SERIAL LEARNING IN THE PIGEON

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Three pigeons learned to peck four colors in a particular sequence, regardless of how these colors were positioned on four response keys and without feedback following each response. This demonstrates that serial learning is possible in subprimate animals.

Key words: serial learning, chaining, serial position effect, successive chaining, simultaneous chaining, representation, pigeon

Behavior typically occurs in rapid, well-integrated sequences of individual responses (for example, the mating rituals of fish, birds, and other animals, rats running through a maze, and chimpanzees emitting sequences of "words"). Learning theorists (e.g., Guthrie, 1960; Hull, 1943; Skinner, 1938) have argued that such sequences are formed by chaining originally discrete responses. This model of behavior, which derives from Sherrington's (1906) formulation of chains of reflexes, assumes that each response of a chain (except the first) is occasioned by a cue that is produced by the prior response. A few studies (Hunter, 1929; Munn, 1950) have tested this model by making unavailable any external cues following each response. As predicted, performance did not rise above chance.

Chaining models of integrated sequences of responses can be challenged on a number of grounds (e.g., Broadbent, 1961; Lashley, 1951; Miller, Galanter, & Pribram, 1960). Lashley noted that everyday behavioral sequences can occur without step-by-step feedback, as for example, in rapid typing and in speaking sentences. Such examples highlight a classic question in psychology: How does an organism perform a voluntary sequence of responses without step-by-step feedback? The typical "chaining" study does not explore this question since the animal is given step-by-step feedback following each response.

We will refer to the traditional chaining paradigm as a *successive* chaining procedure. In performing a successive chain the subject has only to learn what response to make in the presence of each member of a series of discriminative stimuli. Each response results automatically in the presentation of the next discriminative stimulus.

Chaining in which all of the discriminative stimuli are presented simultaneously and in which there is no step-by-step feedback has received little attention in studies of animal behavior. We will refer to this type of paradigm as *simultaneous* chaining. An example is provided by the temporal maze, an apparatus that consists of two adjacent loops (Hunter, 1913, 1920). Each loop shares a common central path that leads away from the starting point. Subjects are required to make n turns in one direction and m turns in the opposite direction. A significant feature of the temporal maze is the constancy of the cues provided at the choice point. Following a loop, either to the left or to the right, the subject is confronted with the same external stimulus configuration it experienced when it started the loop. In order to perform a sequence in which $n=m=2$ (left, left, right, right) the subject has to remember the direction of the last two responses. Nothing in the external environment changes during the sequence. Thus, whatever stimuli the subject used to perform an alternation must have been generated internally.

In the case of the temporal maze, the nature of internally-generated stimuli that would occasion successful performance cannot be proprioceptive because the same proprioceptive

feedback follows each turn in a particular direction. Hunter was unable to train rats and raccoons to perform successfully in the temporal maze. He nevertheless provided an incisive analysis of what positive results would imply. The production of a response sequence that does not rely on successive feedback implies that the subject has learned a *representation* of that sequence. This is so because it is not possible to appeal to different exteroceptive or proprioceptive stimuli that can cue each successive member of a sequence.

There is an abundance of evidence that humans use representations (Fodor, Bever, & Garrett, 1974; Riley, 1976; Shepard, 1975) and some evidence that other primates can do so in performing sequences of responses (Boren & Devine, 1968; Devine & Jones, 1975; Premack, 1976; Rumbaugh, 1976). However, there is no evidence that lower animals can learn a sequence of responses requiring such representation. It is important to keep in mind that the mere occurrence of a sequence of responses does not imply a representation. Consider a procedure used by Thompson (1970, 1975) in which pigeons were trained to peck at arrays of colors presented on three response keys. During each trial the keys were all of the same color. Four colors were used in different sequences. The color identified the correct key. For example, when the keys were red, the center key was correct; when yellow, the right key was correct, and so on. During each session the pigeons were required to peck the keys in a particular sequence as dictated by the sequence of colors—for example, left, center, right, center. Thus, the color and the position of the correct keys were confounded. The best performance reported by Thompson was on the order of 100 errors in 60 trials. It was not clear, however, how these errors were distributed. But regardless of the accuracy of Thompson's subjects, there is no reason to assume that they learned a sequence of colors. In order to perform correctly it was necessary only to associate different key positions with different colors (e.g., red-center, yellow-right, green-left, and blue-right). Further evidence that the subjects did not learn the correct sequence (as opposed to color-position associations) is provided by the results of Thompson's "tandem" procedure in which the keys were always white. Under this procedure "trials" were demarcated by a diminuation of

the intensity of the light following each peck. Note that the tandem procedure provided no basis for associating a particular response with a particular cue, nor did it provide step-by-step feedback. It was therefore a truly simultaneous procedure that required the subjects to learn a representation of the sequence in order to perform correctly. Performance under the tandem procedure did not exceed chance levels.

