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STIMULUS STRINGING BY PIGEONS

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Pigeons were trained to peck one, two, three, and then four colors in a predetermined sequence from a five-key array where, over trials, each color appeared equally often in each position of the array. Incorrect pecks resulted in a buzzer and trial termination, with the same array presented for the next trial. Correct pecks produced feedback and correct strings could produce food. All subjects performed at a high level of accuracy with no difference at asymptote between a continuous and a mixed spectral sequence as the required order. Transfer to a new set of arrays had little effect on accuracy. Errors forward in the sequence had the highest probability, followed by repeat errors, backward errors, and dark-key errors. Some arrays had a higher level of accuracy than others but a corresponding systematic variable could not be identified.

Key words: discrimination learning, serial learning, stimulus strings, key peck, pigeons

Serial learning, long a major topic for research with human subjects, has been relatively neglected in animal research where emphasis has been on simpler paradigms. However, it is clear that animals can learn serial tasks as demonstrated by Olton (1978) using the radial-arm maze and Hulse (1978) using successive trials in a straight runway. Response-sequence learning has been shown in pigeons (Thompson, 1970, 1971) and in monkeys (Boren & Devine, 1968; Hursh, 1977; Sidman & Rosenberger, 1967). Recently a more complex and general task was used by Straub, Seidenberg, Bever, and Terrace (1979) using pigeons as subjects and key colors as the serial elements. Straub et al. pointed out the similarity between their procedure and the procedures used to study language-like behavior in nonhuman primates (e.g., Premack, 1976; Rumbaugh, 1977). Indeed the language-like behavior of nonhuman primates may be the most remarkable demonstration of serial learning by animals.

The present study used a paradigm similar to that of Rumbaugh (1977) and Straub et al. (1979) to study serial learning in pigeons, a paradigm we call stimulus stringing. The purpose of the study was to provide a description of acquisition and stable-state behavior under the stimulus-stringing paradigm.

The stimulus-stringing task requires the subject to peck key stimuli in a given sequence from a set of simultaneously presented stimuli. Stimuli pecked within a trial are referred to as a stimulus string, and the behavior is called stimulus stringing behavior. A given stimulus string is correct or incorrect depending on whether it accords with the stimulus sequence designated as correct.

METHOD

Subjects

Seven racing homing pigeons, experimentally naive at the beginning of the study, were maintained at approximately 75% of their free-feeding weights.

Apparatus

The two test chambers had inside dimensions of 53 cm long, 35 cm wide, and 37 cm high. A 75-dB (re 20 μ N/m^2) white noise was continuously present and a fan provided ventilation.

A jewelled houselight was centered on one wall three cm from the ceiling. Opposite it was an aluminum test panel (see Figure 1). It had a row of five circular openings 22 cm

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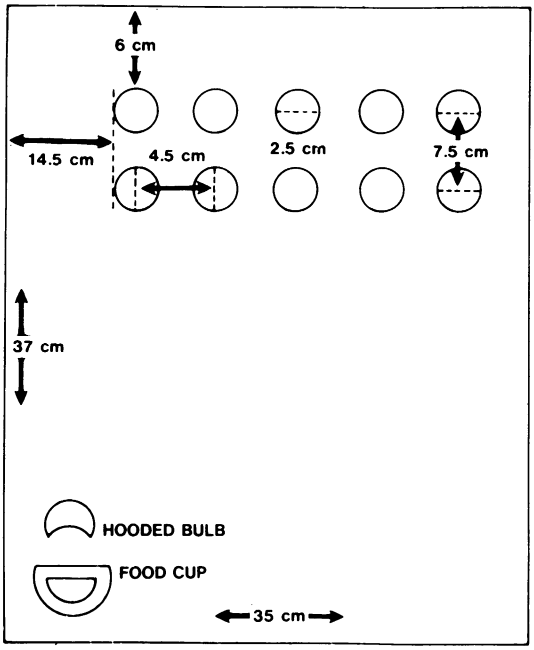

Fig. 1. Schematic drawing of the test panel.

above the floor, the key displays, where pecks were recorded. An identical row of five circular stimulus windows above the keys presented feedback.

Industrial Electronics Engineers series-10 in-line display cells containing four Kodak wratten filters (#65, #74, #99, #73) with peak transmission values of 501, 538, 555, and 576 nm were located behind each key and stimulus window. Each color could be off or at full intensity (6.3V). In addition, the keys could be illuminated at a lower intensity (initially 4V then 5V starting with Session 33). Transparent Lexan paddles in front of key displays were operated by a static force of 5 to 25 g (.05 to .25 N) through an excursion of .5 to 1.0 mm.

