsen, 2000; Yan & Suga, 1996; Zhang & Suga, 1997) showed that repetitive stimulation of auditory cortex can refine and strengthen neuronal firing in the inferior colliculus, a nucleus that is located earlier in the auditory processing stream than the auditory cortex. For example, stimulating an area of the cortex that responds best to a particular frequency range or to a particular delay between sounds seems to strengthen the response of neurons in the inferior colliculus that also respond to that particular frequency range or delay. Inactivating the cortex had the opposite effect: the response in the inferior colliculus was weakened. This neuronal modulation developed over time, from 2 to 30 min, and lasted from minutes to hours. Casseday, Fremouw, and Covey (2002) speculated that this process might help to select, enhance, and maintain processing of specific auditory features over the period of an evening's hunt in the case of a bat.

We wonder if a similar mechanism, perhaps working on spatial frequency, might play a role in local/global attention seen in the base-rate blocking experiments where the dynamics of attention may be relatively slow. Perhaps the high base rate of a particular target level leads to repetitive and prolonged activity of neurons tuned to the appropriate spatial frequency for the corresponding perceptual level. Perhaps once a target level is perceived on a trial, the neurons involved in encoding that level remain active longer and at a higher level than the neurons that encode the nontarget level. Such increased activity might then strengthen and fine-tune the response of neurons to that level in both visual cortex and earlier structures. This enhancement in neuronal response might in turn produce a faster or more accurate perception of subsequent targets at that perceptual level.

Activity in auditory cortex can also enhance specific auditory features in the inferior colliculus on a much faster, stimulus-by-stimulus time frame (Jen, Chen, & Sun, 1998; Zhou & Jen, 2000). Perhaps a similarly fast-acting mechanism plays a role in the visual system and at least partially mediates the local/global attention shifts seen in the priming cue task. We describe these highly speculative possibilities to illustrate how research on animal cognition and research on neurophysiology might mutually inform each other.

In summary, we showed that pigeons display flexibility in switching attention between local and global levels of perceptual analysis much as in the case of humans attending either to the forest or the trees. Thus, pigeons can flexibly display a kind of figure-ground reversal that forms part of the core metatheoretical perspective of Gestalt psychology.

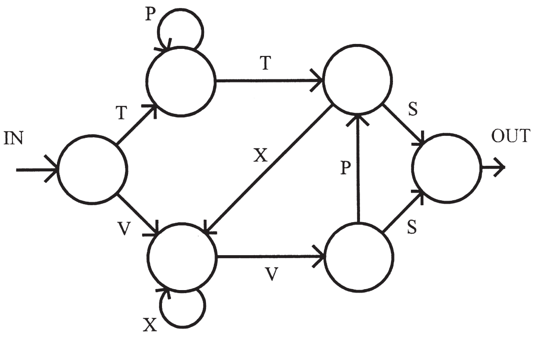

Figure 20.6. The artificial grammar that generated grammatical character strings of lengths 3 to 8. (Adapted from Chomsky and Miller [1958] and Reber [1967]. From: Artificial Grammar Learning in Pigeons: A Preliminary Analysis, by W. T. Herbranson and C. P. Shimp, 2003, *Learning & Behavior, 31,* 98–106. Copyright 2003 by the Psychonomic Society. Reprinted with permission.) Q5

Rule Learning and Memorization Strategies in Artificial Grammar Learning

Thus far, we have seen that pigeons can successfully attend either to one dimension or to both dimensions when they categorize two-dimensional rectangles, that they can attend to either or both of speed and direction of a moving object when they categorize the object in terms of its movement, and that they can be primed to see targets more quickly at one level of perceptual analysis than at another. In plain English, one might say in all these cases that pigeons used their attentional capacity in flexible ways. We next describe a very different task, in which the cognitive flexibility of pigeons is demonstrated in terms of the different memory strategies they use for different kinds of to-be-remembered material.

The idea of an "artificial grammar[1]" (Reber, 1967, 1989) has facilitated our understanding of the differences among various kinds of human memory systems. An artificial grammar is a set of rules for generating strings of characters. An example of one such grammar is depicted in figure 20.5. A character string is generated by entering the grammar at the left, with each transition from one state to another adding a character to the string, until exiting via the "out" arrow at the right. In this manner, each unique path through the grammar produces a different character string. Grammars containing loops like the one pictured here can generate an infinite number of character strings. Limiting the length of character strings naturally decreases this number, but it still results in many unique strings. The simple grammar depicted here, for instance, can generate 43 character strings between 3 and 8 characters in length.