The present experiment shows that pigeons can learn a sequence of four stimuli without successive feedback following each response. The task was to peck four simultaneously available colored keys in a particular sequence (green→white→red→blue), regardless of their position in different linear arrays. Performance on this task occurred at a level much greater than chance, suggesting that pigeons can learn a sequence of responses in a manner previously observed only in primates.

METHOD

Subjects

The subjects, three experimentally naive White Carneaux pigeons, were maintained at $80 \pm 3\%$ of their ad libitum body weights throughout the experiment.

Apparatus

The experiment was performed in an operant conditioning chamber containing four response keys, a grain feeder, and a houselight (Ferster & Skinner, 1957). Both the response keys and the opening to the food hopper were centered on one wall of the panel. The response keys were arranged in a row 9.5 cm apart (center to center) from each other and 13.1 cm above the opening to the grain hopper. An exhaust fan served to mask extraneous noises. Standard electromechanical equipment, located in an adjoining room, was used for programming and data recording.

Procedure

Each subject was trained for at least 18 days on the following "final" paradigm. During each trial a different configuration of the colors (green, white, red, and blue) was presented, each color on a different response key. Between trials, the keys were dark, but the houselight remained on. The average duration of the intertrial interval (ITI) was 20 sec. The dis-

tribution of intervals was computed by the procedure specified by Fleshler and Hoffman (1962). Subjects were reinforced with food only after correctly pecking the entire four-color sequence. Repeated pecks to a particular color were not considered incorrect so long as they did not violate the sequence (green→white→red→blue). Thus, the sequence of responses green→white→white→red→blue was correct, but the sequence green→white→white→red→white was incorrect. Incorrect responses resulted in the immediate cessation of the trial and the darkening of the chamber for 20 sec. During these 20-sec time-outs the programmer that determined the ITI duration was stopped. Immediately after each correct sequence of pecks, the food hopper was raised for four sec. Each session was terminated after 128 reinforcements had been earned. Subjects were run daily so long as their weights fell within 80 ± 3% of their ad libitum weights.

Only 15 of the 24 possible linear arrays of green, white, red, and blue were used. However, the number of times each color appeared on each key was uniform. Each color was projected onto the rear of the key by an IEE inline display unit (model 10300). The arrays used were as follows (as presented from left to right on the panel): (G)reen, (W)hite, (R)ed, (B)lue; GWBR; GBRW; GRWB; WGBR; WRGB; RBGW; RWBG; RGWB; RGBW; BRWG; BRGW; BGWR; BWGR. A quasi-random series repeated these configurations in blocks of 30 configurations each.

Initial training was accomplished by successive approximations (cf. Ferster & Skinner, 1957). In training the subjects to perform a sequence of responses, our original assumption was that "backward" training would be more efficient than "forward" training because in backward training the last member of the chain is closest to reinforcement (cf. Hull, 1943; Skinner, 1938). Accordingly, we first trained each subject to peck at blue, the color closest to reinforcement. Subsequently, configurations of red and blue were presented and subjects were required to peck these colors in the sequence (red→blue). However, the subjects persisted in responding first to blue even after 20-25 days of training. For that reason, we shifted to a forward training procedure. First, pecks to green were followed immediately by reinforcement. Subsequently, green and white were presented simulta-

neously (in different configurations) and the sequence (green→white) was reinforced. This procedure was followed until 75% of all trials were responded to correctly. Subjects 31, 64, and 103 took 2, 6, and 3 sessions, respectively, to satisfy this criterion.

Once the green→white sequence was mastered, configurations of green, white, and red were presented. Within 16 sessions, all of the subjects had mastered the (green→white→red) sequence. Subjects 31, 64, and 103 took 8, 16, and 11 sessions, respectively, to satisfy our criterion of correct completion of at least 75% of the trials. Each subject was then presented with a quasi-random series of 15 configurations of all four stimuli.

Prior to the final 18 sessions, each peck to a correct color resulted in an increase in the illumination of that color. The increment in illumination was programmed by eliminating a 100 ohm resistor normally in series with the light source of the color that occasioned the correct response. This procedure, which is analogous to that used by Rumbaugh (1976) in which a chimpanzee was trained to press sequences of lighted buttons, was discontinued because of the ambiguity it creates in interpreting correctly completed sequences. Subjects could learn to restrict their responses to colors whose luminance had not been incremented.

In order to increase accuracy of performance, a correction procedure was also introduced early in training. Under this procedure each trial which occasioned an error was repeated as the next trial. However, even after extensive training, the correction procedure showed no evidence of improving accuracy of performance. A correction procedure also poses problems of interpreting correctly completed sequences: performance on nonrepeated trials must be separated from performance on repeated trials. Accordingly, the correction procedure was dropped. The elimination of the correction procedure and the increment in intensity following correct pecks resulted in the final paradigm described earlier. The history of each subject is shown in Table 1.

