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AN ANALOG PROCESS OF REPRESENTATION
IN THE PIGEON

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AN ANALOG PROCESS OF REPRESENTATION IN THE PIGEON

By

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ABSTRACT

AN ANALOG PROCESS OF REPRESENTATION IN THE PIGEON

By

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The analog properties of representations in pigeons were investigated through a series of tests of cognitive extrapolation of movement. Rotating stimuli which briefly dissappeared were presented on a video monitor. Pigeons (n=5) were trained to respond "left" or "right" by pecking one of two keys to accurate or inaccurate points of reappearance of the stimuli. Accurate transfer was demonstrated when pigeons made correct choices on probe trials in which the final location of the stimulus was novel.

To determine if the nature of the skill was cognitive, several analyses of the choice responses were conducted. Results indicated that subjects shifted from a stimulus-response (S-R) learning strategy to a more cognitive or rule-governed strategy in the final phase of the experiment. Results of the final phase demonstrated stimulus control of an analog process of representations in the pigeon.

To Mark Rosenberg, and
to Mom, Dad, Angie and
Jimmy, whose support has
been essential in the
completion of this thesis.

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INTRODUCTION

Until recently, many psychologists and philosophers accepted DesCartes's division of organisms into two groups: Humans, who have the capacity to think, and animals, who do not. According to this point of view, animal behavior, no matter how elaborate and complex, could always be reduced to some configuration of reflexes in which thought plays no role. The success of stimulus-response (S-R) models of conditioned behavior had "reinforced" this way of thinking, for nothing seemed to be gained by trying to explain an animal's behavior by appeal to its mental life.

This state of affairs has changed markedly during the past ten years. A variety of studies of spatial memory (Olton, 1978; Olton & Collison, 1979), delayed matching-to-sample (Roitblat, 1980), recall of photographs (Wright, Santiago, Urcuioli & Sands, 1984), serial learning (Straub & Terrace, 1981), natural concept formation (Herrnstein, Loveland, and Cable, 1976), and abstract concept formation (Zentall, Edwards, Moore, & Hogan, 1981) have created unprecedented difficulties for S-R models of behavior. In each of these studies, the behavior in question could not be explained by reference to an immediately available stimulus, or to some covert S-R mediator. Each of these studies demonstrated that animals can encode stimuli and relationships between stimuli that are not immediately present. In each case, the animal's behavior was controlled by representations of stimuli.

Our current understanding of the use and form of animal representations is based on speculation, with causality inferred between theoretical descriptions of memory and observed behavioral phenomena. (See Roitblat, 1982, or a review.) However, a promising technique has been developed by cognitive scientists to study the characteristics of humans' representational system. The technique induces changes of mental representations: the solution of a problem requires subjects to manipulate their representations (Shepard & Cooper, 1982; Kosslyn, 1980; Jagacinski, Miller and Johnson, 1983). In this thesis, behaviors are studied which reflect analog properties of representations of stimuli in pigeons. The aim is to uncover specific characteristics of pigeons' representational system.

Accepted Notions about Animal Representations

Any organism that learns something, i.e., that responds a specific way in the presence of specific objects, must retain a memory of the object and of the consequences of responding in a specific way. The memory of the response-consequent was coined by behaviorists as an association, a more general term implying that some drive, need or emotion was associated with responding in the presence of a stimulus. The behaviorists focused on the response end of the internal process of perceiving and responding, and in doing so, ignored the stimulus end and the power of control in its organizational properties which determine which aspects of a stimulus will be perceptually registered by an organism, and which aspects become the condition for a particular reinforced response. Since stimulus properties were neglected, one of the central problems of learning theory was to explain how organisms behave appropriately to novel stimuli. Stimulus generalization was one well-established mechanism (Rilling, 1977). However, most behavioristic theories of stimulus generalization assumed an invariant internal representation locked to the stimulus in the environment (Schwartz, 1984). Behavioral plasticity, behaving appropriately in the presence of new stimuli, is a criteria for cognitive control of behavior (Pylyshyn, 1984) and necessitates a 'plastic' or changeable form of memory.

To solve the problem, researchers separated out the study of the memory of the object itself. They typically referred to it as a 'representation' (Roitblat, 1982). A representation in this sense was a memory of perceptual information (including size, color, rigidity, movement, etc.) that describes the object. Still the concept of representation was invariant because it was inextricably tied to the percept of the object. So, researchers asserted that plasticity must come from its use (Kosslyn, 1980; Shepard & Cooper, 1982).

With few empirical studies on animal representations, speculation ensued concerning the possible use of representations in animals. The most popular speculation was that animals use some imagery process to represent objects, probably because images seem to be the lowest form of memory, i.e., they are solely based on properties of percepts. Psychologists such as Premack (1983) and Jerison (1973) have used evolutionary arguments to imply that lower animals use images to represent the world. A contemporary ethologist, Griffin (1981) states:

> Mental images obviously vary widely in the fidelity with which they represent the surrounding universe, but they must exist in some form in any conscious organism. (p 6)

These speculations were not met with arguments. Curiously, imagery in animals has been assumed to be the way in which animals represent the world, but it is assumed by default without empirical justification.

Animal Representation as an Analog Process

Within the framework of cognitive psychology and evolutionary theory, Shepard and Cooper (1982) present the strongest logical case describing a representational system in animals. They begin by assuming that animals probably represent perceptual information which describes objects. Next, they assume that organisms that are able to manipulate those representations in order to "anticipate the consequences of structure-preserving transformations" have an evolutionary advantage. Shepard and Cooper do not say that animals retain 'pictures' in their heads which they can move around or transform in order to anticipate change. Shepard (1984) states:

> What is internalized at the deepest and most abstract level is not any particular object or transformation (which are arbitrary with respect to orientation and path) but the set of constraints that in three-dimensional Euclidean space govern the possible projections and transformations of an object. (p 442)

The process Shepard and Cooper describe is an analog process (not necessarily an imagerial one). In an analog process, the relational structure of external events is essentially preserved in the corresponding relational structure of the representation. This relational structure could be preserved in digital form, in picture form, or in some logical form. In any case, there must be a one-to-one relation (or isomorphism, to use Shepard's term) between stages of the internal process and stages of the corresponding external process. Moreover, intermediate stages of the external process are represented even if those external stages are not physically presented. As in the diagram presented in Figure 1, organisms can observe stage A', and then stage C' and retain an internal representation which includes the transformations which occurred between A' and C' (i.e., state B'). Thus an analog process preserves stimulus changes and allows the organism

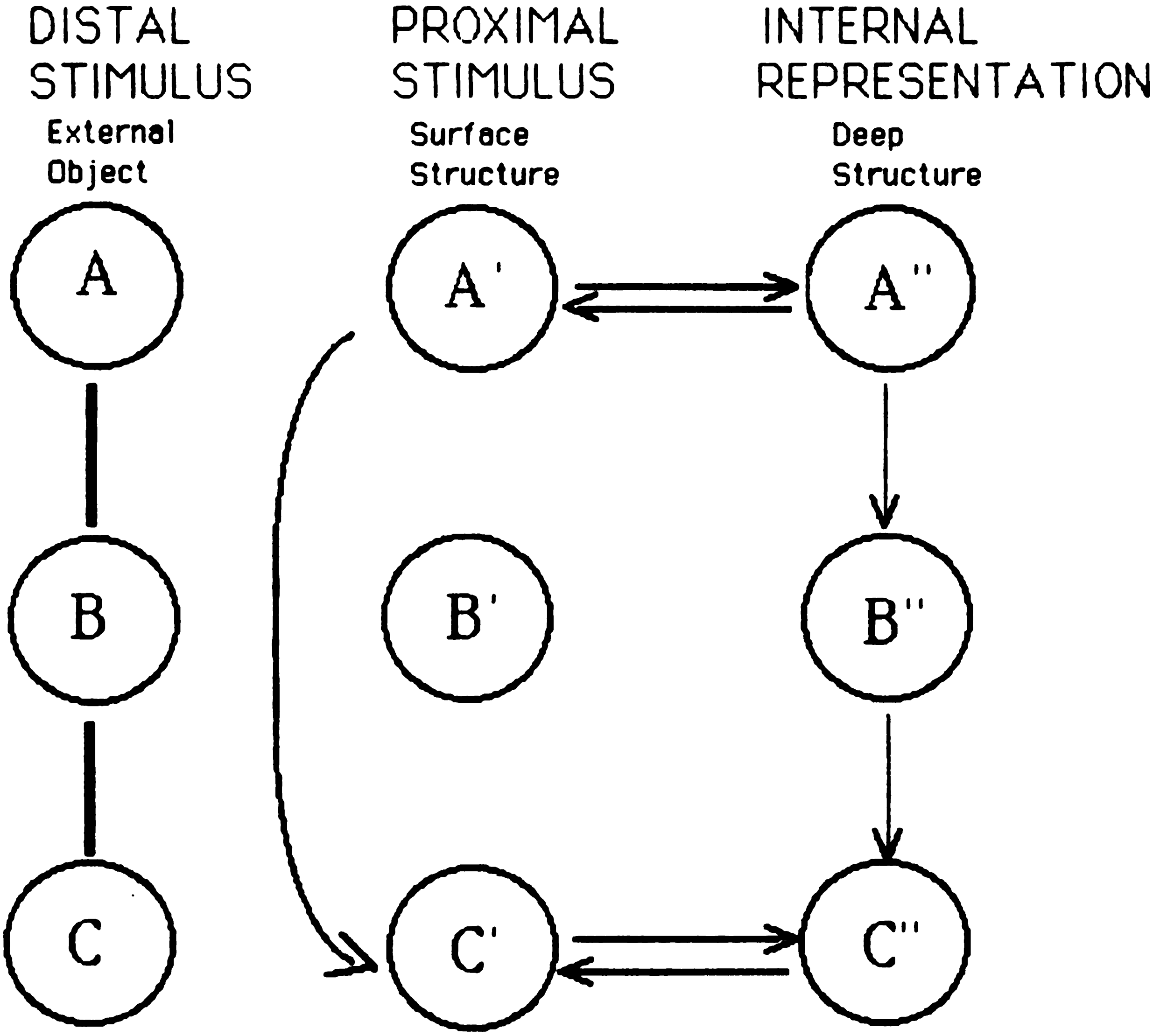


Figure 1. Schema of transformational mappings between distal objects, proximal stimuli, and internal representations. Adapted from Kubovy & Pomerantz, Perceptual Organization, LEA, 1981, p. 295.

to respond appropriately to new stimuli which obey the same rules of change.

Evidence of Analog Processes

Not only is the analog process more logical than were the imagery speculations, but it is also testable. Shepard and Cooper, and their colleagues have developed a quantitative methodology for the study of analog transformations of mental representations in humans. The most well-known are studies of 'mental rotation'. After discrimination training between stimuli and their mirror images, a test stimulus which has physically changed in orientation from its trained presentation is presented to a subject. The dependent variable is reaction time, or time taken to respond if the stimulus matched the standard or mirror image form of the trained stimulus. The well-established finding is that mean reaction times increased linearly as a function of the angular departure from the expected or trained orientation. An analog process is obviously in use, since the subjects' reaction times revealed a one-to-one correspondence between internal process and external presentation of orientation.

From this and other studies on humans, it has been established that humans can represent transformations of objects in analog form. The question which follows is whether other species of animals have a similar cognitive ability.

Pigeons have a very well-developed visual system (Granda & Maxwell, 1979) and have demonstrated the ability to remember features of complex naturalistic photographs (Herrnstein & De Villiers, 1980) as well as features of complex computer-generated stimuli (Cerella, 1980). These demonstrated abilities indicate that pigeons have an accurate memory system for visual stimuli. The possibility that they could also represent visual stimulus properties in some analog form seems great. But, there has only been one study to test the analog process in pigeons, and it produced negative results. Hollard and Delius (1982) borrowed a mental rotation methodology (Kubovy & Podgarny, 1981) to test pigeons. They employed a matching-to-sample paradigm. First, a single sample stimulus was presented to pigeons. Next, two stimuli were presented simultaneously. Pigeons were reinforced for pecking the comparison stimulus which matched the sample stimulus. One test stimulus matched the sample, and the other was a mirror image of the sample. On 80 percent of the trials, both test stimuli were presented at angular orientations which differed from the sample stimulus. The task required pigeons to discriminate between two simultaneously presented stimuli which differed in orientation from the sample, and then to peck the comparison stimulus which matched.

Needless to say, 1000's of sessions were required to train the pigeons how to respond accurately. Many of the orientations were trained as well (0, 45 and 90 degrees). Results of testing indicated that pigeons performed accurately to stimuli oriented to novel 135 degrees and 180 degrees, and they performed accurately to novel stimuli presented in trained (0, 45, or 90 degrees) and novel (135 or 180 degrees) orientations. Pigeons' reaction times to respond, however, were consistently the same across trials.