In a prototypical artificial grammar experiment (e.g., Reber, 1967), undergraduates are shown grammatical character strings generated by a set of rules such as in figure 20.6 and are asked to memorize the strings. Later, they are presented with novel strings, told the earlier strings were generated by a grammar (but are not told the grammar), and asked whether the novel strings conform to the grammar. Despite the participants' inability to accurately describe the rules of the grammar, performance at diagnosing grammaticality is reliably above chance. This result is reminiscent not only of the performance of young children, who recognize grammatical sentences when they hear them without being able to describe grammatical rules, but also of the performance of both humans and pigeons on naturalistic categorization tasks. Naturalistic visual categories, such as "tree," are quickly learned, in the sense that a participant rapidly learns to discriminate visual scenes with or without a tree, even though the basis for the discrimination in the form of a simple rule-based criterion is unclear. From the perspective of the participants, artificial grammars have the virtue of preserving this "family resemblance" characteristic of naturalistic categories, where the basis for the discrimination seems complex and ambiguous. At the same time, from the perspective of the experimenter, artificial grammars have the virtue of simplicity: Unlike the case with naturalistic categories like "tree," the experimenter actually knows the rules, the true structure, of the category.

Recently, we showed that nonhuman animals, specifically pigeons, can learn an artificial grammar. We suspect that artificial grammar learning may be a nonlinguistic precursor of human language and, as such, deserves a comparative analysis (see Fitch & Hauser, 2004, and Seidenberg, MacDonald, & Saffran, 2002, for related discussion). We examined this possibility by attempting to train birds to discriminate between grammatical and nongrammatical character strings (Herbranson & Shimp, 2003). Birds were rewarded for pecking one key when a character string was displayed that conformed to the rules of the grammar in figure 20.6. They were rewarded for pecking a different key when the displayed character string violated the grammar. After extensive training (average of 179 days), birds reached a stable level of above chance performance (62.3% correct) on the training set of 62 character strings (31 grammatical and 31 nongrammatical), suggesting that they had learned something about the grammar.

In order to rule out the possibility that pigeons were simply memorizing specific training exemplars, at least some of which presumably seemed familiar to the pigeons by the end of training, we subsequently presented novel probe strings (12 novel grammatical and 12 novel nongrammatical strings) that the pigeons had not encountered during training. Performance on these novel strings was also reliably above chance (60.7%), supporting the notion that pigeons had acquired a flexible conception of the grammar that went beyond the specific stimuli presented during training. In addition to learning something abstract about the grammar, the pigeons also appeared to memorize some of the shorter strings. Thus, pigeons flexibly adopted different memorization strategies for different aspects of the same task.

Finally, we found that pigeons more accurately categorized grammatical than nongrammatical character strings. Although we initially found this difference to be puzzling, we now believe that this result nicely fits with the idea that artificial grammar learning is a form of learning abstract categories. Consider that grammatical strings shared a stronger family resemblance with each other than did nongrammatical strings with each other. Nongrammatical strings were random distortions of grammatical strings, and therefore necessarily violated the family resemblance shared by grammatical strings. We speculate this increased within-category variability might make the category of nongrammatical strings more difficult to learn.

In summary, pigeons learning an artificial grammar displayed cognitive flexibility in at least two ways familiar in human cognition, but less so in nonhuman animals. First, pigeons satisfied the traditional criterion for learning abstract concepts: they learned the training set of stimuli and generalized to novel stimuli. Although we do not know if the abstractions the pigeons learned corresponded exactly to the abstract rules of the grammar, the fact that learning generalized to new exemplars is part of the traditional definition of what it means to learn something abstract (although it has been shown that exemplar theory can generate what appears to be the learning of an abstract prototype, as in Medin & Schaffer, 1978). Second, pigeons demonstrated flexible memorization strategies, because it seems as though they used abstract concepts to categorize complex, more difficult-to-remember strings and simply memorized strings in some cases involving simple, easier-to-remember strings.

COMMENTS ON INTERRELATIONS WITH OTHER RESEARCH ON CATEGORIZATION

The following comments suggest how our research on avian visual categorization interrelates with the larger literature on animal and human cognition (also see Cook, 2001).

Rule Learning

The ability to learn abstract rules was formerly seen as a distinctly human ability, but two advances cast doubt on that simplistic view. First, philosophical and theoretical advances on the basic nature of an abstraction have clarified what it means to claim an organism has learned a rule (Ashby & Maddox, 1998; Ryle, 1949; Wittgenstein, 1953). Second, we have shown, at least by conventional standards, if not by entirely satisfactory theoretical standards, that pigeons behave as if they learn abstract rules both in the two-dimensional categorization task and in the artificial grammar learning task (see also Cook & Wasserman, chapter 16, Huber & Aust, chapter 17, and Jitsumori, chapter 18, this volume). We believe that further advances will depend greatly on whether corresponding theory is developed by which the various demonstrations of cognitive flexibility in nonhuman animals can be interpreted. We suggest that empirical progress will depend on theoretical and conceptual advances in our understanding of the rules that nonhuman animals can learn, on how these rules can be explained by evolutionary considerations, and on what it means to find the underlying neurobiological mechanisms.