A Scientific-Prototype food cup on the test panel could be illuminated when food (45-mg Noyes pigeon pellet) was delivered.

An Interdata-732 computer controlled the experimental task and data collection.

Procedure

At the beginning of each trial during the final condition, four dimly lit colors (A, B, C, and D) and a dark key were presented in random positions on the keys. One peck at each of A, B, C, and D in that order was a correct string. Each correct peck produced an increase in brightness of the pecked key and presentation of a matching color in the leftmost unoccupied stimulus window. A correct string was followed by a primary or conditioned reinforcer and termination of the trial. Incorrect pecks (e.g., D after A, B) were followed by a buzzer and trial termination. The experimental task, then, was to peck in a predetermined sequence all colors presented on the keys.

The number of colors presented and thus to be placed in order varied from one to four and defined the problems, e.g., a three-stimulus problem had three colors presented on the keys. The different color arrangements on the five keys are called arrays; the number of possible arrays for an N-stimulus problem is 5!/(5-N)!. Five arrays were presented for the one-stimulus problem and 10 for all other problems, except for transfer tests which used a second set of 10 arrays. Sets of 10 arrays were chosen such that color and key were not confounded (see Table 1) in randomized blocks of 20 trials, each array occurring twice in each block. The number of dark keys in an array was five minus the number of colors.

The correct order of colors was a continuous spectral sequence of 501, 538, 555, and 576 nm for Chamber A (Group A, Subjects 201, 203, 205, and 207) and a mixed spectral sequence of 555, 501, 576, and 538 nm for Chamber B (Group B, Subjects 202, 206, and 208).

After adaptation to the chamber and magazine training, subjects were trained to peck one color by the method of successive approximation (501 nm for Group A, 555 nm for Group B), a one-stimulus problem. Other

Table 1

Arrays Used for the Four-Stimulus Problem

Array #	*Array Set 1*	*Array Set 2*
1	A C D B -	C A B D -
2	D B A - C	B D C - A
3	C - D A B	A - B C D
4	B D - C A	D B - A C
5	- A C D B	- C A B D
6	A C B D -	C A D B -
7	B D A - C	D B C - A
8	C - B A D	A - D C B
9	D B - C A	B D - A C
10	- A C B D	- C A D B

Note: The stimuli had to be selected in the order A B C D. The five columns represent the five positions with the left column representing the leftmost key.

colors were added one at a time in forward-chaining fashion until the four-stimulus problem was reached.

Each session was preceded by a 4 to 5 min adaptation period in the dark chamber. Then the houselight was illuminated and the first array presented dimly illuminated. A correct peck produced two kinds of feedback: the pecked key changed from dim to bright and the same color appeared in the leftmost unoccupied stimulus window. After correct strings, the food-cup light was lighted for 2 sec and, if scheduled, food was delivered. An incorrect peck resulted in offset of all displays and a .5-sec buzzer. A discrete-trials procedure with a 5-sec dark-key intertrial interval and between-trials correction was used so that each array was repeated until a correct pecking sequence occurred. After the last trial all lights went off.

Initially, all correct trials were followed by a 45-mg Noyes pigeon pellet. Then correct pecking sequences were reinforced according to a variable-ratio 1.5 schedule and starting with Session 3, a variable-ratio 2 schedule composed of the values 1, 2, and 3 occurring three times each in each block of nine reinforced trials.

Each session was terminated after *N* correct strings or *X* min, whichever occurred first. *N* was set at 150 for the one-stimulus problem, 140 for the first six sessions of the two-stimulus problem, and 100 for the rest of the study. *X* was 50 or 45 min.

The experimental conditions were divided into two phases (see Table 2 for order and number of sessions of the experimental conditions). In Phase I subjects were trained on the one-, two-, three-, and four-stimulus problems, in that order, using array-set 1. In addition, a transfer test with array-set 2 was included for the two- and four-stimulus problems to determine if performance was specific to the training arrays.

In Phase II subjects were switched to the alternate chamber and then back to their original chamber while holding each group's required color sequence (spectral or mixed) constant to determine if a group difference at the end of Phase I was due to the chamber or to the required color sequence.