Because the reaction times function did not increase linearly with angular disparity, Hollard and Delius concluded that pigeons do not 'mentally rotate' stimuli in the continuous fashion that humans do. Upon reading this, most assume that the study provides evidence that pigeons do not have the type of representational system that Shepard and Cooper discuss. The study demonstrates that pigeons CAN represent stimulus properties in an analog fashion, and they can use their analog representational system to solve the task when novel stimuli and novel orientations are employed. How else could they perform so accurately, unless they coded a one-to-one correspondence between represented stimulus orientations at standard or mirror image form? Pigeons did not produce the reaction time function that reveals a 'mental rotation' process. However, pigeons had to solve the problem through the use of some analog process, as Hollard and Delius admit in their discussion:

> Pigeons solved the problem differently (from humans) and more efficiently, presumably through a parallel mode of information processing. (p 806)

By 'parallel mode', they mean something which produces the same response accuracy as mental rotation does, but not the same timing considerations; i.e., some other type of analog process.

The reaction time function was the only negative finding of this study. However, this is due, in part, to the fact that pigeons are easily distracted from a task by outside noises, temporary changes in the experimental environment, and so forth. The primary reason that reaction time is never a valuable variable in operant study is that it is not measured appropriately. In cognitive tasks, reaction times are meaningful in reflecting time for internal processing only if subjects are asked to respond as quickly as possible. A time constraint could easily be placed on responding such that pigeons are forced to respond as quickly as possible. But in most pigeon experiments, including Hollard and Delius's, reaction times are simply measured with no time constraints. Because of the methodological and measurement flaws, the question of analog processes of representation in the pigeon remains open.

New Methodology to Study Analog Processes

Since Hollard and Delius failed to obtain clear evidence for an analog process (i.e., mental rotation) in pigeons using Shepard and Cooper's procedure, I decided to employ a different methodology. There is an area of human cognitive psychology in which the experimenter presents moving stimuli to the subject for the purpose of drawing inferences about humans' representation of movement. An experiment by Jagacinski, Miller and Johnson (1983) is a prototype for testing this ability. The basic task was to estimate stimulus location at various times after a moving stimulus dissappeared. This ability required "cognitive extrapolation" based on information gained about the stimulus while it was present. The stimulus moved from left to right and dissappeared. In its absence, subjects had to make some mental manipulation of the remembered information about location, direction, and speed of motion in order to accurately predict location. Subjects pressed a button when they thought a dissappeared moving stimulus would have reached a particular spatial location. Their response was a yes/no judgment. With feedback, humans made accurate mental transformations of stimuli, and this cognitive skill was accurately applied to novel situations. The task involved an analog process through which subjects represented stimulus movement.

This procedure might be reasonable for testing pigeons. Movement is not implied by static displays of changed stimuli, as in the mental rotation task, so excessive training is not necessary. Examples of movement are presented so that any 'mental extrapolation' is based on representations of perceived physcial transformations.

If these representations are retained in some analog fashion, pigeons should be able to accurately extrapolate stimulus movement to novel locations.

Specific Plan

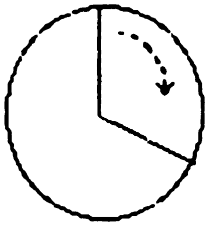
The present experiment investigated pigeons' ability to use analog transformations of representations of stimuli. The methodology was a synthesis of the Jagacinski et al. (1983) study of movement extrapolation and of Shepard and Cooper's (1982) research on mental rotation. The basic idea was to determine if after discrimination training of movement to two locations, transfer is obtained at a new intermediate location. The aim was also to discover if two boundary location conditions must be trained before an analog process is applied to a novel location.

The task was a conditional discrimination with movement and location used as discriminative stimuli. The stimulus was a lighted rectangle which rotated in a clockwise fashion on the screen of a video monitor. Three different types of trials were trained: 1) a perceptual type in which the rotating stimulus moved continuously to a certain point and was always physically present, 2) an imagery type in which the rotating stimulus disappeared at a specific point and then reappeared at the point it would have reached if it continued moving while it was absent, and 2) violation types in which the rotating stimulus dissappeared and reappeared at a location which was incompatible with the time it was absent and its speed of motion. According to Shepard and Cooper (1982) mental transformations are performed in the absence of external counterparts, i.e. during the delay. An example of each of the trial types is presented in Figure 2.

A trial began with the stimulus presented at 12:00. After certain contingencies were met (an FR-12 on the middle response key of a three-key display in front of the monitor), the stimulus started its rotation. For all perceptual trials the stimulus moved continuously and then stopped at a specific location. For all imagery and violation trials, the stimulus moved to 3:00, dissappeared, and then reappeared after some time. For imagery trials, the stimulus reappeared at the location it would have rotated to on a perceptual trial. For violation trials, the point of reappearance was incorrect assuming that the stimulus continuously moved during its absence. Left key responses were reinforced for perceptual and imagery types. In both cases, the stimulus moved at some constant rate even though it may have dissappeared for some time. Right key responses were reinforced for violation type trials, indicating that the point of stimulus reappearance was incompatible with constant stimulus motion.

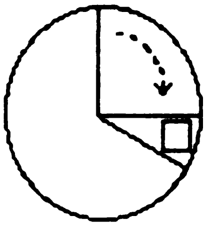
4:00 Training

perceptual



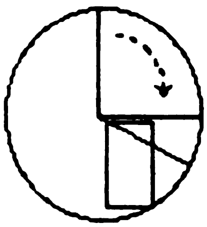
The stimulus rotates from 12:00 to 4:00. It is always present. Left key responses are reinforced

imagery



The stimulus rotates from 12:00 to 3:00. It then dissappears, and is absent during the time it would take to rotate from 3:00 to 4:00. After this delay, it reappears at 4:00. Left key responses are reinforced.

violation



The stimulus rotates from 12:00 to 3:00. It then dissappears, and is absent during the time it would take to rotate from 3:00 to 6:00. It then reappears at 4:00. Right key responses are reinforced.

Figure 2. An illustration of a perceptual, an imagery, and a violation trial type.

Birds were first given discrimination training with all trials ending at 4:00. After the 4:00 task was mastered they were next given training at 6:00. In the 4:00 condition, there was a perceptual trial type in which the stimulus moved continuously from 12:00 to 4:00, an imagery type in which the stimulus dissappeared at 3:00 and reappeared after a short delay at 4:00, and a violation type in which the stimulus dissappeared at 3:00 and reappeared after a long delay at 4:00.(For an illustration, refer to Figure 2.) Contingencies of reinforcement were based on the response requirements previously described.

After acquisition of 80% accuracy at 4:00 with the different trial types (perceptual-imagery-violation), a transfer test was given. The question of interest was whether the birds accurately responded to novel stimulus presentations ending at 5:00. Only a few examples of these probe trials were presented within typical training sessions of the 4:00 condition. This strategy was used in an effort to prevent the birds from learning 5:00 contingencies, since these were re-tested later after both boundary conditions (4:00 and 6:00) were trained. In the 5:00 condition, four different trial types were tested (see Figure 3). In the perceptual type, the stimulus moved from 12:00 to 5:00 continuously. In the imagery type the stimulus moved from 12:00 to 3:00, dissappeared for a "medium" delay and then reappeared at 5:00. Also, there were two violation types: one in which the stimulus dissapeared for a short time and reappeared at 5:00, and one in which the stimulus dissappeared for a long time and reappeared at 5:00. Reinforcement was given for correct responding to the 5:00 condition trials (i.e., left = perceptual and imagery, right = violations).

After training of a single condition (4:00), response accuracy to probes is predicted to be lower than response accuracy to trained examples. Subjects can learn to respond to the 4:00 condition accurately by simply learning a temporal discrimination which does not apply to all of the 5:00 probes (see Figure 5). During training, subjects can respond "left" if the stimulus never dissappears, respond "left" if the stimulus dissappears for a brief time, and respond "right" if the stimulus dissappears for a long time. By applying this temporal discrimination, birds can receive reinforcement on 100% of the trials in the 4:00 condition. Given that this type of learning occurred to the 4:00 condition, the only transfer (high accuracy of response) predicted to the novel 5:00 condition is for those trials types which are compatible to the S-R associations learned. For the (5:00) perceptual type and for the (5:00) violation type with the long delay, the temporal discrimination learning yields accurate responses (see Figure 5). For the (5:00) violation type with a short delay, the learned response is inaccurate (i.e., short delay =/ left in that condition). For the imagery type, 50% response accuracy is predicted since the birds have no

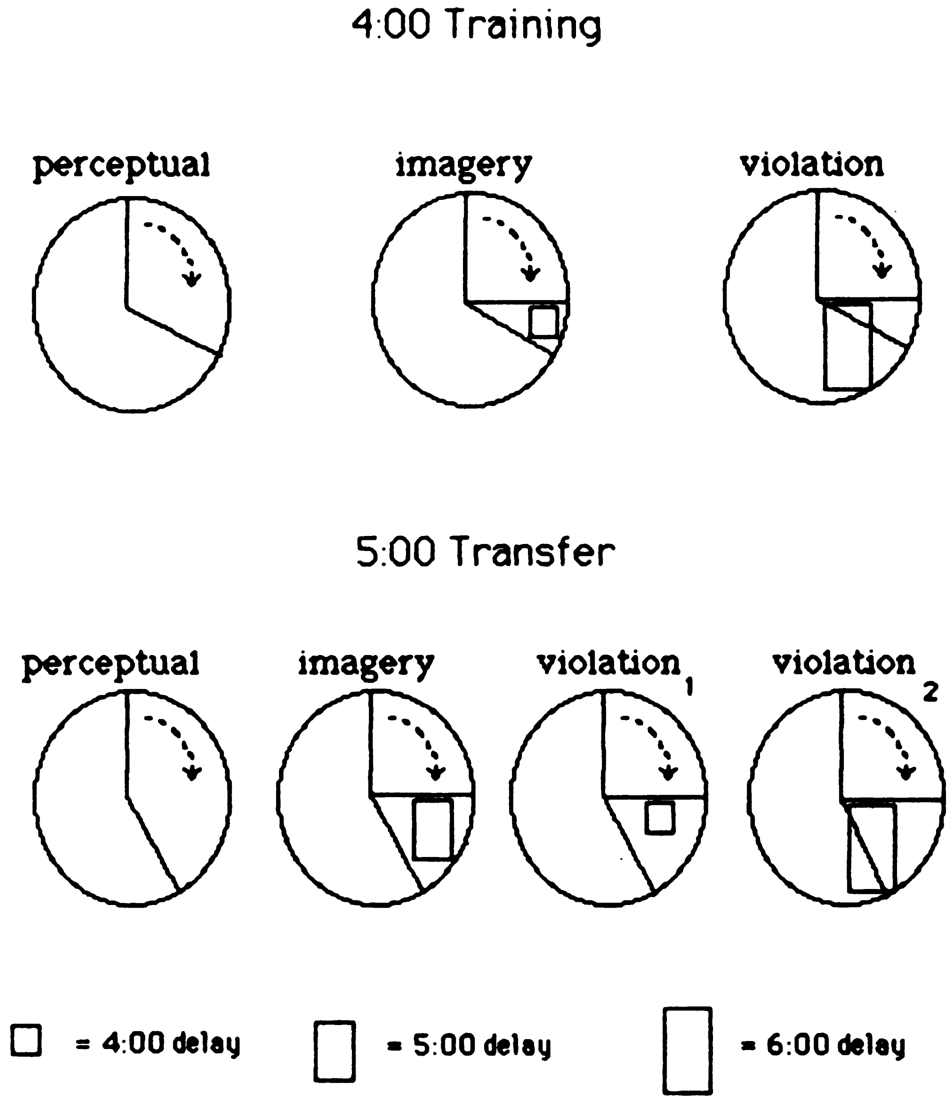


Figure 3. Trial types for 4:00 training and for 5:00 probes.

previous association to the location or to the new "medium" delay. A graph of predicted results to 5:00 probes given S-R learning to the 4:00 condition is presented in Figure 6a.

Following training at 4:00, a condition for which all stimulus presentations end at 6:00 was introduced. A 6:00 condtion was trained to solve two problems: 1) to counterbalance the temporal discrimination so it no longer applied, and 2) to identify the analog process by training boundary conditions (4:00 and 6:00) and testing an intermediate location (5:00). Again a perceptual type (continuous movement from 12:00 to 6:00), an imagery type (movement from 12:00 to 3:00, dissappearance for a long delay, and reappearance at 6:00), and a violation type (movement from 12:00 to 3:00, dissappearance for a short delay, and reappearance at 6:00) were trained (see Figure 4). Contingencies of reinforcement were the same as in the 4:00 condition: left responses were reinforced in perceptual and imagery trials, and right responses were reinforced in violation trials. The 6:00 condition was trained until response accuracy reached 80%. Then birds were exposed to alternate days of 4:00 and 6:00 training.