Ambiguity and Gestalt Reversible Images

Ambiguity is rarely claimed to be a virtue of scientific theory. Ambiguity may look different, however, from the perspective of naturalistic categorization, from the perspective of family resemblance, and from the perspective of Gestalt psychology. We believe that ambiguity plays a necessary role in everyday categorization and, correspondingly, in empirical research and scientific theories of categorization. Ambiguity is not something that always needs to be replaced by logical clarity, given that one of our goals is to understand the messy complexity of everyday categorization. We note in passing that research on decision making in the face of uncertainty has recognized as much for many years.

Memorization Strategies

We believe that the ability of pigeons to switch memorization strategies merits further empirical investigation because it bears on the common, but we suspect incorrect assumption that few nonhuman animals can switch memorization strategies on a moment-to-moment basis, as a function of what is momentarily adaptive (Herbranson & Shimp, 2003; Wright, 2001; Wright, chapter 9, this volume).

Flexible Allocation of Attention

We believe that future progress in comparative cognition will hinge on the development of theories that can integrate demonstrations that pigeons can either selectively attend to individual elements or divide attention among them (e.g., Herbranson et al., 1999, 2002), can be primed either to see the forest or the trees in the local/global task, and can be primed in a multitude of other ways in visual search (Blough, 1991; Blough, chapter 5, this volume; Tinbergen, 1960). We tend to think that plain English is too often assigned the job of integrating these various phenomena; this job instead should be the task of well-articulated scientific theory.

Optimality

The question of whether humans and animals behave in optimal ways is so great in scope that a general treatment is far beyond the limits of this chapter (Gould & Lewontin, 1979; Kahneman, Slovic, & Tversky, 1982). We would like only to note that pigeons display a remarkable ability to behave not only in ways that appear rational but also in ways that are quantitatively close to optimal.

PERSPECTIVES ON CATEGORIZATION FROM WITTGENSTEIN'S TWO PHILOSOPHIES

Research on categorization, in general, and on rule learning and cognitive flexibility, in particular, raises difficult interpretative and evaluative issues because, by interrelating human and nonhuman animal cognition, it indirectly addresses the fundamental question of the nature of the human condition. Such a difficult question has many different kinds of answers; those who see the answer one way may disagree quite profoundly with those who see it some other way. Correspondingly, the same categorization literature may look either good or bad depending on the evaluative standards one adopts.

We believe that some of the important evaluative differences gain perspective when viewed in the light of Wittgenstein's two philosophies, both of which address some of the deepest issues in the nature of the human condition. Each of his philosophies carries with it its own evaluative standards. For our limited present purposes, there is no need to provide comprehensive descriptions, explanations, or criticisms of either of these philosophies. The following brief summary of those parts of the philosophies that are relevant to the present chapter is adapted from Shimp (2004a), which should be consulted for a somewhat more detailed treatment.

Relevant Features of the Tractatus Logico-Philosophicus (1922)

Wittgenstein's (1922) picture theory addressed the relation between language and reality; it assumed that a factual proposition in some sense has the same logical structure as the corresponding natural phenomenon. An examination of the visual appearance of the *Tractatus* reveals symbolically expressed logical propositions and truth tables but no pictures: the picture in the picture theory was abstract and static. (As an aside, we speculate that the development of the technology of motion pictures hastened the abandonment of this age-old tendency to think of mental representations in terms of static images.) In a manner not explained, a static factual proposition was supposed to capture what unfolds dynamically over time in actual behavior. Complex propositions were assumed to be built up from independent "atomic facts." The *Tractatus* assumes that logical clarity, logical rigor, unambiguity, and parsimony are vital virtues.

Relevant Features of the Philosophical Investigations *(1953)*

Wittgenstein is reputed to have rejected his first philosophy after having served briefly as an elementary school teacher, when he decided that his philosophy was of little practical use in dealing with how people really behave. He subsequently developed a system that was designed to show how to avoid making the kinds of conceptual and linguistic mistakes that led to the problems *Tractatus* was designed to solve.