Conditions were changed when there was no systematic trend in percentage of correct trials over four sessions. Conditions had to be changed for all subjects on the same day due to apparatus limitations.

Pecks with very short interresponse times were not counted. Initially the interresponse time criterion was 60 msec, then 80 msec after Session 37, 100 msec after Session 41, and 150 msec after Session 45. It appeared that one peck would occasionally operate the response switch twice very rapidly. Excluding pecks with very short interresponse times prevented these second switch operations from being treated as errors. The bulb voltage for the dim state was raised from 4 to 5 V at the beginning of the three-stimulus problem (Session 33), because a color to be added was barely visible at the 4 V setting. Thus later sessions are not directly comparable with earlier sessions.

Table 2

Order and Number of Experimental Conditions

	Condition	*# Sessions*
Phase I	One-Stimulus Problem	16
	Two-Stimulus Problem	
	Array-Set 1	12
	Array-Set 2 (transfer test)	4
	Three-Stimulus Problem	22
	Four-Stimulus Problem	
	Array-Set 1	19
	Array-Set 2 (transfer test)	24
Phase II	Four-Stimulus Problem	
	Array-Set 2	
	Baseline	11
	Chamber Reversal	24
	Chamber Reversal	18

RESULTS

Phase I Accuracy

Accuracy of performance (number of correct strings/total number of strings) is plotted in Figures 2 and 3 for blocks of two sessions (except for the first point of the four-stimulus problem array-set 1, which is one session's data). The first block plotted represents Sessions 17 and 18, the first two sessions of the two-stimulus problem.

Pecking the lit key was acquired during the first session of shaping. Considerable disruption occurred when the two-stimulus problem was introduced; only Bird 201 completed 140 correct trials during the 50-min time limit. Subject 203 had 66 correct trials; the others had no correct trials and stopped responding after a few (7 to 41) incorrect trials. Subject 202 responded correctly during the next ses-

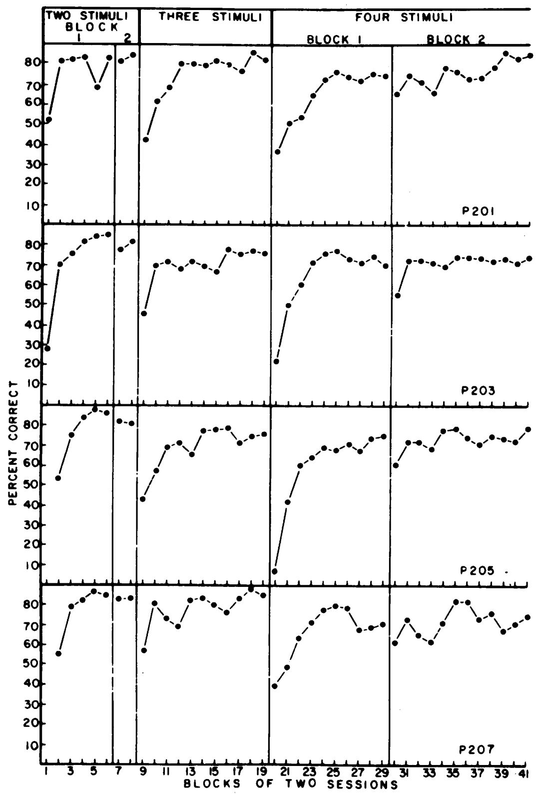

Fig. 2. Accuracy: Individual subjects' data, Group A.

sion; the other four subjects were given special training (food was occasionally delivered for an approach to the keys and for pecking the first stimulus as well as for correct strings). One session of special training was sufficient for all subjects except 205 (2 sessions) and 206 (3 sessions). The data plotted in Figures 2 and 3 do not include any sessions where special training was used. No special training was required upon introduction of the three- and four-stimulus problems.

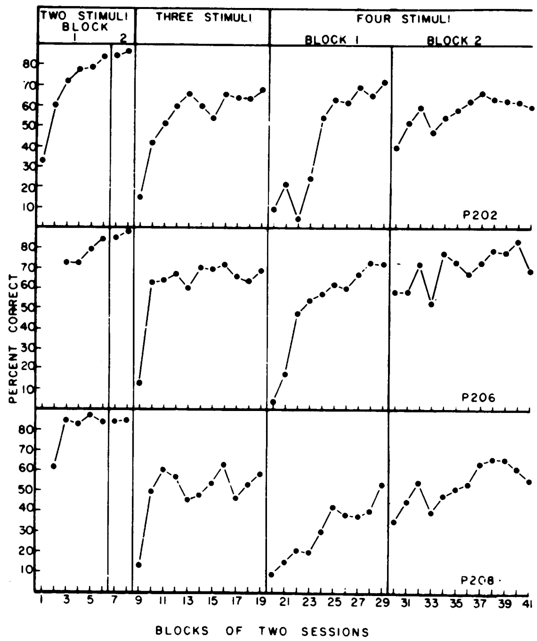

Fig. 3. Accuracy: Individual subjects' data, Group B.