Figure 4 illustrates both 4:00 and 6:00 condition trial types. Responses to temporal discriminations were now counterbalanced by the 6:00 condition. Simple S-R associations of a temporal discrimination only produced

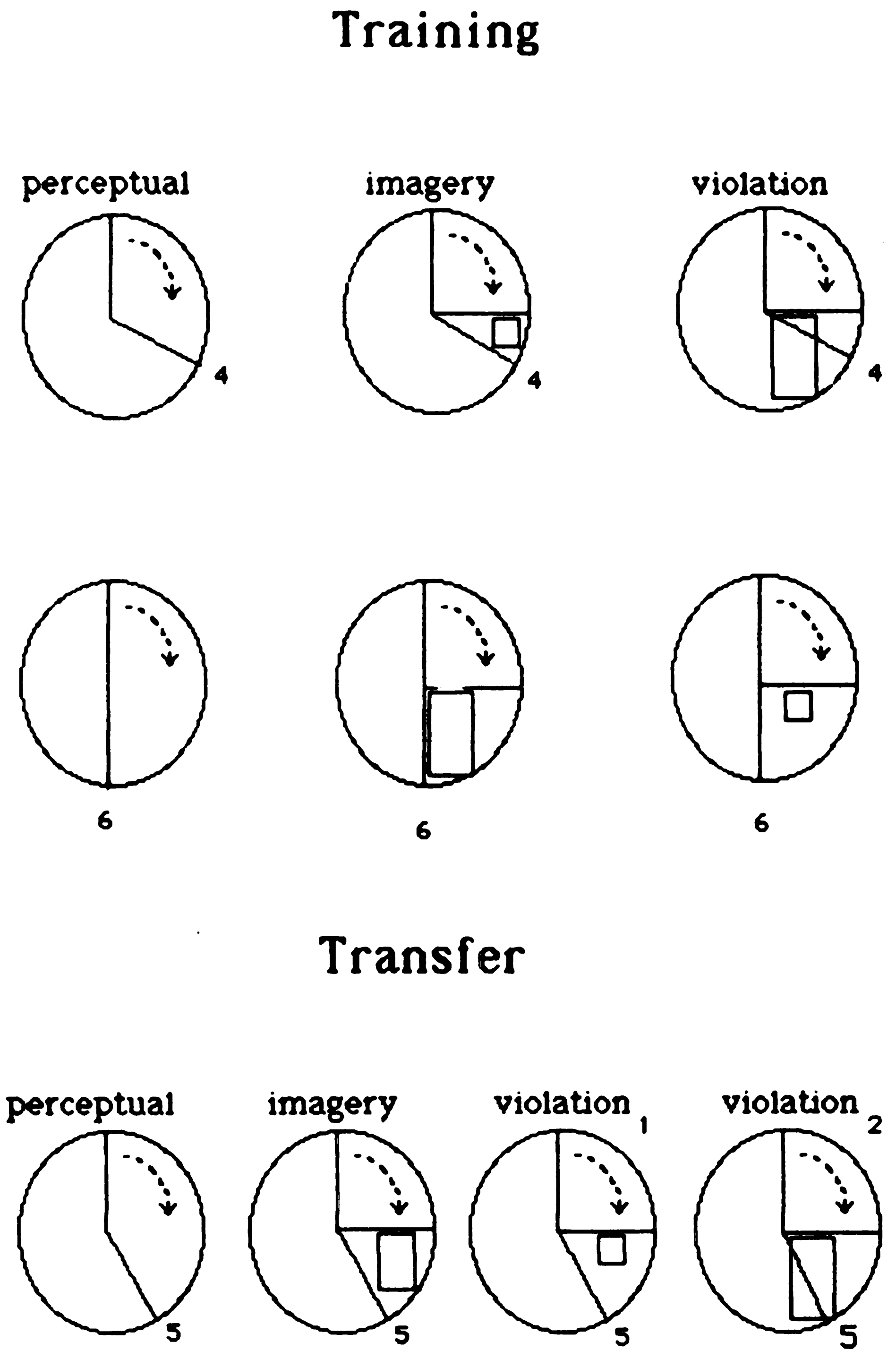


Figure 4. All trial types for training and transfer conditions

Training	Learning Strategy	Transfer
4:00	S-R associations: no delay - go left short delay - go left long delay - go right	Very little: perceptual: yes imagery: no violation_1: no violation_2: yes
4:00-6:00	Conditional rules:	Very little:
If 4:00 then	no delay - go left short delay - go left long delay - go right	perceptual: yes imagery: no violation_1: no violation_2: no
If 6:00 then	no delay - go left long delay - go left short delay - go right	
4:00-6:00	Cognitive Extrapolation	Immediate
	accurate stimulus - go left movement	perceptual. yes
	accurate stimulus - go left movement	imagery: yes
	inaccurate stimulus - go right movement	violation_1: yes violation_2: yes

Figure 5. Amount of transfer produced by different learning strategies and different training.

accurate responding in the perceptual trials. For all other types, birds were forced to either use an analog process of representation, or alternatively, to formulate bi-conditional S-R associations contingent upon location. (For an illustration, see Figure 5, 4:00-6:00 training.) If they used a bi-conditional learning strategy, the following would be learned: in the cases where stimuli ended at 4:00, short delays require left responses and long delays require right responses; but, in the cases where stimuli ended at 6:00, short delays require right responses and long delays require left responses. Bi-conditional learning produces discrete S-R associations which have little applicabilitiy to novel probes. If an analog process is used, subjects represent 4:00 and 6:00 in some analog fashion. If pigeons use an analog process to preserve transformations of the stimulus from 4:00 to 6:00, they also retain an analog form for an intermediate location, i.e., 5:00. By this method, they respond to novel probes accurately.

The 5:00 condition was tested after 80% proficiency was observed to alternate days of 4:00 and 6:00 training. This time 5:00 probes were introduced alternately within 4:00 training sessions and within 6:00 training sessions. Immediate transfer to the perceptual type is predicted because the S-R association still holds (e.g., no delay - go left). However, no immediate transfer is predicted for the imagery or the violation types unless an analog process

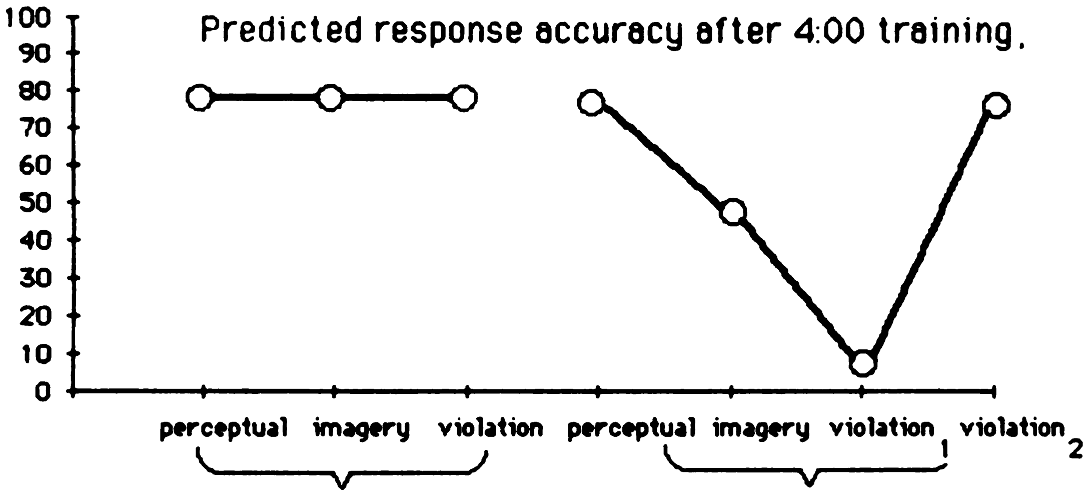


Figure 6a. 4:00 5:00

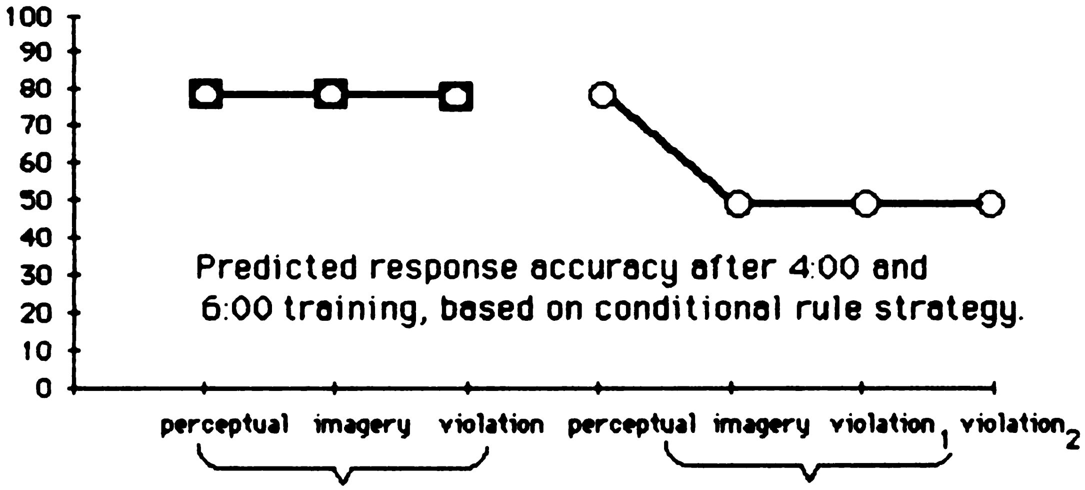


Figure 6b . 4:00-6:00 5:00

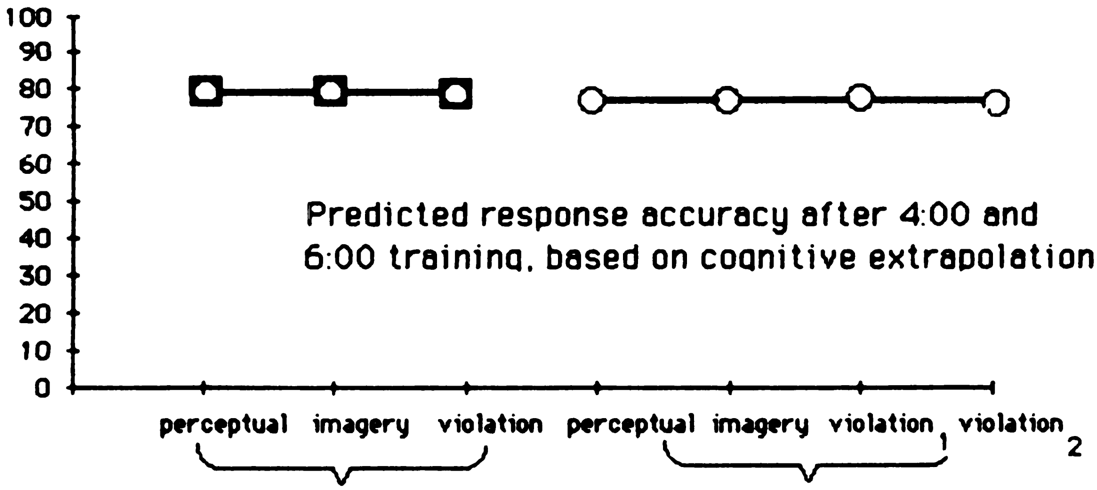


Figure 6c. 4:00-6:00 5:00

of representation is used. The possible conditional rules learned from 4:00 and 6:00 training are based on the location of the stimulus (i.e., if at 4:00, then one set of S-R rules; if at 6:00, then an alternate set). Since the new probes are located at 5:00, neither of the sets of conditional rules are applicable. Since 5:00 is between 4:00 and 6:00, simple generalization of the location rules yields 50% response accuracy to all the imagery and violation types. But, if an analog process is being used, 5:00 is accurately represented in the preserved transformations of the stimulus from 4:00 to 6:00. Response accuracy to 5:00 probes is high and immediate, if an analog process is applied. Figure 6b illustrates response accuracy predictions to 5:00 probes after both 4:00 and 6:00 training resulting in the learning of conditional rules. If response accuracy to 5:00 probes is higher than in this prediction, then predictions of an analog model are supported. (See Figure 6c for predicted results, and see Figure 5 for predicted learning strategies.)

METHOD

Subjects

Five White Carneaux pigeons served as subjects. They had previously participated in some preliminary investigations which involved pecking response keys to stimuli presented at different locations on the screen of the video monitor. There was no specific response bias trained by the previous research to the locations used in the present study. Additionally, this type of movement and time delays were never used before as discriminative stimuli.

Subjects were maintained at 80 percent +/- 20 g. of their free-feeding weights throughout this experiment. Subjects were individually housed in a temperature-controlled, constantly illuminated colony room wherein water and grit were always available. Subjects were transported daily to an experimental room in which they participated in the experiment. Each subject was fed in the colony room immediately following its daily session.

Apparatus

A Life Sciences Associates secondary video monitor (CAT #509-MD1000-190) with a 12 cm. X 9.5 cm screen was fixed to the stimulus panel of a Lehigh Valley Electronics pigeon chamber. It was positioned on the stimulus panel 6 cm from the top of the chamber and centered from the sides. The secondary monitor was interfaced to a TRS-80 MIII microcomputer through which computer graphics were used to present stimuli. The microcomputer was also interfaced to electromechanical equipment which controlled the chamber operanda.