Wittgenstein's *Philosophical Investigations* (1953) does not rely on logical rigor and abstract propositions; instead, it relies on careful analysis of how everyday language is used. An examination of the visual appearance of *Philosophical Investigations* reveals numerous drawings to illustrate Gestalt principles of visual perception, especially in the form of reversible images, figure/ground reversals (e.g., the duck/rabbit illustration), and the ambiguity inherent in the idea of family resemblance. It emphasizes how the same visual image can be an exemplar of either one or another category, as in the duck/rabbit illustration, and it examines in close detail actual, everyday, ordinary language use. It emphasizes how the meaning of elements depends on context: how the meaning of words in a sentence depends on grammatical context or how the meaning of a sentence depends on its larger context. Finally, through appeal to the Gestalt tradition, there is a sense of psychological dynamism in *Philosophical Investigations* that is lacking in *Tractatus*. Just as Gestalt psychology acknowledged a more dynamic approach to perceiving, remembering, and problem solving than did the more static and mechanical aspects of associative theories of learning and memory deriving from British empiricism, *Philosophical Investigations* acknowledged, or even welcomed, a more dynamic approach to perceiving, remembering, and problem solving than did *Tractatus*.

Wittgensteinian Evaluative Perspectives on Avian Visual Categorization

Wittgenstein's two philosophies offer different perspectives on what constitutes meaningful analyses of cognition, in general, and of categorization, in particular. These perspectives can even be seen as categories themselves; that is, we may try to categorize research on categorization into the two alternatives that Wittgenstein provided. When we look at the two alternatives in this way, we immediately see that they conform rather well to the idea of family resemblance in *Philosophical Investigations*, in the sense that exemplars of empirical research on categorization have no defining features that unambiguously assign them to one category or the other. It is still useful, we believe, to list ways in which the research that we have described fits one or the other of the perspectives, even if none of the research perfectly fits either.

First, *Tractatus* assumes that an understanding of complex cognition involves the use of simple logical rules and propositions. We made a similar assumption in three of our demonstrations of avian categorization, in our use of decision rules to interpret the results of both of our experiments on categorization of multidimensional stimuli (Herbranson et al., 1999, 2002), and in our use of abstract rules to interpret the results of our experiment on artificial grammar learning (Herbranson & Shimp, 2003). We believe that the contrasting perspectives of *Tractatus* and of *Philosophical Investigations* are illuminating in this case, because it was largely the "cognitive revolution" (Gardner, 1985; Shimp, 1989) that permitted rigorous experimental psychologists to feel comfortable attributing abstract rules, including grammatical rules, to humans. From the perspective of the cognitive revolution, rule learning looks modern; however, from the perspective of Wittgenstein's two philosophies, rule learning looks conceptually obsolete, because it was part of *Tractatus*, not *Philosophical Investigations*, from which perspective logical, abstract rules actually look old because they reflect a less-naturalistic, less-detailed, less-dynamic, more-idealized kind of mental representation.

Second, if we consider how *Philosophical Investigations* acknowledges some descriptive value in ambiguity and looks favorably on the dynamics of Gestalt reversible images, whereas *Tractatus* does not, then we get a different perspective on the statistical ambiguity in the multidimensional categorization task (Herbranson et al., 1999, 2002) and on the rapid, dynamic priming in the local/global task (Fremouw et al., 2002). In these ways, our research appears more constructive when viewed from *Philosophical Investigations* than from *Tractatus*.

Third, the two different memorization strategies that we hypothesized pigeons use to learn artificial grammars—the acquisition of abstract rules and the memorization of specific character strings—seem to us to reflect *Tractatus* and *Philosophical Investigations*, respectively. If one viewed it as a virtue to adopt a consistent position and to adhere to either *Tractatus* or *Philosophical Investigations*, but not both, then our attribution to pigeons of this kind of dual memorization strategy would seem inconsistent and undesirable. This dual strategy may also be viewed in terms of the distinction between explicit memory involving abstract rules and implicit memory involving memory for specific procedures or behaviors (Reber, 1967, 1989). Memory for the logical rules that form part of the definition of explicit memory seems more compatible with *Tractatus,* whereas memory for specific, detailed behaviors that form part of the definition of implicit memory seems more compatible with *Philosophical Investigations*. If we apply this distinction to our experiment on artificial grammar learning, we see that pigeons seem to have used two systems: a system for learning and remembering abstract, general, logical, clear, and unambiguous explicit grammatical rules, in a manner compatible with *Tractatus*, and a system for learning and remembering specific strings of characters, outside the context of a system of logical rules, in a manner more compatible with *Philosophical Investigations*.

Fourth, it is a prominent feature of *Philosophical Investigations*, but not of *Tractatus*, to address the flexibility of attention. Much of our work is therefore more consistent in this sense with *Philosophical Investigations* than with *Tractatus*, because we have interpreted much of our data in terms of attentional flexibility, a pigeon using either selective or divided attention (Herbranson et al., 1999, 2002) and using either local or global levels of perceptual analysis, whichever is primed. One might expect a researcher committed to *Philosophical Investigations* to strongly endorse this aspect of our work but a researcher committed to *Tractatus* to be much less favorably inclined toward it.