Following the 18 sessions on the final paradigm, each subject received six generalization test sessions identical to the final paradigm with the exception that two of the training arrays were replaced by the novel arrays RBWG and GRBW during the first block of three test
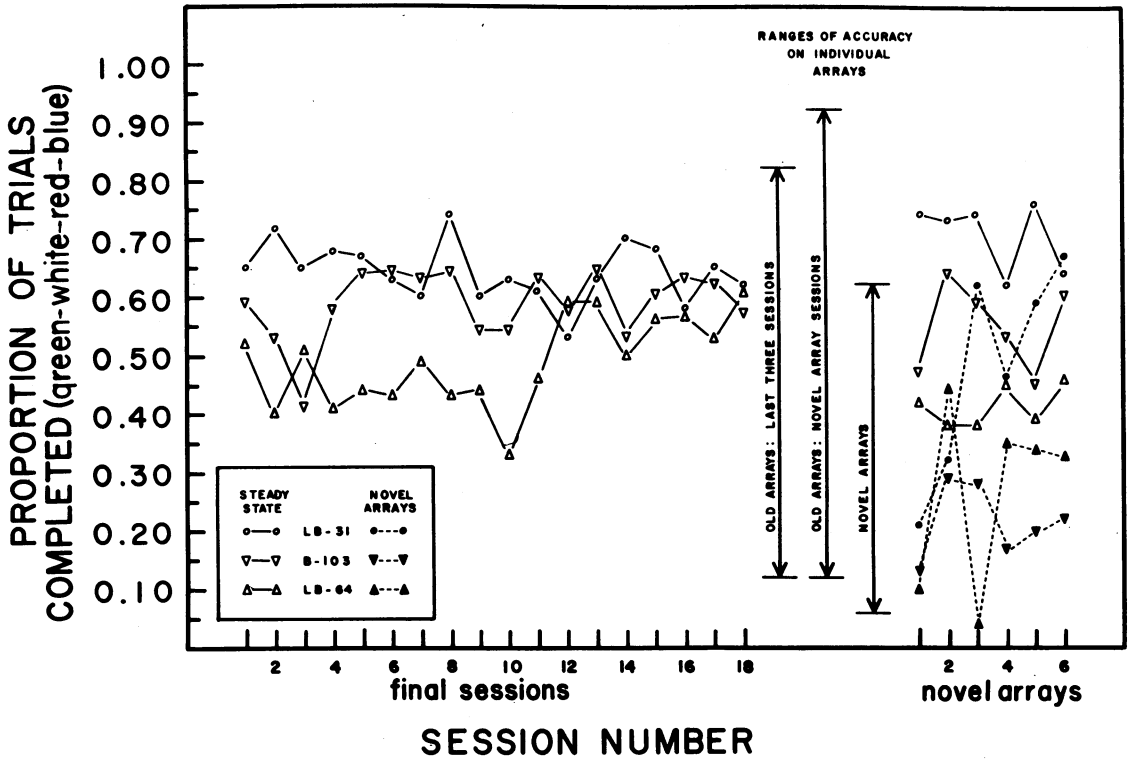
Fig. 1. Left hand panel: proportion of trials (for each subject) completed correctly (pecks in the sequence green →white→red→blue) during final 18 sessions of training. Right hand panel: performance on 13 old and 4 new configurations. Vertical lines indicate ranges of accuracy of performance at the end of training and during the sessions in which novel configurations were presented.

sessions and by the novel arrays BWRG and WBGR during the second block of three test sessions.

RESULTS

All of our subjects learned to peck the sequence, green→white→red→blue, as presented in 15 different arrays, at a level that far exceeded chance performance. The average proportion of trials completed correctly for all subjects during the last 18 sessions of training was .57 (range .36-.77). Figure 1 (left-hand panel) shows the individual functions for all 18 sessions and the ranges of accuracy on individual arrays during the last three sessions. A random choice model predicts correct performance on fewer than 1% of the arrays. This was calculated as follows. The probability of a correct response to the first color = .25. After the first response, repeats to the same color were counted as correct responses. Thus, p(correct response on the second, third, and fourth

colors) = .33. Note that any response technique that guarantees only one peck per color, i.e., pecking in a fixed physical order or not returning to a color that has been pecked,

Table 1

Training History of Each Subject

Subject	Intensity Change		Time out		Correction		Sessions
	Yes	No	Yes	No	Yes	No	
64	X			X		X	20
		X	X			X	19
103	X			X		X	26
	X		X		X		33
	X		X			X	13
		X	X			X	18
31	X			X		X	27
		X		X		X	14
	X			X		X	10
	X		X		X		8
	X		X			X	15
		X	X			X	19

Table 2

Distribution and Latency of Responses at Each Position of the Sequence

Position in sequence	Number of pecks	Green	White	Red	Blue	
Green	1760	.86 (1.51)	.12 (2.32)	.02 (2.98) →	<.01 (0.81) →	Forward Three-Step Errors
White	2311	.34 (0.51)	.54 (0.96)	.12 (1.60)	.01 (2.07) →	Forward Two-Step Errors
Red	2207	.02 (0.95)	.41 (0.38)	.53 (0.94)	.04 (1.40) →	Forward One-Step Errors
Blue	3031	<.01 (0.11)	.01 (0.73)	.63 (0.33)	.36 (0.91)	
		↓ Backward Two-Step	ERRORS ↓ Backward One-Step	↑ Repetitive Responses	↑ Correct Responses	

proportion correct without repeats
.86   .82   .90   .98

Note. Each row represents a specific position in the sequence. Column values refer to the percentage of all responses in a given position made to each color. Numbers in parentheses are the average latencies (in seconds) of each type of response. For example, given a correct peck to green, 54% of responses in the next position (where white is correct) were actually made to white (with an average latency of .96 second), 34% were green repeats, and 12% and 1% were errors made to red and blue respectively.

raises the probability to .04 (1.0 × .25 × .33 × .50 = .042).