A three-key pigeon chamber, measuring 35 X 35 X 30 cm., was used. The 2.54 cm.-diameter clear plastic keys were positioned in front of the video monitor: 13 cm. from the top of the chamber, 2 cm. apart from each other, 12 cm. from the sides of the chamber, and 22 cm. from the bottom of the chamber. The keys were mounted in a row across the middle of a sheet of plexiglass (dimensions: 20.5 cm. X 16.5 Cm.). The plexiglass was mounted 3 cm. from the screen of the video monitor, and holes were cut out for the response keys' activation areas. The keys required a force of 15 g. (.15 N) for activation. The houselight, a 28 V. dc GE 757 light, was positioned at the top center of the back wall adjacent to the stimulus panel. The grain magazine was 5 X 5 cm., and was located 9 cm. from the bottom of the chamber and centered under the middle key.

The chamber and monitor were housed in an insulated chamber equipped with a fan to provide ventilation and mask noise. The microcomputer was housed in an adjacent room and connecting wires between the computer and the chamber ran through a conduit in the wall.

During each session, the microcomputer recorded the type of trial presented, the type of response emitted, the time taken to respond, and whether or not reinforcement was provided. This trial-by-trial data was dumped to a printer after each session. At the end of each session, the microcomputer also calculated percent correct scores for each trial type. Tests were given based on the accuracy of these percent correct scores.

Procedure

From preliminary investigations, subjects had already been trained to eat from the magazine hopper and to peck the response keys. Next, the five subjects were exposed to both 4:00 and 6:00 conditions within single sessions of training. The original plan of this research was to train the birds on both conditions within the same session, and then to probe-test at 5:00. However, months of simultaneous training produced no better than chance performance for both conditions in all subjects (See Appendix A for data.). The birds could not acquire the task with all 4:00 and 6:00 trial types presented within the same session. The task was simplified by breaking training down into two conditions. A test after each was conducted to determine the learning strategy used by the subjects at different points in the experiment.

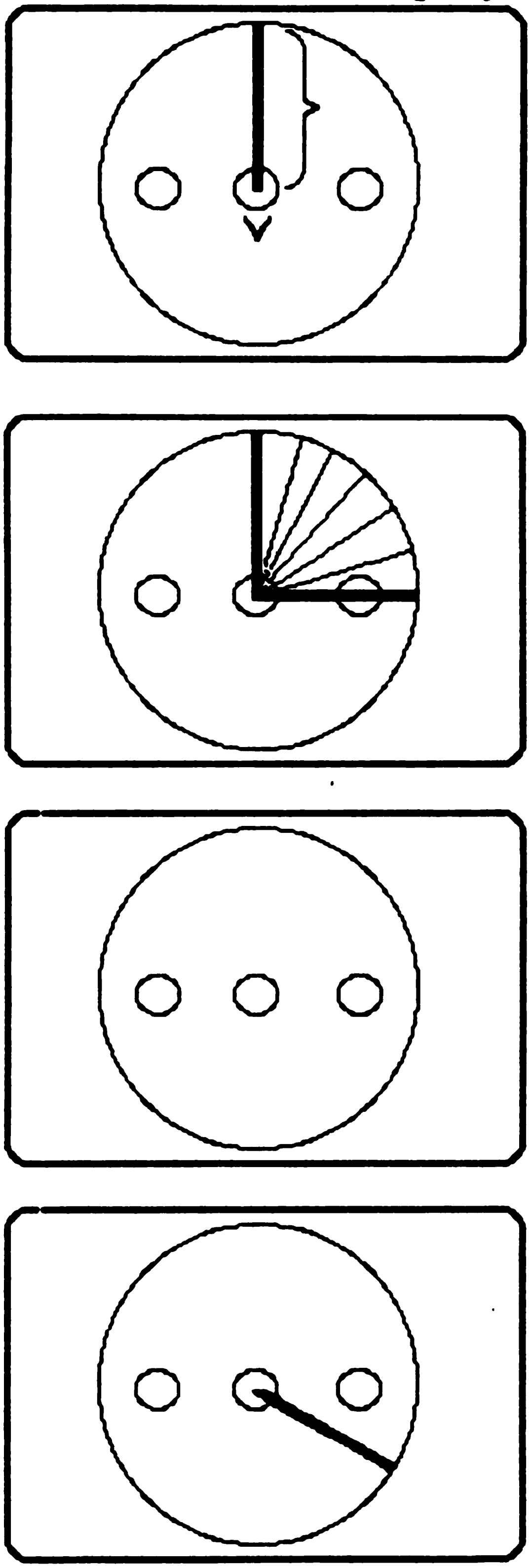
Before participating in this present study, the birds were placed on a continuous reinforcment (CRF) schedule contingent upon a peck to any of the three keys in the chamber. Each bird was run on the CRF schedule until it was pecking approximately 33% of the time to each of the three keys. This was accomplished by decreasing the availability of reinforcement on favored keys until all keys were equally pecked. All five subjects reached this proficiency within five sessions.

Training on the 4:00 condition discrimination was outlined in Figure 2. The stimulus used throughout this experiment was a bar that rotated clockwise. The stimulus parameters followed the description in Figure 7. Typically, the stimulus was always presented in a 12:00 position at the beginning of each trial. After 5 seconds of this presentation, a fixed ratio (FR) 12 on the middle key initiated the movement of the stimulus. This response requirement prior to movement insured that each subject was looking at the screen when movement occurred. The bar stimulus moved in a clockwise fashion at a rate of 90 degrees/second. Seven presentations occurred within a 90 degree change, so that the bar stimulus actually flashed on and off, while moving at approximately 13 degrees per change and at a rate of 1 flash every 150 milliseconds.

The stimulus either continued its movement and stopped, or dissappeared for some amount of time and then reappeared at some location. In either case, the trial ended with a static presentation of the bar stimulus at some location. The ending locations were always either 4:00, 5:00, or 6:00. The times of dissappearance were 0.5 seconds, 0.75 seconds, or 1 second. The ending locations and times of dissappearance were counterbalanced to provide perceptual, imagery and violation trials for each of the three location conditions. (For an illustration, see Figure 8.)

The possibility of obtaining reinforcement was present in all trials. Right responses produced reinforcement in the violation trials and left responses produced

Video Monitor Display | **Procedural Description**



5-second presentation
FR-12 on the middle key
to start the trial

Movement for 1 second

Delay condition
(i.e., 0.5 seconds)

Test Stimulus

Correct response is
left key. Stimulus
remains on until
a response occurs on
the left or right key.

Figure 7. Stimulus parameters and trial progression

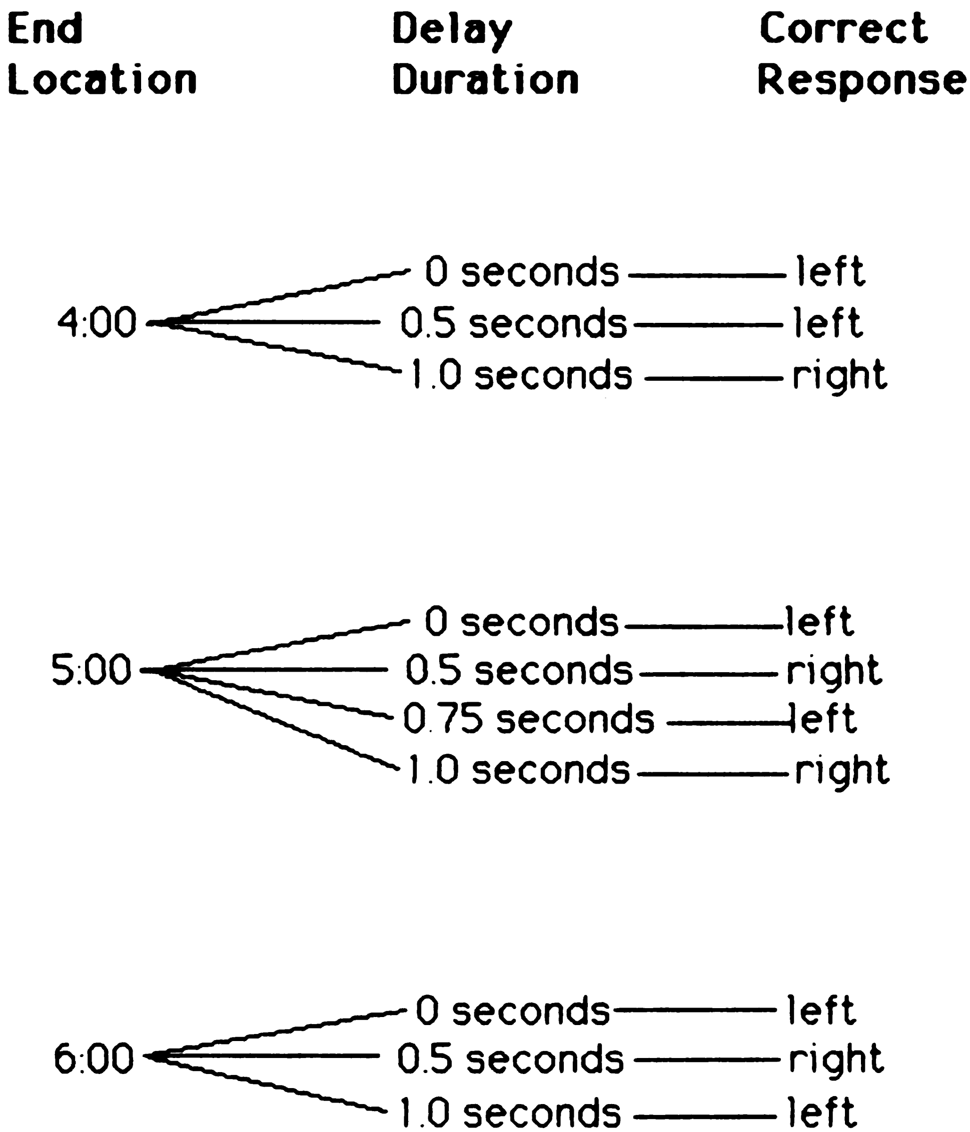


Figure 8. Delay durations and response requirements counterbalanced within conditions.

reinforcement in the perceptual and imagery trials. Reinforcement consisted of three seconds of access to mixed grain in the magazine hopper. Probe trials were also reinforced according to the same contingencies.

The number of exposures to trial types was controlled so that equal numbers of left and right responses were required per session. During 4:00 and 6:00 training, 16 perceptual trials, 16 imagery trials and 32 violation trials were presented each day for a total of 64 trials in which 32 were reinforced for left responses and 32, for right. The types were pseudo-randomly presented with the constraint that no more than 3 of a single type were consecutively repeated.

For sessions with 5:00 probes, only 2 of each of the four 5:00 trial types (perceptual, imagery, violation and violation) were presented within typical training sessions. The frequency of exposures to probes was kept extremely low (less than 5% of the trials per session) so that learning of them would probably not occur. The probes were pseudo-randomly presented within training sessions. Approximately 24 exposures to each 5:00 probe type were presented within 12 sessions of probe testing. Probes were tested in this way twice: once after 4:00 training, and again after 4:00 and 6:00 training.

Correct and incorrect responses for each trial were recorded by the microcomputer, and percent correct scores were calculated for each trial type. Criterion for testing was 2 consecutive training sessions with averages of 80% or better response accuracy across trials.

RESULTS

Transfer

The most basic test of these data is to determine if response accuracy achieved in training transferred to a set of novel probes. Positive transfer is evidenced by accurate responding to ALL 5:00 probe types. To demonstrate maximum or complete transfer, response accuracy to 5:00 probes must be nonsignificantly different from response accuracy to trained 4:00 and/or 6:00 trial types. A further test of transfer is that choice performance is significantly different fom 50% or chance level.

Figures 9a and 9b show average percent correct scores to 5:00 probes after the two training phases (4:00, and 4:00-6:00). Figure 9a shows response accuracy to probes after only 4:00 training. In Figure 9a, response accuracy to two 5:00 probe types is obviously different from response accuracy to the 4:00 trained examples. This accounts for the significant condition effect found by an analysis of variance with repeated measures ($F(1,150) = 10.9074$, $p < .005$, see Table 1). Because of this difference, there was also a significant type effect found by an analysis of variance ($F(2,145) = 22.4792$, $p < .001$, see Table 1). (The subject effects and its interaction effects were nonsignificant in both analyses).

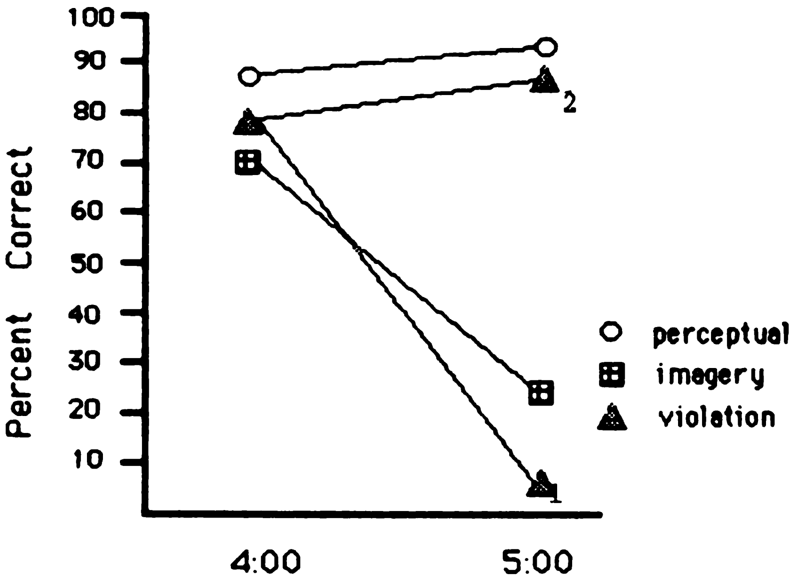


Figure 9a. Response accuracy to probes after 4:00 training.