Fifth, the issue of optimality seems more closely to resemble *Tractatus* than *Philosophical Investigations* to the extent to which optimal behavior is viewed as related to the issue of whether behavior is efficient and parsimonious and displays logical, rule-driven solutions to environmental problems.

In summary, we believe that our work is characteristic, in important ways, of much contemporary research on categorization, and on cognition in general; contemporary research often displays a sort of methodological and theoretical incoherence if it is viewed from the perspectives of two of the most influential philosophies of the previous 100 years. If one wanted to adopt a consistent position, as Wittgenstein certainly did, then much contemporary research fails to meet his standard, because research methodology tends to be an uncomfortable hodgepodge of both positions. It has been our experience (Shimp, 2004a, 2004b) that some researchers are more comfortable with one of Wittgenstein's philosophies than with the other. As a result, it is likely that judgments of the scientific merit of a research program, as in peer review of publications and grants, are influenced by the extent to which a research program conforms to a preferred philosophical position (Shimp, 2004a, 2004b).

QUESTIONS FOR THE FUTURE

What are the important questions about categorization that need answering? Our review of Wittgenstein's two philosophies suggests that the answer to this question depends on what one thinks it means to categorize something. This, in turn, depends on how one prioritizes the important jobs for a philosophy of mind, language, and behavior.

If one were committed to *Tractatus*, for example, then one might believe that we need to discover simple, logical, and general rules in terms of which idealized laboratory categorization performance could be explained. If one were committed to *Philosophical Investigations*, on the other hand, then one might believe it was important to postpone or to abandon the search for such simple and general, or even universal, rules. Instead, one might concentrate on describing the complex details of specific, naturalistic, everyday categorizing.

It would therefore be presumptuous to try here to describe all facets of categorization that need theoretical description and explanation: The problem depends in too complex a manner on metatheoretical as well as conventional scientific choices. We can, nevertheless, try to imagine what kind of locally applicable theory might be able to handle the results that we have reviewed here, and we might try to look for ways in which such a theory might fit more closely with one philosophy than with the other.

It would appear that such a theory of categorization needs to deal with the learning of abstractions, including abstract rules that work in the face of ambiguity: how and why an animal, depending on task demands, learns abstractions or instead memorizes specific stimuli; how attention can be almost optimally selective or divided across tasks involving categorization of rectangles or moving objects; and, how attention can be primed, either through base rate manipulations or through trial by trial priming cues, to local or global levels of perceptual analysis. What kind of theory might be able to handle all of these results? In our judgment, there is at present no theory remotely capable of achieving all of these goals.

First, it seems to us that we can reject some entire categories of theory. For example, theories known as "molar" theories in behavior analysis seem unlikely candidates, because such theories typically reject the importance of fine-grain detail, deal with static aggregate summaries of behavior rather than with the reality of actual behavior streams, and emphasize instead logical rules and simple algebraic formulas. In short, their evaluative standards seem largely derived from *Tractatus* and it is not clear how they could be modified to satisfy the standards of *Philosophical Investigations*.

Second, where might one find sufficiently flexible theoretical methods that might handle our results? Consider the possible relevance of the field of robotics and of what has been called "behaving theory." A theory that generates real-time behavior streams, which then can be compared with behavior streams of actual participants, must deal with the fine-grain detail of behavior and automatically confront details of the local sequential patterning of behavior, as required by the complex evaluative standards of *Philosophical Investigations*. Such a theory, unlike a molar theory, which produces only aggregate averages of behavior, could control the movements of a robot. Such a "behaving theory" automatically generates the messy complexity of real behavior. We would like to offer computational processing models developed by Staddon and his colleagues (Staddon, 2001; Staddon & Higa, 1999), by Catania (in press), and by Shimp and his colleagues (Shimp, 1979, 1984a, 1984b, Q2 1992, 1994; Shimp, Childers, & Hightower, 1990; Shimp & Friedrich, 1993) as preliminary examples of behaving theories that are somewhat more in the spirit of *Philosophical Investigations* than are most current quantitative theories.

Third, we can hear researchers committed to the methods of *Tractatus* objecting that a scientific theory need not deal with all the messy details of real-world, everyday behavior. In short, is a robotic behaving theory simple or complex, and which should it be? Consider that variability in laboratory behavior seems different from variability in naturalistic, everyday behavior. Indeed, that this is so is part of the justification for bringing real-world behaviors into the laboratory, where variability can be reduced. In short, one might say that laboratory behavior is relatively simple and that naturalistic behavior is relatively complex. As yet there is, however, no general theory, formula, or science to describe or to explain what is simplicity. In short, "fine-grain detail" is complex from the perspective of a theory that emphasizes logical rules or simple algebraic formulas, but it is simple from the perspective of a more naturalistic theory because it characterizes the very details without which one cannot describe or understand real-world, everyday behavior.