In order to obtain a detailed picture of the birds' performance, we calculated the probability and latency of responding at each position of the sequence during the last three sessions of training on the final paradigm. The average values of these measures are shown in Table 2. The data shown in the minor diagonal indicate that the probability of repeat pecks increases as the subject nears the end of the sequence. If one excludes repeat pecks, the probability of a correct response at each step of the sequence ranges from .82 to .98 (see bottom row of Table 2). These data indicate a slight serial position effect; accuracy is lowest in the middle of the sequence.

The function of repeat pecks during the performance of the sequence is unclear. That their frequency increased as the subject progressed through the sequence suggests that they may help the subject find its place in the sequence. This hypothesis was not confirmed by an analysis of the relative frequency of correct and incorrect sequences following repeats. At each step of the sequence there was a slightly *greater* number of *incorrect* responses following a repeat than following a step in which repeats did not occur.

Figure 2 shows the probability of a correct transition at each step of the sequence following repetitive and nonrepetitive responding to the previous color. The probability of correct and incorrect transitions was not influenced by prior repetitive responding.

The frequencies and latencies of errors suggest that forward errors occur because the bird runs through its representation of the sequence, sometimes missing a complete peck. Ninety percent of the errors were "forward" errors to a later color than the correct one (637 in absolute number), while only 10% were "backward" errors (57 in absolute number). Even after correcting for the greater number of opportunities to make forward errors (6 ways of making a forward error as compared with 3 ways of making a backward error), the difference between the two types of error is substantial.

Prior to making a forward error, subjects were often observed (via a video monitor) to peck in the direction of the key showing the
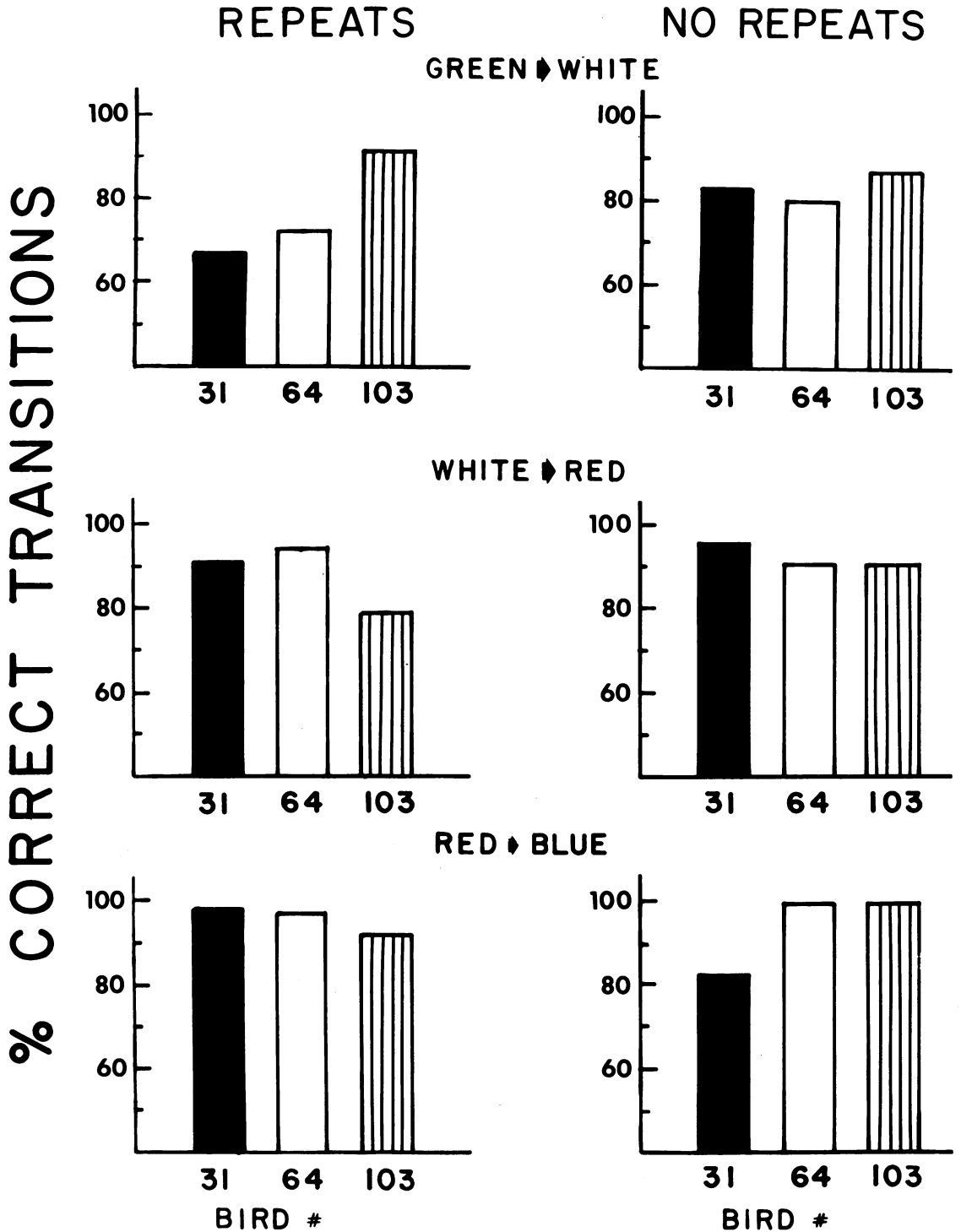
Fig. 2. Probability of correct and incorrect transitions following repetitive and nonrepetitive responding at each step of the sequence.