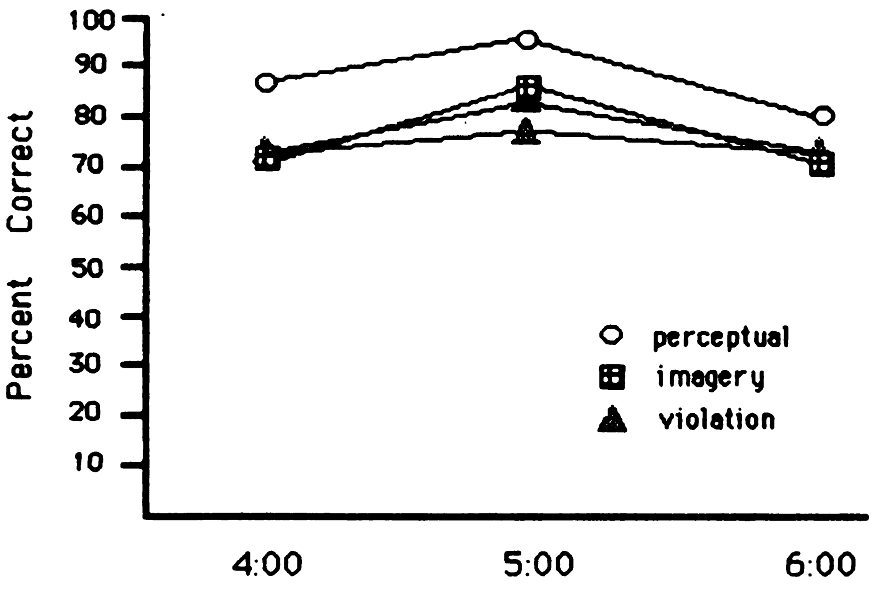


Figure 9b. Response accuracy to probes after 4:00 and 6:00 training.

Table 1.
Analyses of Variance with Repeated Measures.

Two-Way ANOVA: Location Condition X Subject

	SS	df	MS	F	Sig.
4-5	4.592	1	4.592	10.9074	<.005
Subjects	0.452	4	0.113	0.2664	n.s.
Interact	0.924	4	0.231	0.5487	n.s.
Within	63.172	150	0.421		
Total	69.140	159			

Two-Way ANOVA: Type X Subject

	SS	df	MS	F	Sig.
P-I-V	15.151	2	7.5755	22.4792	<.001
Subject	0.452	4	0.113	0.3353	n.s.
Interact	4.672	8	0.584	1.7329	n.s.
Within	48.865	145	0.337		
Total	69.140	159			

Response accuracies to two 5:00 types, the perceptual type and the violation type with a 6:00 delay, did show evidence of transfer because they were not significantly different from response accuracy to trained counterparts when tested by Tukey analysis (perceptual, $q = .01501$, $p > .05$; violation $q = .05678$, $p > .05$). But response accuracy to the 5:00 imagery type and the 5:00 violation type with the 4:00 delay showed no evidence of transfer: they were significantly different from their trained counterparts (imagery, $q = .3649$, $p < .01$; violation, $q = .5136$, $p < .01$). Since response accuracy to two of the four 5:00 probe types was significantly different from accuracy to trained examples, complete positive transfer did not occur here. These data are discussed later in this section to determine why some probes did transfer while others did not.

Figure 9b shows response accuracy to 5:00 probes after 4:00 and 6:00 training. Average response accuracies to 4:00, 5:00 and 6:00 conditions were 73.5%, 82.2%, and 73.7% respectively. By analyses of variance with repeated measures, no significant difference was found between conditions ($F(1,165) = 0.1229$, $p > .05$) or between trial type ($F(2,165) = 2.43668$, $p > .05$). (Additionally, there were nonsignificant subject and nonsignificant interaction effects.) These data meet the criterion of complete transfer, i.e. there was no difference between response accuracy to probes and response accuracy to trained examples (see Table 2).

Table 2.
Analyses of variance with repeated measures.

Two-Way Anova: Location Condition X Subject

	SS	df	MS	F	Sig.
4-5-6	0.174	2	0.087	0.1229	n.s.
Subjects	0.161	4	0.041	0.0594	n.s.
Interact	0.504	8	0.063	0.0890	n.s.
Within	116.765	165	0.707		
Total	117.604	179			

Two-Way ANOVA: Type X Subject

	SS	df	MS	F	Sig.
P-I-V	3.349	2	1.674	2.4367	n.s.
Subject	0.161	4	0.041	0.0597	n.s.
Interact	0.739	8	0.093	0.1354	n.s.
Within	113.355	165	0.687		
Total	117.604	179			

Evidence of transfer is typically defined as response accuracy to probes at better than chance level (> 50%). To further verify the transfer result, a sign test was conducted to test whether the probe data for each bird was significantly better than chance level. Besides supporting the definition of transfer, this test was necessary because the analyses of variance results were not sufficiently meaningful. The variances were quite heterogeneous between probe data and training data because probe data was based on very few exposures and training data was based on a large number of exposures. In the analyses of variance, these large variance differences were virtually ignored. The resulting nonsignificant results which support the hypothesis might be due to large variances which masked differences. The sign test tests each bird's mean percent correct scores across 12 sessions for perceptual, imagery, and violation types against an hypothesized 50% score. The variance problem does not exist because the test does not take into account variance. In order for there to be clear evidence of positive transfer, subjects' scores must be significantly greater than chance level (> 50%). In every case, the birds' percent correct scores were significantly greater than 50% ($p=.031$). The results confirm the interpretation that there was positive transfer to 5:00 probes after 4:00 and 6:00 training.

Strategies

Transfer has been demonstrated and verified in the probe data produced after 4:00 and 6:00 training. The next question is what type of strategy had the birds used which produced accurate responding after 4:00 and 6:00 training? And what strategy were the birds using after 4:00 training which produced the inconsistent results in Figure 9a? A determination of the strategies used requires consideration of specific theories. A detailed review of the response predictions and hypothesized strategies mentioned in the introduction is necessary at this point.

There are three strategies hypothesized: 1)S-R learning, linked with 4:00 training only, and 2) bi-conditional learning strategy and 3)analog transformation of a representation, the latter two linked with 4:00 and 6:00 training. The S-R learning strategy is based on a simple temporal discrimination which can be learned from training of a single example (i.e., 4:00). In 4:00 training, maximum reinforcement can be obtained if birds respond 1) left to trials with no delay (perceptual type), 2)left to trials with a short delay (imagery type), and 3) right to trials with a long delay (violation type). If this temporal discrimination is applied to 5:00 probes, responses to the perceptual type and the violation type with the long delay transfer because the length of delay - response associations still apply (i.e., "no delay - go left, long delay - go right"). However, responding to the

5:00 violation type with the short delay transfers NEGATIVELY, beqause short delay means "go left" in training and short delay indicates "go right" in probe testing. And the 5:00 imagery type carries no association, since the length of delay here is not previously observed in training. The response prediction associated with this strategy is accurate responding to the 5:00 perceptual type and to the 5:00 violation type with the long delay, very low response accuracy to the 5:00 violation type with the short delay, and chance performance to the 5:00 imagery type.

Bi-conditional learning strategy is based on temporal discriminations conditional to location which are learned from two examples (i.e., 4:00 and 6:00). These are still S-R associations, but they are based on two dimensions: time and location. Different length of delay - response associations are used, depending upon the location condition. If a 4:00 trial is presented, birds respond left to no delay, left to a short delay, and right to a long delay. If a 6:00 trial is presented, birds again respond left to no delay, but right to a short delay and left to a long delay. For 5:00 presentations, then, response accuracy remains high only to the 5:00 perceptual type, for which the association "no delay - go left" is still valid. But for the 5:00 imagery and violation types, birds respond at chance level because their learned temporal associations do not apply to the new location condition.

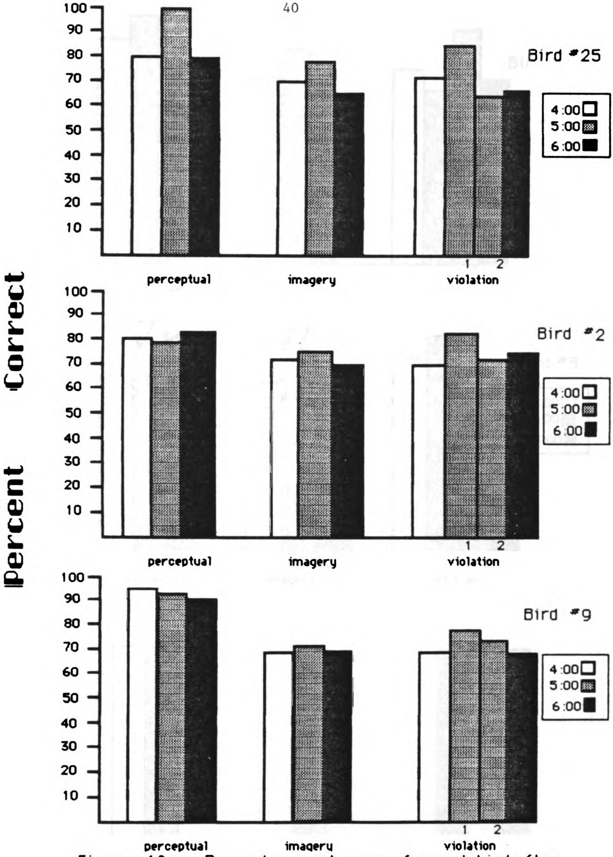
Analog transformation of a representation is based on certain cognitive processes. First pigeons must retain some memory or mental representation of the stimulus in movement. This representation must contain information about length of time of movement relative to stimulus location. This information is encoded in an analog form, for instance, in an image-like form in which the stimulus is actually represented as moving, or by some absolute timing mechanism through which specific "times" are associated with stimulus movement to specific locations. Both the example representational methods involve analog transformations: for each there is a one-to-one correspondence between a physical transformation and a mental representation.

By learning how to respond to 4:00 and 6:00 examples, pigeons mentally represent stimulus movement in some analog form. When 5:00 probes are presented, pigeons can respond to them accurately and immediately because a representation of 5:00 is already retained within analog representations of 4:00 and 6:00.

Besides the analog process of representation, a general cognitive rule is used to determine the choice response. This cognitive rule is as follows: If the stimulus appears at the accurate location given the length of time of movement (plus delay time), choose the left key; but if the stimulus appears at a location which violates continuous stimulus movement, choose the right key. By representing the moving stimulus in some analog form and by applying this cognitive decision rule, pigeons are able to respond to all 5:00 probes as accurately as they respond to 4:00 and 6:00 training examples.

Which of these strategies did pigeons use in different phases of this experiment? Certainly the strategy supported strongly by the probe data after 4:00 and 6:00 training is the analog transformation strategy. Figures 10a-e show birds' percent correct scores to the various trial types after 4:00 and 6:00 training. Figure 10f shows the various predictions made from the two strategies which apply to this type of training. The bi-conditional learning strategy does not explain the accurate 5:00 probe data because the data are significantly higher than 50% (as was demonstrated by the sign test presented earlier). The results confirm the prediction that birds followed the cognitive rule and represented stimulus movement by some analog process in order to solve the problems posed by the probes.

The strategy which best explains the 5:00 probe results after 4:00 training is the S-R learning strategy. Figures 11a-e show birds' percent correct scores to trial types after 4:00 training. Clearly, the 5:00 perceptual and violation type with the 6:00 delay transferred, as was predicted by the S-R learning strategy. And response



Figures 10a-e. Percent correct scores for each bird after 4:00 and 6:00 training.