This same difference of perspective on simplicity is seen in research on categorization. Researchers examining naturalistic behavior, robotics, and the dynamics and sequential structure of behavior, appear, we believe, to be reducing the weight they give in evaluating research on categorization to a kind of parsimony based on "simple" laboratory behavior and increasing the weight they give to a newer kind of parsimony based on "complex" naturalistic behavior (Shimp, 2004a, 2004b). Accordingly, if research on nonhuman animal categorization continues to evolve in the direction of Wittgenstein's later views described in *Philosophical Investigations*, then the future may see a greater emphasis on how the fine-grain details of the local temporal structure of complex naturalistic behavior determine membership in a category. And, regardless of the accuracy of this prediction, researchers will probably continue for a long time to have their opinions about what constitutes good research on categorization determined in part by which of Wittgenstein's philosophies feels more compelling.

Fourth, we believe, however, that future advances in the real-time dynamics of the mechanisms of categorization may ultimately impact the necessity of choosing between philosophical positions. Consider that our research has shown that pigeons can apparently shift memorization strategies consistent with one philosophy or the other and that they can do so as a function of a particular trial's character string. Phenomena such as these encourage us to consider the possibility that different mechanisms compatible with either *Tractatus* or *Philosophical Investigations* may operate virtually simultaneously. That is, individual underlying mechanisms, such as rule-learning mechanisms or statistical-learning mechanisms, may resemble one philosophy more than the other (*Tractatus* or *Philosophical Investigations*, respectively). If we view the system as a whole, however, we may see performances that display features of both perspectives, so that an emerging literature on categorization, in particular, and on cognition, in general, may ultimately become more tolerant of what might appear, from the two philosophical perspectives, to be incoherence.

SUMMARY

Several psychological processes commonly associated more with human cognition than with nonhuman animal cognition have been identified in avian visual categorization. Pigeons learn abstract rules to categorize exemplars; pigeons demonstrate flexibility in how they memorize exemplars, that is, they demonstrate memorization strategies; pigeons switch attention between local and global levels of perceptual analysis; and in some cases, pigeons achieve levels of categorization performance that approach optimality.

We reviewed some of this evidence from our own experiments on how pigeons categorize rectangles varying in length and width or objects moving at varying speed and direction, how pigeons switch attention between local and global levels in hierarchically organized complex characters, and how they categorize character strings in artificial grammar learning tasks.

We gave perspective on these results by placing them in the context of Wittgenstein's two philosophies: those of *Tractatus* (1922) and *Philosophical Investigations* (1953). We suggested that certain traditional features of research consistent with *Tractatus*, especially unambiguous logic, parsimony, and highly simplified laboratory tasks, continue to describe some aspects of research, but there is a growing influence of features more consistent instead with *Philosophical Investigations*, especially influences from evolutionary biology and Gestalt psychology, in the form of naturalistic or everyday categorization and complex and ambiguous stimuli. We suggested that different research programs on categorization reveal different methodological commitments to one or another feature of Wittgenstein's two philosophies. A researcher's commitments may make some features of other research on categorization appear misguided, irrelevant, or simply wrong if the methodological commitments are different (Shimp, 2001, 2004a, 2004b). Finally, we suggested that some phenomena in avian categorization research imply that neither of Wittgenstein's philosophical perspectives provides a comprehensive account of categorization and that elements of both perspectives may be found to operate nearly simultaneously.

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Note

1. While the term "grammar" carries linguistic connotations, artificial grammar learning appears to have relatively little to do with the notion of meaning as conveyed in natural language, but it has much to do with categorization and orthographic regularity (Herbranson & Shimp, 2003).

References

Ashby, F. G., & Ell, S. W. (2001). The neurobiological basis of category learning. *Trends in Cognitive Sciences*, *5*, 204–210.

Ashby, F. G., & Gott, R. E. (1988). Decision rules in the perception and categorization of multidimensional stimuli. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14,* 33–53.

Ashby, F. G., & Maddox, W. T. (1998). Stimulus categorization. In M. H. Birnbaum (Ed.), *Measurement, judgment, and decision making: Handbook of perception and cognition* (pp. 251–301). San Diego, CA: Academic Press.

Blough, P. M. (1991). Selective attention and search images in pigeons. *Journal of Experimental Psychology: Animal Behavior Processes*, *17*, 292–298.