Acquisition with each problem was a negatively accelerated growth function with most of the increase occurring within 11 sessions. Group B accuracy was below Group A accuracy throughout Phase I except for array-set 2 of the two-stimulus problem.

Table 3 shows a gradual increase in accuracy over blocks of 20 correct strings, for the first three sessions of the four-stimulus problem. Data are not presented for blocks with fewer than 20 correct trials as practice would be confounded with array.

The transfer tests with array-set 2 showed a change in percentage of correct of −4.4 for the two-stimulus problem (range 6.2 to −17.6) and −21.3 for the four-stimulus problem

Table 3

Percent correct strings in blocks containing 20 correct trials, first three sessions of four-stimulus problem array-set 1.

		Session														
		55					56					57				
Trial	*Blocks*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
S	201	38	32	48	33	39	36	57	47	53	53	50	67	48	56	65
U	202	9					23					18	40			
B	203	19	20	27			30	44	59	69	63	50	47	61	48	51
J	205	7					22	39	48	51	54	36	40	46	56	59
E	206						16	28				12	35			
C	207	31	42	46	50	35			Data lost			32	56	56	74	46
T	208	9							Data lost			14	19			

Table 4

Change in accuracy from the last pre-transfer session to the first transfer test session for the two- and four-stimulus problems, mean of first exposure to each array.

	Subject						
	201	*202*	*203*	*205*	*206*	*207*	*208*
Two-Stimulus Transfer	−20	−10	0	−30	−10	20	0
Four-Stimulus Transfer	10	0	10	−10	−20	0	10

(range −14.7 to −25.5) for the comparison of the last session of array-set 1 and the first session of array-set 2. Comparisons of mean accuracy over the first presentation of each array in the pre- and post-transfer sessions (Table 4) showed the mean change in accuracy to be −7.1 for the two-stimulus problem (range −20 to 20) and zero for the four-stimulus problem (range −20 to 10).

Array-set 2 of the four-stimulus problem was inadvertently introduced while the accuracy of Bird 208 was increasing. Some subjects (e.g., 201 and 203) showed little between-session variability after the initial change at each string length. Others (e.g., 208) showed considerable between-session variability throughout the study.

Phase I Error Type

Errors were classified into four types: selections further in the sequence (forward errors), selections backwards in the sequence (backward errors), the immediate repetition of a correct selection (repeat error) and selection of a dark key (dark-key error). The probability of each error type is given in Table 5 for the first and last three sessions of array-sets 1 and 2 of the four-stimulus problem. The errors per opportunity (probability) statistic takes the number of opportunities for each error type into account and is computed by dividing the total number of errors of a given type by the number of opportunities to make an error of that type. The number of opportunities is based on the number of pecks (correct and incorrect) made in each serial position. For example, the number of opportunities for a forward error in a data set for a 4-stimulus problem is the number of pecks in the first serial position times three plus the number of pecks in the second serial position times two plus the number of pecks in the third serial position. The number of opportunities for each type of error depends on the subject's behavior.

Table 5

Probability of each error type during the four-stimulus problem.