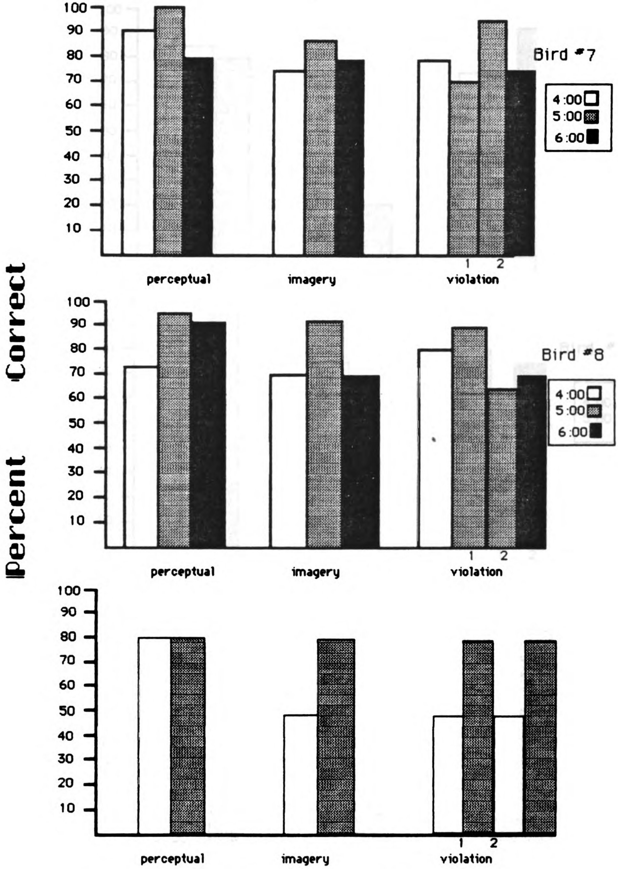


Figure 10f. Response accuracy predictions to 5:00 probes

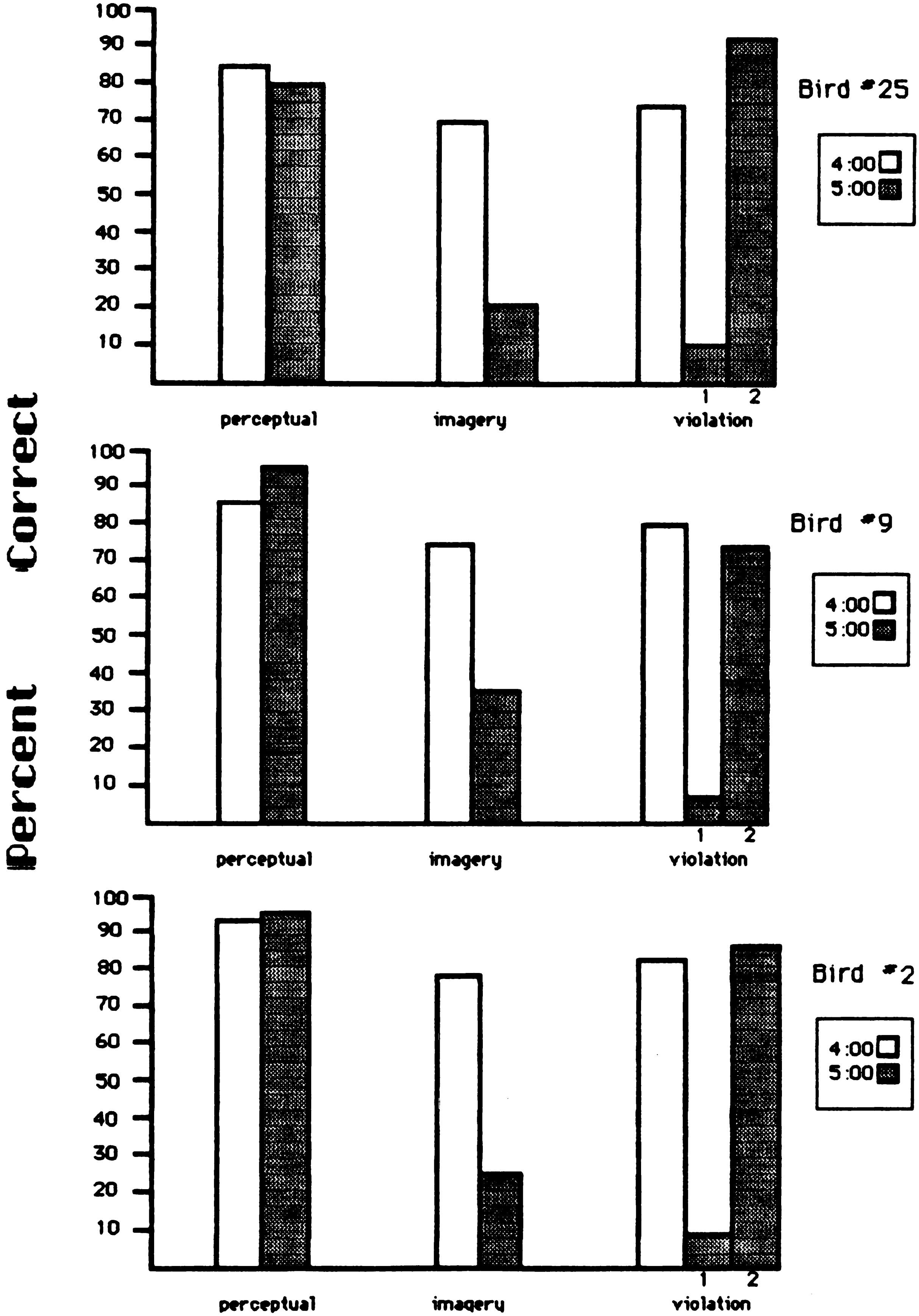


Figure1 1a-e. Percent correct scores per bird after 4:00 training.

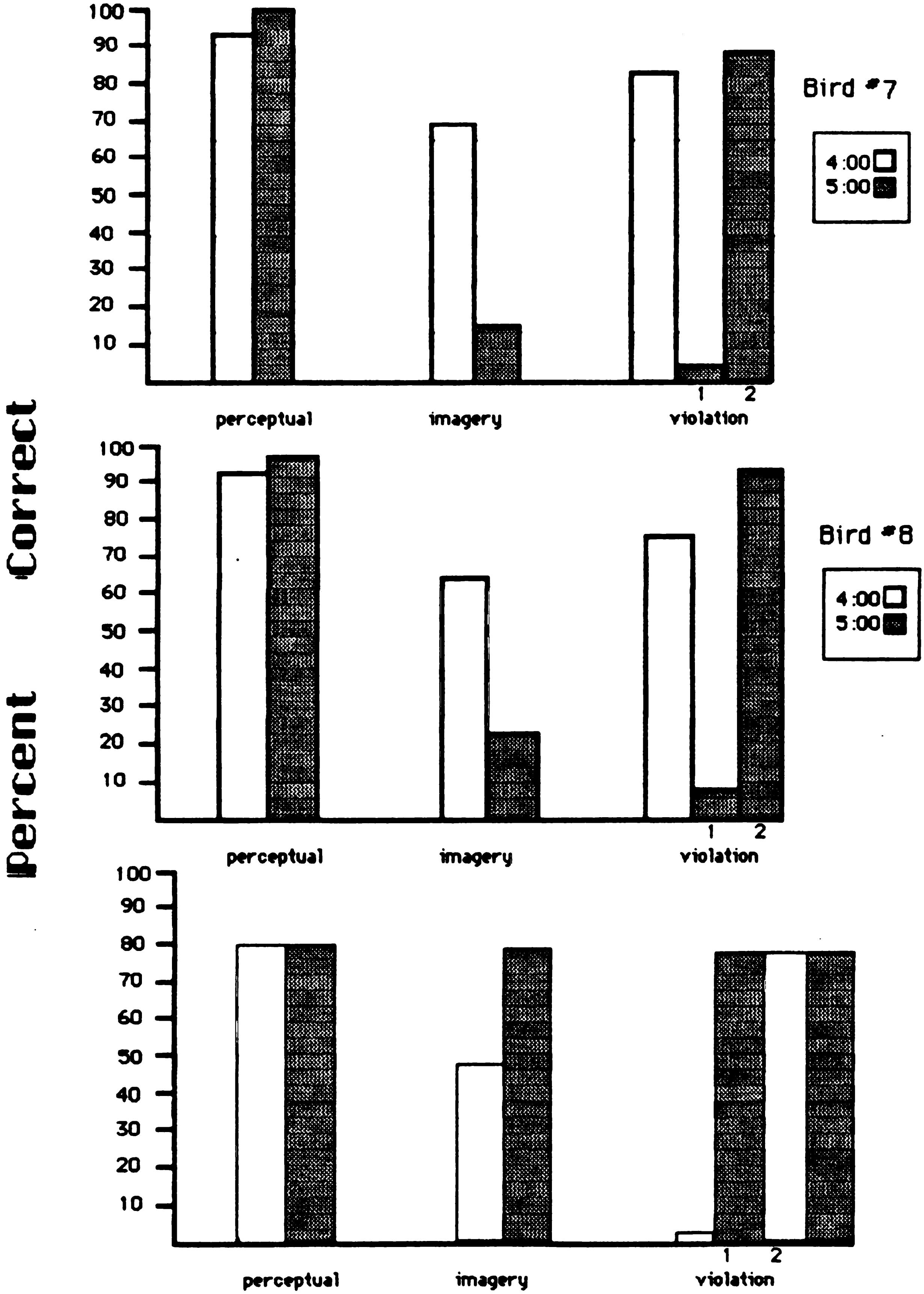


Figure 11f. Response accuracy predictions to 5:00 probes after 4:00 training.

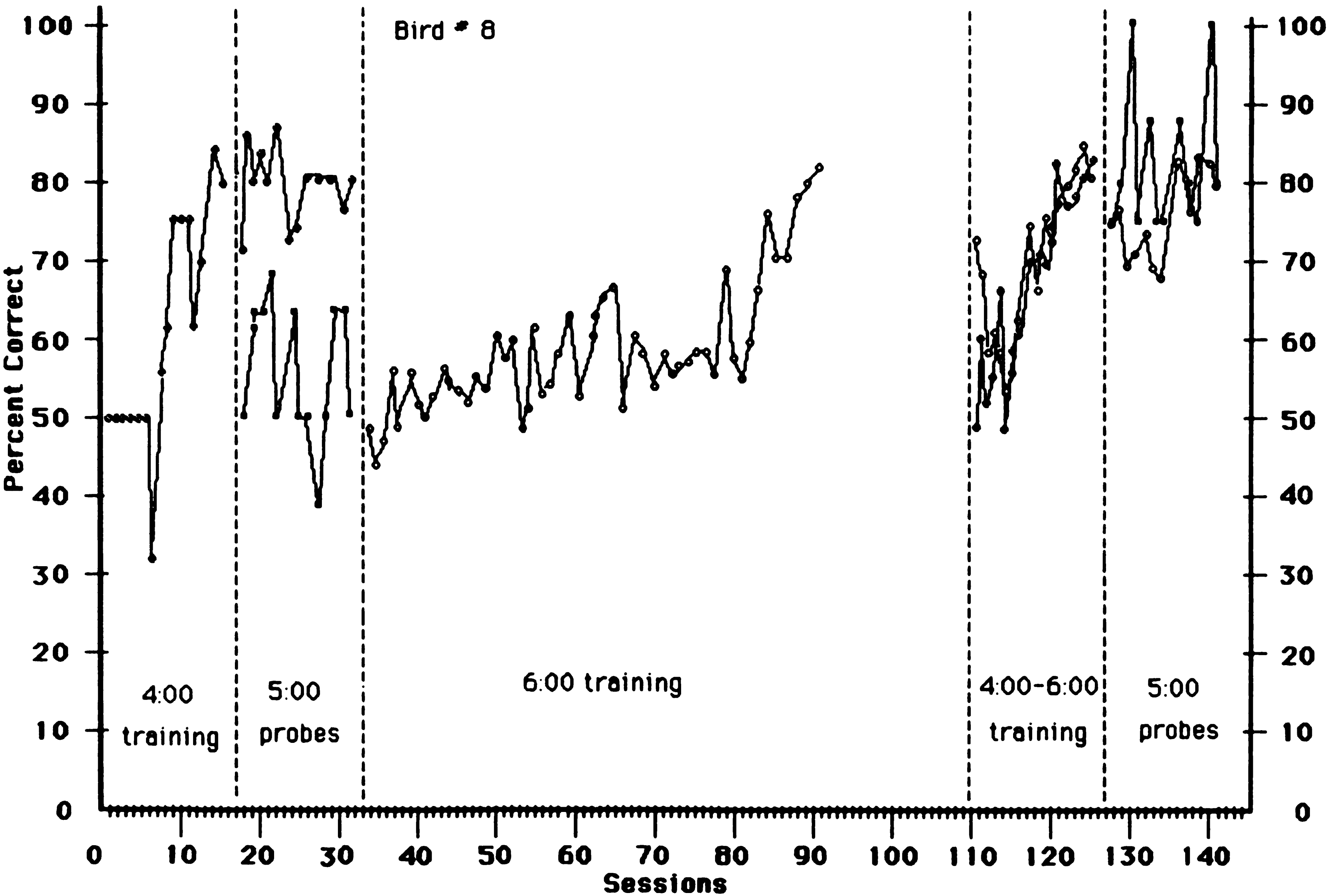
accuracy to the 5:00 imagery and the other 5:00 violation type was obviously at or below chance level in every case. Moreover, the S-R learning strategy predicted that responding to the 5:00 violation type with the 4:00 delay should be near 0%, since the learned association transfers negatively in this case. Indeed, the range of scores for this 5:00 type was between 4 and 13% for all subjects. Figure 11f describes the predictions. The data clearly support the prediction made from S-R learning strategy. The strategy first used after 4:00 training was an S-R strategy. This strategy did not work for both 4:00 and 6:00. Therefore, the birds had to learn a new strategy. The interpretation which best fits the data is that the birds represented stimulus movement in an analog fashion and applied a cognitive decision rule after 4:00 and 6:00 training.