Casseday, J. H., Fremouw, T., & Covey, E. (2002). The inferior colliculus: A hub for the central auditory system. In D. Oertel, R. R., Fay, & A. N. Popper (Eds.), *Integrative functions in the mammalian auditory pathway* (pp. 238–318). New York: Springer-Verlag.

Catania, A. C. (in press). The operant reserve: A computer simulation in (accelerated) real time.
Q3 *Behavioural Processes*.

Chomsky, N., & Miller, G. A. (1958). Finite-state languages. *Information & Control, 1,* 91–112.

Cook, R. G. (Ed.). (2001). *Avian visual cognition.* Retrieved August 27, 2005, from http://www.pigeon.psy.tufts.edu/avc/.

Fitch, W. T., & Hauser, M. D. (2004). Computational constraints on syntactic processing in a nonhuman primate. *Science*, *303*, 377–380.

Fremouw, T., Herbranson, W. T., & Shimp, C. P. (1998). Priming of attention to local or global levels of visual analysis. *Journal of Experimental Psychology: Animal Behavior Processes, 24,* 278–290.

Fremouw, T., Herbranson, W. T., & Shimp, C. P. (2002). Dynamic shifts of avian local/global attention. *Animal Cognition, 5,* 233–243.

Gardner, H. (1985). *The mind's new science: A history of the cognitive revolution.* New York: Basic Books.

Gould, S. J., & Lewontin, R. (1979). The spandrels of San Marco and the Panglossian paradigm: A critique of the adaptationist programme. *Proceedings of the Royal Society, B205,* 581–598.

Herbranson, W. T., Fremouw, T., & Shimp, C. P. (1999). The randomization procedure in the study of categorization of multi-dimensional stimuli by pigeons. *Journal of Experimental Psychology: Animal Behavior Processes, 25*, 113–135.

Herbranson, W. T., Fremouw, T., & Shimp, C. P. (2002). Categorizing a moving target in terms of its speed and direction. *Journal of the Experimental Analysis of Behavior (Special Issue on Categorization), 78,* 249–270.

Herbranson, W. T., & Shimp, C. P. (2003). Artificial grammar learning in pigeons: A preliminary analysis. *Learning & Behavior, 31,* 98–106.

Herrnstein, R. J., & Loveland, D. H. (1964). Complex visual concepts in the pigeon. *Science, 146,* 549–551.

Jen, P. H., Chen, Q. C., & Sun, X. D. (1998). Corticofugal regulation of auditory sensitivity in the bat inferior colliculus. *Journal of Comparative Physiology [A] 183*, 683–697.

Kahneman, D., Slovic, P., & Tversky, S. (1982). *Judgment under uncertainty: Heuristics and biases*. Cambridge: Cambridge University Press.

Lamb, M. R., London, B., Pond, H. M., & Whitt, K. A. (1998). Automatic and controlled processes in the analysis of hierarchical structure. *Psychological Science, 9,* 14–19.

Lamb, M. R., & Robertson, L. C. (1988). The processing of hierarchical stimuli: Effects of retinal locus, locational uncertainty, and stimulus identity. *Perception and Psychophysics, 21,* 226–232.

Lamb, M. R., Yund, E. W., & Pond, H. M. (1999). Is attentional selection to different levels of hierarchical structure based on spatial frequency? *Journal of Experimental Psychology: General, 128,* 88–94.

Ma, X., & Suga, N. (2003). Augmentation of plasticity of the central auditory system by the basal forebrain and/or somatosensory cortex. *Journal of Neurophysiology*, *89*, 90–103.

Malloy, T. E., Jensen, G. C., Song, T., Herbranson, W. T., Fremouw, T., & Shimp, C. P. (2001). Interactive demonstration of avian categorization. Retrieved September 15, 2005, from http://www.psych.utah.edu/shimp/Avian_Categorization.htm.

Medin, D. L., & Schaffer, M. M. (1978). Context theory of classification learning. *Psychological Review*, *85*, 207–238.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology, 9,* 353–383.

Navon, D. (1981). The forest revisited: More on global precedence. *Psychological Research, 43,* 1–32.

Plaisted, K. (1997). The effect of interstimulus interval on the discrimination of cryptic targets. *Journal of Experimental Psychology: Animal Behavior Processes, 23,* 248–259.

Plous, S. (1998). Signs of change within the animal rights movement: Results from a follow-up survey of activists. *Journal of Comparative Psychology*, *112*, 48–54.

Reber, A. S. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning & Verbal Behavior, 6,* 855–863.

Reber, A. S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General, 118,* 219–235.

Ryle, G. (1949). *The concept of mind.* London: Hutchinson & Co.

Seidenberg, M. S., MacDonald, M. C., & Saffran, J. R. (2002). Does grammar start where statistics stop? *Science*, *298*, 553–554.