Table 3

Percentage of Correct Transitions to Each Color on Each Key

Subjects	Key 1				Key 2				Key 3				Key 4			
	G	W	R	B	G	W	R	B	G	W	R	B	G	W	R	B
B-64	84	82	95	97	80	75	97	100	57	73	76	97	84	81	96	98
	x = 89.5%				x = 88.0%				x = 76.2%				x = 89.7%			
B-31	88	71	96	99	93	81	95	100	92	84	90	100	94	79	99	92
	x = 90.0%				x = 92.2%				x = 91.5%				x = 91.0%			
B-103	99	95	96	96	87	99	84	100	81	81	71	96	83	75	81	92
	x = 96.5%				x = 92.5%				x = 82.2%				x = 82.7%			
All Birds	90	82	95	98	86	85	92	100	75	80	78	98	87	78	91	93
	x = 91.0%				x = 91.0%				x = 83.0%				x = 87.0%			

Note. Each value is the average percentage of correct responses made to a particular color on each key.

correct color before pecking the next color of the sequence. This would explain why the relative frequency of forward errors one removed (.08) is considerably greater than the relative frequency of forward errors two removed (.015). Latencies of errors also suggest that pecking was mediated by a representation of the sequence. The latency of forward errors one removed was 1.9 sec, almost twice the average latency of a correct peck (1.00 sec). The latency of two-step forward errors was larger still. This difference would be expected if, in making forward errors, the subjects took time to skip past or "air-peck" the correct color before pecking the incorrect one.

The relatively small number of physical arrays makes it possible that the subjects utilized some systematic physical strategy. This would predict that the different arrays should show the same pattern of relative difficulty across birds. The following analyses revealed, however, no evidence that accuracy of responding was influenced by (a) preferences for pecking particular keys, (b) preferences for pecking particular colors or, (c) the distance (number of keys) traveled in moving from one step to the next.

Table 3 shows the percentage of times that each bird pecked each key correctly as a function of the color of that key. No systematic differences are apparent in accuracy of performance either as a function of the physical position of the key or of the color of the key that defined the correct response. Figure 3 shows the percentage of correct transitions from one color to the next as a function of the physical distance (as measured in response keys) that exists between successive colors in

different arrays. The changes in accuracy, as a function of distance, are small and of different slopes. Overall, it appears reasonable to conclude that distance had no effect on accuracy of responding.

We also analyzed performance on different arrays with the hope of discovering a rule for predicting the difficulty of an array as a function of how the subject had to move from one key to another in completing the sequence. Table 4 lists the arrays with respect to rank order of difficulty for each bird and the correlations of these ranks across birds. The correlations are all nonsignificant. This indicates there was no general sensitivity to the physical arrays. Also shown in Table 4 are the number of times each array required the subject to skip over one or more keys (skips) and the number of times the subject had to change direction (shifts) in completing the sequence. Neither the number of skips nor the number of shifts required by an array influenced the accuracy of performance to that array.

The lack of a correlation in the rank orders of array difficulty between birds leaves open the possibility that individual birds were utilizing different kinds of physical strategies. However, we could not detect any systematic patterns. Furthermore, no obvious systematic patterns of adjacent colors characterized the individual bird's performance (cf. Table 4).