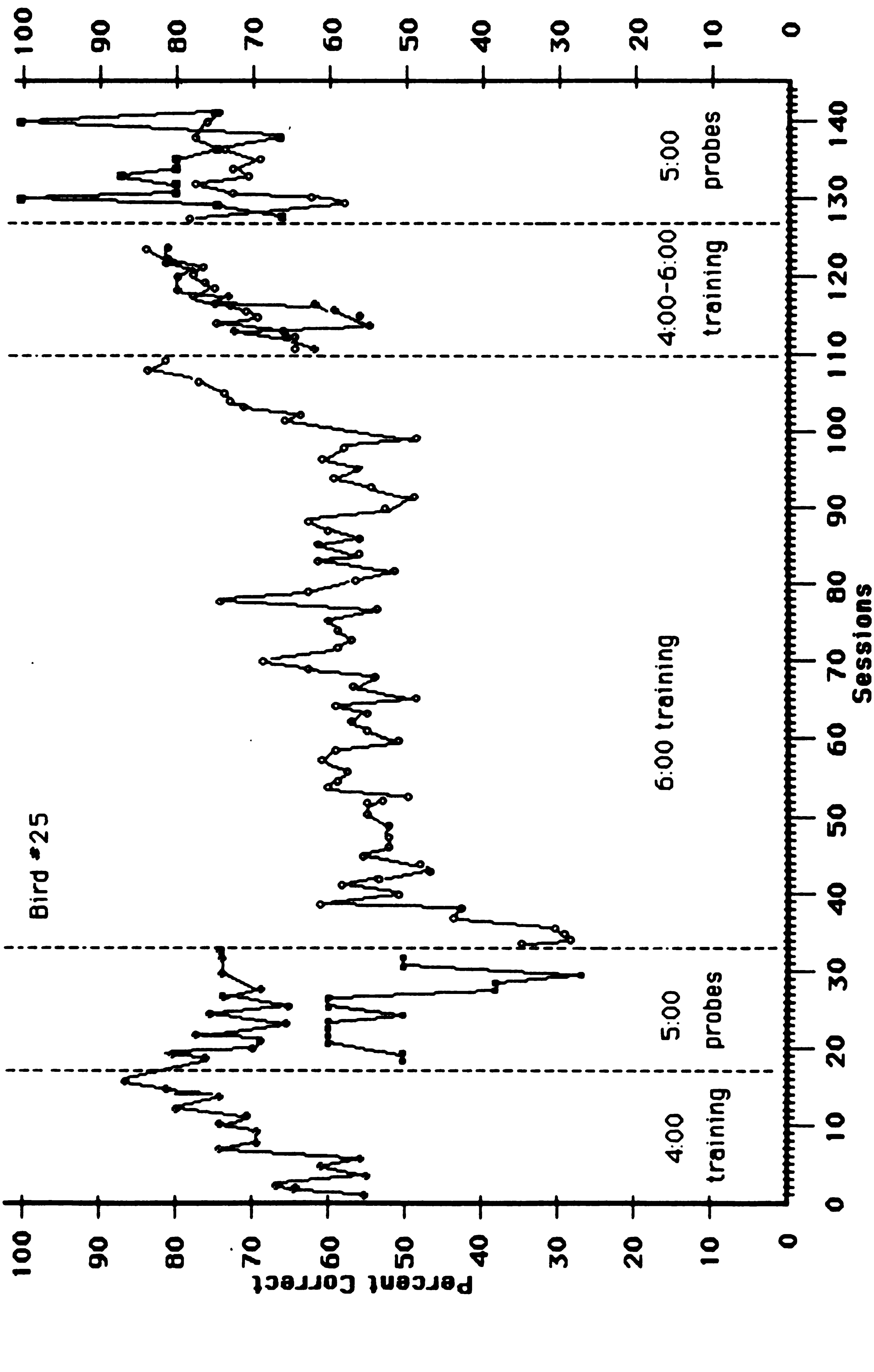
Practice Effect

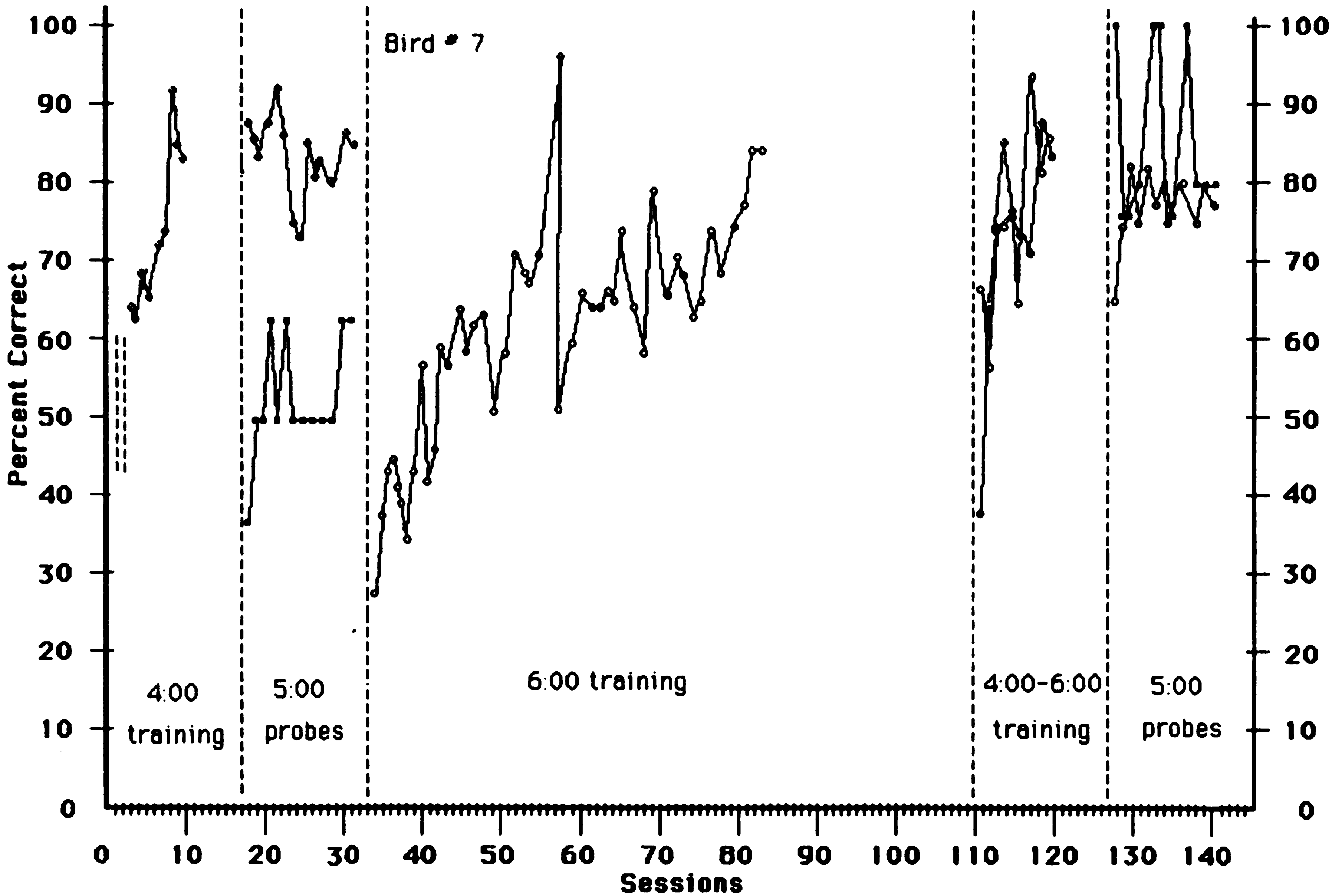
Another question of interest was whether birds performed so much better on 5:00 probes after 4:00 and 6:00 training becuase they had previously been exposed to these probes and had learned how to respond to them by the second test. Figures 12a-e show birds' percent correct scores for each session throughout the experiment. The point of interest is that in the first 5:00 probe phase, the birds consistently responded around chance level without any pattern of increased response accuracy across sessions. In

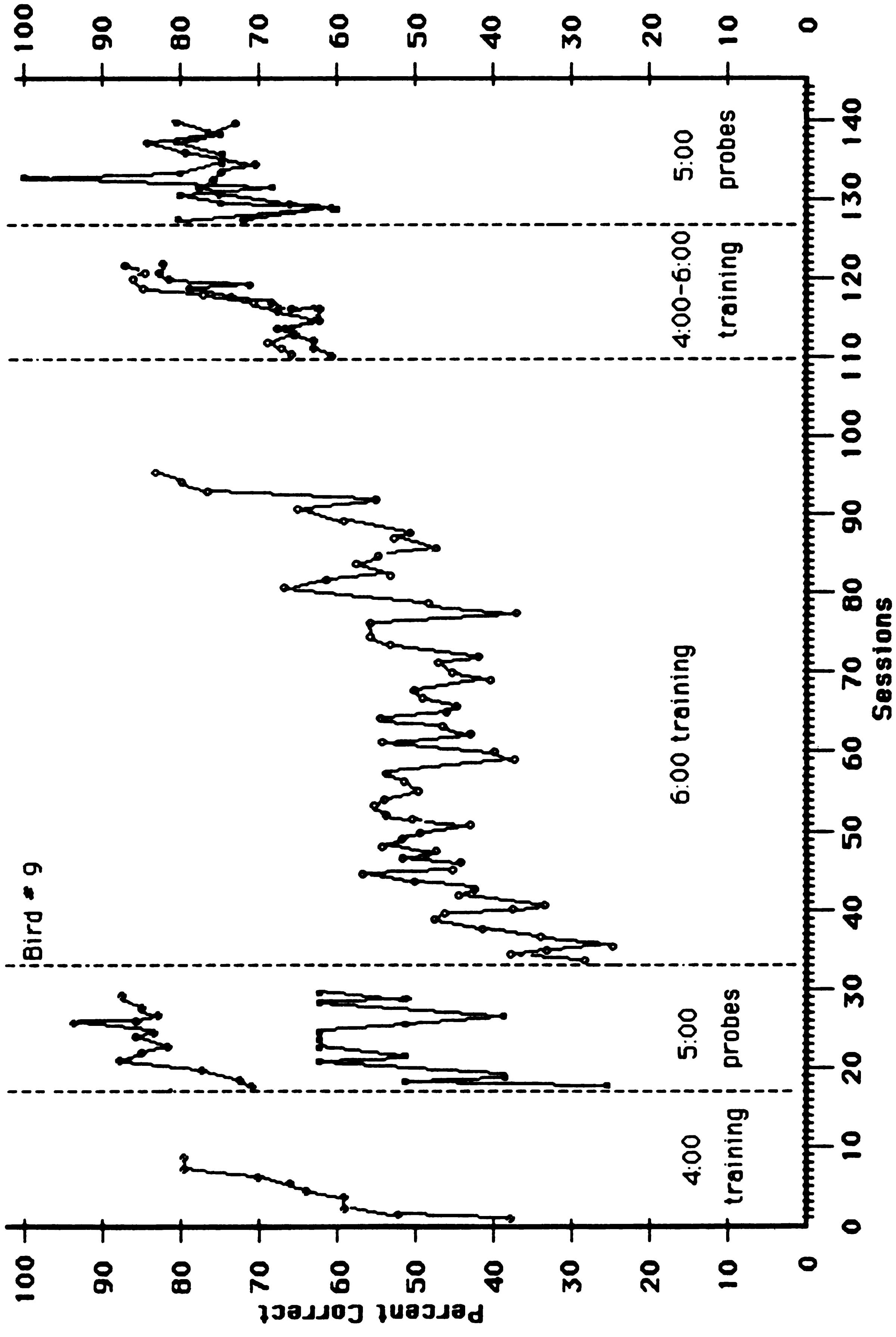
Key	⊘	4:00 training
For	○	6:00 training
Graphs:	■	5:00 probe testing

Figures 12a-e. Percent correct scores for each bird for each session throughout the experiment.