Shimp, C. P. (1979). The local organization of behavior: Method and theory. In M. D. Zeiler & P. Harzem (Eds.), *Advances in analysis of behavior, Vol. 1: Reinforcement and the organization of behavior* (pp. 262–298). Chichester, U.K.: Wiley.

Shimp, C. P. (1984a). Relations between memory and operant behavior, according to an associative learner (AL). *Canadian Journal of Psychology (Special Issue on Animal Memory), 38,* 269–284.

Shimp, C. P. (1984b). Timing, learning and forgetting. In J. Gibbon & L. Allan (Eds.), *Timing and time perception,* Vol. 423 (pp. 346–360). New York: New York Academy of Sciences.

Shimp, C. P. (1989). Contemporary behaviorism versus the old behavioral straw man in Gardner's *The mind's new science: A history of the cognitive revolution. Journal of the Experimental Analysis of Behavior, 51,* 163–171.

Shimp, C. P. (1992). Computational behavior dynamics: An interpretation of Nevin (1969). *Journal of the Experimental Analysis of Behavior (Special Issue on Behavior Dynamics), 57,* 289–299.

Shimp, C. P. (1994). Computational behavior and behavior analysis: An interpretation of Catania and Reynolds (1968). In E. Ribes Inesta (Ed.), *B. F. Skinner, In memoriam.* Guadualajara, Mexico: University of Guadalajara Press. (In Spanish)

Shimp, C. P. (2001). Behavior as a social construction. *Behavioural Processes*, *54*, 11–32.

Shimp, C. P. (2004a). Ambiguity, logic, simplicity, and dynamics: Wittgensteinian evaluative criteria in peer review of quantitative research on categorization. *Behavioural Processes, 66,* 333–348.

Shimp, C. P. (2004b). Scientific peer review: A case study from local and global analyses. *Journal of the Experimental Analysis of Behavior, 82,* 103–116.

Shimp, C. P., Childers, L. J., & Hightower, F. A. (1990). Local patterns in human operant behavior and a behaving model to interrelate animal and human performances. *Journal of Experimental Psychology: Animal Behavior Processes, 16,* 200–212.

Shimp, C. P., & Friedrich, F. J. (1993). Behavioral and computational models of spatial attention. *Journal of Experimental Psychology: Animal Behavior Processes, 19,* 26–37.

Shimp, C. P., Herbranson, W. T., & Fremouw, T. (2001). Avian visual attention in science and culture. In R. G. Cook (Ed.), *Avian visual cognition.* Retrieved August 27, 2005, from http://www.pigeon.psy.tufts.edu/avc/shimp/.

Shulman, G. L., & Wilson, J. (1987). Spatial frequency and selective attention to local and global information. *Perception, 16,* 89–101.

Smith, D. J., Shields, W. E., & Washburn, D. A. (2003). The comparative psychology of uncertainty monitoring and metacognition. *Behavioral and Brain Sciences*, *26*, 317–373.

Staddon, J. E. R. (2001). *The new behaviorism: Mind, mechanism, and society*. Philadelphia, PA: Taylor & Francis.

Staddon, J. E. R., & Higa, J. J. (1999). Time and memory: Towards a pacemaker-free theory of interval timing. *Journal of the Experimental Analysis of Behavior*, *71*, 215–251.

Suga, N., Gao, E., Zhang, Y., Ma, X., & Olsen, J. F. (2000). The corticofugal system for hearing: Recent progress. *Proceedings of the National Academy of Science U S A, 97*, 11807–11814.

Tinbergen, L. (1960). The natural control of insects in pinewoods. I. Factors influencing the intensity of predation by songbirds. *Archives Neerlandaises de Zoologie*, *13*, 265–343.

Wittgenstein, L. (1922). *Tractatus Logico-Philosophicus*. London: Routledge & Kegan Paul.

Wittgenstein, L. (1953). *Philosophical Investigations*. New York: Macmillan.

Wright, A. A. (2001). *Learning strategies in matching to sample.* In R. G. Cook (Ed.), *Avian visual cognition.* Retrieved August 27, 2005, from http://www.pigeon.psy.tufts.edu/avc/wright.

Yan, J., & Suga, N. (1996). Corticofugal modulation of time-domain processing of biosonar information in bats. *Science*, *273*, 1100–1103.

Zhang, Y., & Suga, N. (1997). Corticofugal amplification of subcortical responses to single tone stimuli in the mustached bat. *Journal of Neurophysiology*, *78*, 3489–3492.

Zhou, X., & Jen, P. H. S. (2000). Brief and short-term corticofugal modulation of subcortical auditory responses in the big brown bat, *Eptesicus fucus*. *Journal of Neurophysiology*, *84*, 3083–3087.