The data shown in the right-hand portion of Figure 1 show that knowledge of the sequence did generalize from the original training set of 15 arrays to the new configurations. The proportion of new-array trials completed correctly was .32, again significantly greater than chance. Of the 385 novel configuration
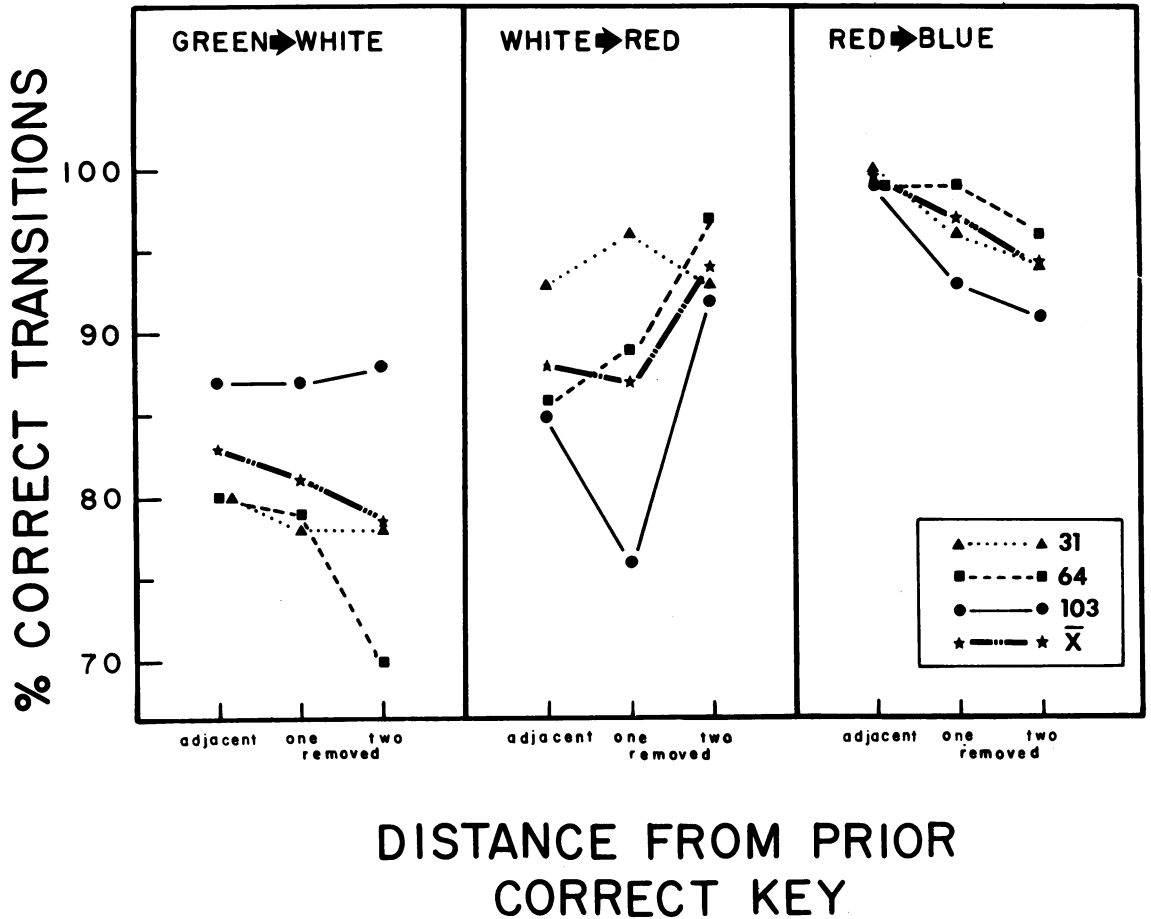
Fig. 3. Percentage of correct transitions as a function of physical distance from the previous color.

trials presented during the test sessions, 122 were responded to correctly. Accuracy of performance on the four new configurations was as follows: GRBW, 28%; WBGR, 21%; BWRG, 35%; RBWG, 41%. It is of interest to note that the accuracy of responding on the new configurations (32%) was lower than the accuracy of performance on the original configurations (55%). Within each session, accuracy of performance on each configuration ranged between 12% and 100%.

The difference in performance on the old and new configurations can be attributed to a number of factors. The new configurations could have been more difficult than the old configurations. Also, the subjects could have discriminated the new configurations as different. At present we cannot test the validity of either interpretation. Our data on array dif-

ficulty indicated that there is no *a priori* method of specifying the relative difficulty of each configuration. As described earlier, subjects' rankings on each configuration (by accuracy of performance) were not correlated, nor was there any discernible pattern within the rankings that would provide a rule for predicting difficulty.

DISCUSSION

The birds' ability to peck sequences correctly, their capacity to generalize to new configurations, the pattern of latencies and errors —all indicate that the birds abstracted the correct sequence of colors. In concluding that our subjects learned a representation of the sequence (green→white→red→blue), we are simply noting that no external cues were available

Table 4

Rank Order of Arrays (re. percent Correct) and the Number of Skips and Shifts of Direction within Each Array