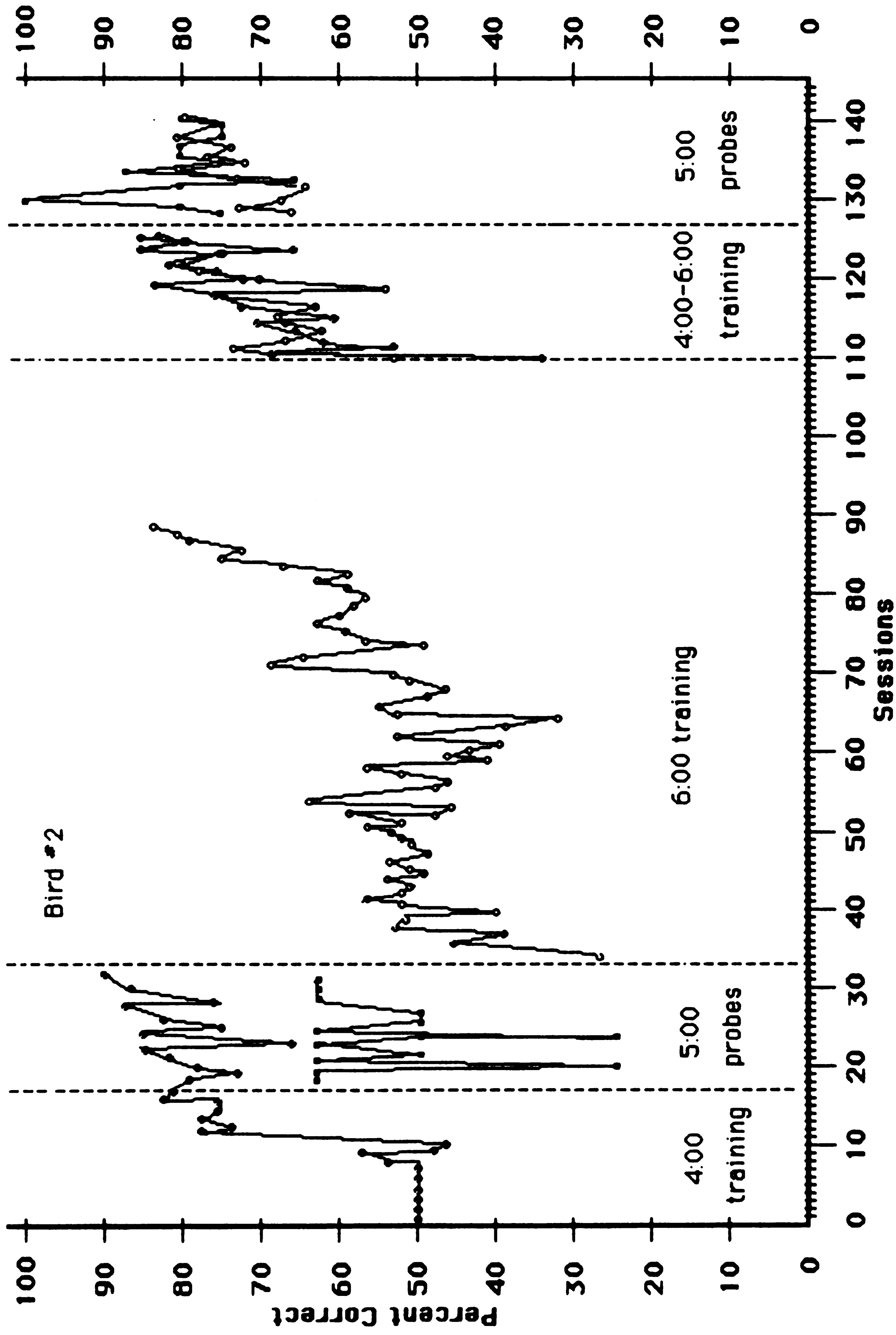

Bird # 8
Percent Correct
Sessions
4:00 training
5:00 probes
6:00 training
4:00-6:00 training
5:00 probes
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140


Bird #25
4:00 training
5:00 probes
6:00 training
4:00-6:00 training
5:00 probes
Sessions
Percent Correct


Bird # 7
Percent Correct
100
90
80
70
60
50
40
30
20
10
0
4:00 training
5:00 probes
6:00 training
4:00-6:00 training
5:00 probes
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Sessions



Bird # 9
4:00 training
5:00 probes
6:00 training
4:00-6:00 training
5:00 probes
Percent Correct
Sessions
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140


Bird #2
Percent Correct
Sessions
4:00
training
5:00
probes
6:00 training
4:00-6:00
training
5:00
probes
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140

the second 5:00 probe phase, birds consistently responded around 80% from the first session of probe testing without any systematic increase in response accuracy across sessions. Two sign tests were run to verify this finding and thereby reject the hypothesis that the birds had "learned" how to respond accurately to probes from practice. The first compared the mean of each subject's first five scores with the mean of its last five scores within the first 5:00 probe test phase. The rationale was that if subjects were improving with practice, there should be a tendency for the last few scores to be consistently higher than the first few scores within a particular probe test phase. The result of this sign test, depicted in Table 3, was that there was no consistent increase or decrease in scores between the first and last five probe sessions. Thus the results of probe testing do not appear attributable to practice.

Table 3.
Sign test of mean percent correct scores per bird to first and last five probe sessions in first probe phase.

Subject	First 5	Last 5	Difference
25	57.5	50.0	+
2	52.5	57.5	-
9	45.0	60.0	-
7	50.0	55.0	-
8	60.0	52.5	+

Nonsignificant Difference (N=5, x=2; p=0.50)

The second sign test compared the first and last five scores per subject during the second probe test phase -- again to determine if there was an increase in scores due to practice. Table 4 shows the nonsignificant results of this test.

Table 4.
Sign test of mean percent correct scores per subject from first and last five sessions of second probe phase.

Subject	First 5	Last 5	Difference
25	80.4	79.4	+
2	80.2	78.0	+
9	72.2	77.0	-
7	86.0	83.0	+
8	83.5	84.5	-

Nonsignificant Difference (N=5, x=3; p=0.80)

The result of the sign tests was that the increase in response accuracy in the second 5:00 probe phase was not simply due to practice, because scores did not consistently increase across sessions in either of the probe test phases.

A final sign test was conducted to demonstrate that scores in the first 5:00 probe phase were significantly different from scores in the second 5:00 probe phase. Response accuracy was significantly different between the two testing phases (p = 0.031).

DISCUSSION

Significance

This study tested pigeons' performance to novel instances after specific types of training. The purpose of the test was to determine whether pigeons can apply analog transformations to represent movement. This purpose was accomplished by a behavioral demonstration of positive transfer to novel probes (5:00) after extensive training of two examples (4:00 and 6:00). The interpretations from the two test phases of this experiment were as follows: 1)after training of a single example, chance level performance to some of the novel probes indicated the use of a simple temporal discrimination, and 2)after training of two examples for which the temporal discrimination no longer applied, highly accurate performance to all novel probes demonstrated the use of some generally applicable cognitive process. No S-R learning strategy accounted for the highly accurate performance to probes; a cognitive process was at work.

The following processes emerged from this study. First, pigeons demonstrated the use of a cognitive process. The results of the final phase of the experiment support the interpretation that pigeons employed a cognitive process in order to respond so accurately. The counterargument, that pigeons used a bi-conditional learning strategy, was not supported by the data since the data were significantly better than 50% for all probe types. The only explanation predictive of the data is that the pigeons acquired some cognitive process by which they could predict stimulus location based on remembrances of speed of motion, time, and location.

Second, pigeons used an analog process in order to respond accurately. By this statement, I adhere to Cooper and Shepard's (1982) definition of an analog process:

> We classify an internal process as the analog of a particular external transformation if and only if the intermediate stages of the internal process have a demonstrable one-to-one relation to intermediate stages of the corresponding external process -- if that process were to take place. (1982, p 13)

The 5:00 example was an intermediate stage of the rotation of the stimulus from 4:00 to 6:00. In training, this intermediate stage never took place in physical form. But, accurate performance to 4:00 and to 6:00 indicated a unique correspondence between choice response and external stage. Consequently, accurate responding to 5:00 probes after 4:00 and 6:00 training indicated a one-to-one correspondence between this physcial intermediate stage and its represented internal intermediate stage.

Note that this does not necessarily mean that pigeons use "imagery", i.e., that they rotated a representation of the stimulus in their heads to represent 4:00, 5:00, or 6:00. To speculate, they could just as easily have started counting when the stimulus moved from 12:00 to its end location. By this method, they retain a true "number" system to represent 4:00 and 6:00 from which they could generate or generalize the representative "number" for 5:00. For example, they might count to "10" in a perceptual 4:00 trial and they might count to "15" in a perceptual 6:00 trial. From this they know that if the stimulus ends at 4:00 and they count to any number other than "10", they respond on the right key, but if they count to "10" and the stimulus stops at 4:00, they respond on the left key. Similar rules apply to 6:00 trials: if the stimulus stops at 6:00 and they count to "15", they respond to the left; if the count to any other number while the stimulus stops at 6:00, they respond to the right. To a novel perceptual or imagery 5:00 probe, they may count to "13". Now they must decide if this "number" is appropriate, given the 5:00 location, and then respond accordingly. This "number" system is not an erroneous suggestion, for there is some evidence that pigeons can count to time objects (Davis & Memmott, 1982).

By using "rotating pictures in the head", or by applying the true "number" system, accurate performance to 5:00 probes results. And, in both cases an analog process is being used. For each, there is a one-to-one correspondence between each physical stage (4:00, 5:00, or 6:00) and its internal stage (i.e., a pictorial representation, or a "number").

Third, pigeons were demonstrated to have behavioral plasticity. That is pigeons behaved appropriately when stimuli of the environment changed. Moreover, pigeons' strategies of response were demonstrated as somewhat plastic in this study. Pigeons used an S-R strategy when training was based on a single simple example and when that strategy produced high levels of reinforcement. Pigeons switched to a cognitive strategy after the S-R strategy no longer produced reinforcement, and after they had been exposed to sufficiently complex training examples. This study demonstrated behavioral plasticity in the pigeon, and more importantly, it tracked the development of the acquisition and use of a cognitive process.

Limitations of Study and Future Directions

This study supported a general cognitive process interpretation, it indicated that an analog process was being used, and it demonstrated some behavioral plasticity. But these general findings lack specific description. What components of the stimulus controlled or cued the cognitive process? What form did the analog process take -- an imagerial form, a unique representative form? How plastic were the demonstrated behaviors? These questions cannot be answered by the present study. Certain experimental manipulations are suggested which test these issues.

Constraints of the Cognitive Process. There are two stimulus dimensions about which information must be encoded in order for the process to work: time and location. Decisions about choice response must be made from information about the duration of the delay as well as about the stimulus location at the beginning and at the end of the trial. Information processed about either of these dimensions may provide the context for responding to probes and for applying the process. For example, it may be that the location of the trained examples must be physically near the location of the probes in order for there to be accurate application of the cognitive process. Or, it may be that, which increasingly longer delays between stimulus movement and final stimulus presentation, application of the analog process deteriorates. In order to determine the context specificity of the process and the limited application of the process, I need to find location and time constraints. Location constraints could be tested by introducing a new probe example, i.e., 7:00, within different training session. Accuracy of response to 7:00 perceptual, imagery and violation proves could be collected within 4:00 training sessions, and within 6:00 training sessions. I hypothesize that within 6:00 training, positive transfer would occur to 7:00 probes, but within 4:00 training, positive transfer would probably not occur. This hypothesis suggests that the cognitive process uses some generalization of time-location which is only accurate if applied in a limited fashion and only to examples physically near those in training.

Another variable which may prove important in the cognitive process is initial placement of the stimulus. In order to test this, the start location of the stimulus can be altered, while the other dimensions of the task remain constant but altered by the same amount. For instance, I could start the stimulus at 1:00, and stop it at 5:00, 6:00 and 7:00. This experiment tests the variability in the process for overall general physical changes (i.e., complete transformation by a few degrees).

Time constraints could be investigated by lengthening the duration of delay within a few probe trials and within a few training trials. This would test the hypothesis that the process is inaccurate if taxed by long delays. In addition, the accuracy of the time component of the cognitive process can be tested by systematically altering the delays already used in training. For example, how much longer must I extend the 0.75-second delay before pigeons treat it as a 1.0-second delay? This test would indicate how generalized or how specific time discriminations are within the cognitive process.

Form of Analog Process. In order to determine if subjects are using visual images to solve a task, cognitive psychologists typically introduce a visual interference task and observe whether performance deteriorates. Such a task is invoked while the remembered stimulus of the primary task is absent, so that the visual nature of the secondary task interferes with the visual-like mental process required to solve the primary task. In the present experiment, an hypothetical imagery process would be used during the delay in which the rotating stimulus is absent. In the delay, subjects using imagery would have to mentally rotate a representation of a stimulus in their heads in order to have an accurate picture of stimulus location at the end of the delay. To interfere with the imagery process, a simple secondary task which requires a visual discrimination could be employed. In theory, performance in the primary task should deteriorate if imagery is being used since the visual system and visual memory are being taxed by a secondary task. In practice, performance of the primary task could deteriorate due to any type of interference, for it is well-established that pigeons' performance changes drastically with small environmental changes (i.e., turning the houselight off in the middle of a task can severely impair performance in the task). The form of the analog process is difficult to discover, because of the critical tie between environmental change and pigeons' performance. A better idea might be to pursue a set of converging operations which point to an analog process, i.e. like representational momentum (Fryde & Finke, 1984) and directional scanning (Finke & Pinker, 1983).

Behavioral Plasticity. Another variable of interest is the changes in response and the strategy shifts caused by changes in the environment. The plasticity, or the general applicability in the face of change, of the cognitive process and the resulting behaviors can be investigated by altering crucial components of the stimulus, like its speed of motion, its direction of motion, the duration of its motion, etc. Variable manipulations mentioned in the constraints section also test the plasticity of behavior in this task.

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