B-31	%	skip	shift	B-64	%	skip	shift	B-103	%	skip	shift
				TRAINING ARRAYS							
BRWG	82	0	0	GWBR	77	1	1	RGBW	82	4	2
GWBR	81	1	1	WRGB	75	2	2	GWBR	76	1	1
RGWB	78	3	2	RGWB	74	3	2	RGWB	72	3	2
GBRW	77	2	1	RGBW	67	4	2	WRGB	71	2	1
RWBG	71	2	1	GRWB	58	2	2	GBRW	70	2	1
BWGR	71	2	1	WBRG	54	3	2	GRWB	69	2	2
RGBW	69	4	2	BRGW	52	1	1	GWRB	66	0	0
RBGW	66	2	2	BRWG	51	0	0	RWBG	60	2	1
WBRG	64	3	2	RWBG	51	2	1	BGWR	56	2	1
GRWB	58	2	2	BGWR	49	2	1	BWGR	54	3	2
BGWR	57	2	1	GWRB	47	0	0	WGBR	51	2	2
BRGW	56	1	1	RBGW	44	2	2	WBRG	51	3	2
WRGB	50	2	1	BWGR	28	3	2	BRWG	42	0	0
GWRB	45	0	0	GBRW	12	2	1	BRGW	40	1	1
				NOVEL ARRAYS							
RBWG\	62	1	1	RBWG	41	1	1	WBGR	36	4	2
GRBW	55	3	2	BWRG	27	2	2	BWRG	23	2	2
BWRG	53	2	2	GRBW	19	3	2	RBWG	19	1	1
WBGR	23	4	2	WBGR	06	4	2	GRBW	08	3	2

r31 · 64 = .069
r31 · 103 = .052
r64 · 103 = .334

to guide the subject through the sequence. The subjects appear to have learned the rule: "Peck green; having done so, peck white; having done so, peck red; having done, so, peck blue" without the aid of any physical changes in the array or any change in the external environment.

The form of the representation of this rule cannot, of course, be specified. It is doubtful, however, that proprioceptive feedback following each peck could mediate this sequence. Each color appeared on each key equally often. Thus, there is no basis for postulating different kinds of proprioceptive feedback following correct and incorrect responses or, for that matter, following correct responses to different keys or different colors. We can also reject the hypothesis that each color could be a "chain" stimulus for the next response. All of the colors were available simultaneously, and their position varied across different trials. Thus, any information regarding which color to peck next must have been generated by the pigeon. The basis of the pigeon's choice of each color of the sequence is what we refer to as a representation.

Why Mediating Responses Fail as an Explanation of Performance on Simultaneous Chains

Sequential behavior is often explained by reference to mediating behavior not explicitly required by the experimenter's contingency, e.g., Blough's (1959) analysis of delayed matching-to-sample performance. In our situation, however, the postulation of mediating behavior fails for two reasons: lack of evidence and the tautological nature of such an explanation. Having watched our subjects perform the sequence (by a closed circuit video camera), we saw nothing that suggested a differential response to each stimulus (such as approaching green from one angle, white from another, and so on). As mentioned earlier, the physical requirement for each response was the same. Accordingly, we will have to turn to more subtle overt responses or to covert responses as mediators of sequential performance.

Suppose the bird stood on its left leg when pecking green, closed one eye when pecking white, and stood on its right leg when pecking

red. At the covert level, the pigeon could twitch its neck while pecking green, its right side while pecking white, and its left side while pecking red. On this view, pecking green gives rise to a distinct proprioceptive cue either from an overt or covert response. That cue becomes the occasion for pecking white. Since the feedback provided for the pigeon from standing on its left leg or from twitching its neck is unique to pecking green, it would seem that such feedback could, in principle, serve as a cue for pecking white, the next stimulus of the sequence.

There are two reasons to question this type of explanation. One is the lack of any evidence that a pigeon might develop such behaviors without explicit training. It also seems doubtful that explicit training could produce such an outcome. Even if one were willing to accept this argument, an argument that cannot be verified empirically, it poses another problem. The argument that the stimulus complex consisting of the green light and stepping on the left leg functions as a discriminative stimulus for pecking white does not define the response "peck white." Pecking white can mean pecking *any* of the keys. Arguing that the response is "looking for white" does not suffice. Looking for white is what has to be explained. Postulating that this is what the bird is doing is begging the question.

The Significance of Correct Responses of Short Latency

Another weakness of a chaining explanation of the sequential behavior we established is empirical. Certain successive responses followed each other too quickly for self-generated feedback. As Lashley (1951) has argued, if the time between successive responses is faster than the fastest reaction time, then the sequence is a manifestation of an integrated "program" of responses. The modal time for repeats in the present experiment (380 msec) provides a good estimate of the fastest interpeck time on a single key in the absence of a stimulus discrimination. The critical question is, what is the latency of correct pecks to different keys with no intervening repeats? For the last three sessions the mean latency of this class of pecks was 970 msec. Seven percent of those pecks (145 in absolute number) had latencies of 380 msec *or less*. Only .8 percent of the latencies of incorrect responses (6
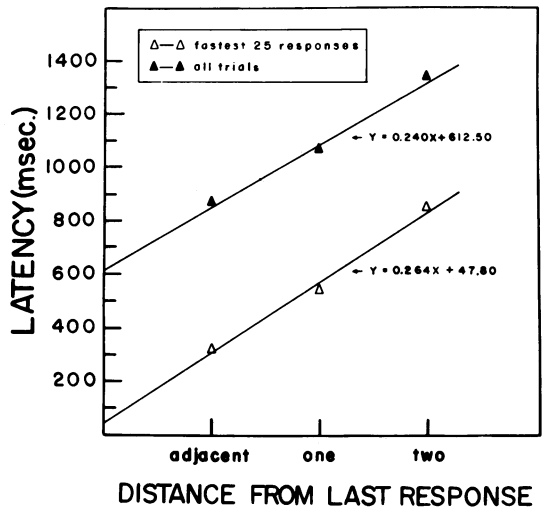

Fig. 4. Upper function: average latency of correct responses as a function of proximity to the last color responded to correctly (adjacent key, one or two keys distant). Lower function: same for fastest 25 responses.

in absolute number) had latencies of 380 msec or less. Thus, correct responses with fast latencies can be considered a subset of the distribution of correct responses. They support the conclusion that, in some instances, the birds were executing sequences of responses that could not be guided by step-by-step feedback.

An independent way to demonstrate the existence of integrated subunits of the response sequence is to separate two components of response latency: travel time and decision time. This can be done by comparing the latencies of pecks which involve different physical distances between successive keys of the sequence. Figure 4 shows the average latency of correct responses when they occurred on an immediately adjacent key, on a key one removed, and on a key two removed. An analysis of these latencies with respect to the direction in which the pigeon had to move showed no differences between latencies of responses producing a shift to the left and latencies of responses producing a shift to the right. Accordingly, data from both kinds of shifts were combined.

The orderly increase in latency as a function of physical distance provides a good basis for estimating the amount of time needed to move from one key to another. The value of the slope of this function (travel time) is

240 msec/key. This is in good agreement with the modal time for repeat pecks (380 msec). An estimate of theoretical decision time including the time needed to execute the peck is provided by the value of the y-intercept (613 msec). The lower line in Figure 4 represents the same function for the 25 fastest responses in the last three sessions at each physical distance. Its slope is 264 msec/key. The y-intercept for these fast responses is 47.8 msec. This appears to be the fastest possible physical movement. In these cases there is clearly not enough time for the previous response to function as a cue for making the next response. Thus, short latency responses appear to be a manifestation of a representation.

Hypothesizing that the bird relies on a representation of the stimuli in order to perform the sequence does not imply that it has a representation of the entire sequence. It could adopt a set of conditional rules such as "having just pecked green, peck white; having just pecked white, peck red; and, having just pecked red, peck blue." On this view the bird has learned $S_G \rightarrow S_W$; $S_W \rightarrow S_R$; and $S_R \rightarrow S_B$; but not necessarily $S_G \rightarrow S_W \rightarrow S_R \rightarrow S_B$. Postulating a representation of the sequence or a "cognitive chain" is not tantamount to saying that the subject represents the sequence as a whole. It is, however, saying that the subject goes from one step to the next without the guidance of mediating responses.

Implications for Interpretations
of Sequential Performance
of Higher Organisms

The present demonstration of serial learning in the pigeon raises a great many questions —about pigeons in particular and sequence learning in general. It suggests that the ability of nonhuman primates to learn sequences (Premack, 1976; Rumbaugh, 1976) is shared by simpler organisms. Undoubtedly, a chimpanzee and other primates can learn arbitrary sequences of greater complexity and variety than those learned by a pigeon. It is also likely that primates would learn such sequences more rapidly. However, in evaluating a chimpanzee's performance when it "writes a sentence" of plastic chips or "lexigrams," it is important to consider whether those sequences are merely rote chains of responses in the service of an incentive.

Consider, for example, the following four-word "sentences" of two subjects of independent studies of the linguistic ability of chimpanzees: *Mary give Sarah apple* (cf. Premack, 1976) and, *Please machine give apple* (cf. Rumbaugh, 1976). These stock sentences can be characterized as ABCX sequences where X is the name of an incentive (apple, coke, chocolate, and so on). It has yet to be shown that pigeons can master ABCX problems (where X1 might be one type of grain, X2 a different type of grain, X3 water, X4 the opportunity to see or to attack another pigeon, and so on). If a pigeon can learn such sequences (a not unlikely outcome), one wonders what is to be gained by assigning "names" to each member of the sequence—for example, referring to the sequence green, white, red, blue, as *Trainer give 31 grain*. To conclude that a chimpanzee has produced a sequence of words as opposed to nonsense symbols, it is necessary, at the very least, to demonstrate that it understands the meaning of *each* word of the sequence and the nature of the relationships between different words (cf. Terrace, 1979).

Other aspects of our results are tantalizingly similar to those observed in studies of verbally mediated responses in humans. For example, the relationship between accuracy of responding and position in the chain (cf. the last row of Table 2) is similar to the serial-position functions obtained in human list learning (Glanzer, 1972; Slamecka, 1972). By studying how animals other than primates learn complex sequences it may be possible to explore biological and structural universals that govern the formation of complex behavior in animals and humans.

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