	Error type			
Subject	*Forward*	*Repeat*	*Backward*	*Dark key*
A. First three sessions (55 to 57) of four-stimulus problem array-set 1.				
201	.0749	.0340	.0071	.0010
202	.0889	.1463	.0575	.0039
203	.1024	.0140	.0140	.0037
205	.0704	.1440	.0245	.0004
206*	.1142	.0438	.0209	.0000
207*	.0922	.0211	.0044	.0000
208*	.1493	.0935	.0241	.0000
Mean	.0995	.0710	.0218	.0013
B. Last three sessions (71 to 73) of four-stimulus problem array-set 1.				
201	.0364	.0128	.0010	.0000
202	.0360	.0185	.0082	.0013
203	.0433	.0088	.0030	.0035
205	.0368	.0129	.0030	.0035
206	.0387	.0162	.0066	.0000
207	.0493	.0000	.0031	.0000
208	.0628	.0741	.0134	.0000
Mean	.0433	.0205	.0055	.0012
C. First three sessions (74 to 76) of four-stimulus problem array-set 2.				
201	.0511	.0117	.0034	.0000
202	.0731	.0513	.0085	.0057
203	.0622	.0139	.0077	.0006
205	.0519	.0265	.0044	.0012
206	.0675	.0128	.0077	.0012
207	.0542	.0140	.0028	.0000
208	.0918	.0452	.0203	.0000
Mean	.0645	.0250	.0078	.0012
D. Last three sessions (95 to 97) of four-stimulus problem array-set 2.				
201	.0254	.0052	.0000	.0015
202	.0504	.0303	.0115	.0065
203	.0357	.0130	.0051	.0036
205	.0331	.0120	.0071	.0014
206	.0376	.0245	.0038	.0000
207	.0419	.0071	.0021	.0007
208	.0644	.0305	.0037	.0006
Mean	.0412	.0175	.0048	.0020

*Based on two sessions

Table 6

Number (in parentheses) and mean latency of selections at each position in the string for the first (74 to 76) and last three sessions (95 to 97) of four stimulus problem array set 2.

Serial Position	Stimulus Selected A	B	C	D
1 First	1.05[1]	1.96(311)[2]	3.73(41)[3]	5.94(43)[4]
Last	1.05[1]	3.24(218)[2]	6.50(30)[3]	1.76(10)[4]
2 First	.86(54)[5]	.90[1]	1.37(284)[2]	1.28(109)[3]
Last	.72(37)[5]	.81[1]	1.43(194)[2]	1.28(39)[3]
3 First	1.06(14)[6]	.95(76)[5]	.90[1]	1.29(678)[2]
Last	.92(9)[6]	1.00(42)[5]	.78[1]	1.42(217)[2]
4 First	.75(2)[7]	.86(61)[6]	.81(113)[5]	.87[1]
Last	.60(1)[7]	.85(27)[6]	.76(50)[5]	.78[1]

The number of correct selections was 300 for serial position 4 and more than 300 for the other serial positions.

Notes:
[1]Correct selections in that serial position
[2]Forward one-step errors
[3]Forward two-step errors
[4]Forward three-step errors
[5]Repeat errors
[6]Backward one-step errors
[7]Backward two-step errors

Forward errors were most probable, followed by repeat, backward, and dark-key errors in that order. Only 7 comparisons of 84 violate this ranking and in only three cases (202 and 205, Sessions 55 to 57; 209, Sessions 71 to 73) was another error type (repeat) more probable than forward.

Table 6 gives the mean latency of pecks and the number of pecks (in parentheses) for each stimulus selected (columns) at each serial position (rows) in the string for the first and last three sessions of array-set 2 of the four-stimulus problem. The first peck of a string (top row) had a longer latency than later pecks. Correct pecks, repeat errors, and backward errors had approximately the same latencies whereas forward errors had longer latencies. Individual subjects' data showed the same pattern.

Forward errors decreased as the distance from the correct stimulus to the pecked stimulus (steps) increased except for the three-step error of serial position one, first three sessions, $F(2,12) = 43.64$, $p < .0001$ and $F(2,12) = 43.55$, $p < .001$ for serial position one, first and last three sessions respectively. $F(1,6) = 97.22$, $p < .0001$ and $F(1,6) = 17.21$, $p < .006$ for serial position two, first and last three sessions re-

Table 7

Summary of Errors in the First Session of the Three-Stimulus and the Four-Stimulus Problems.

Subject	201	202	203	205	206	207	208
Three-Stimulus Problem (Session 33)							
First Error	B	C	ABZ	B	C	B	C
Total # Errors	186	271	170	165	269	119	165
# of First Correct Trial	1	25	14	3	63	1	35
# of AB__ Errors	12	40	50	38	2	12	4
# of ABB Errors	9	33	24	34	2	9	4
# of Errors to C	107	173	68	63	196	58	99
Four-Stimulus Problem (Session 55)							
First Error	AA	C	ABD	D	AD	AC	D
Total # Errors	169	301	251	283	88	153	273
# of First Correct Trial	5	79	9	7	15	7	40
# of ABC__ Errors	0	59	14	55	53	10	36
# of ABCC Errors	0	32	6	47	26	7	27
# of Errors to D	124	89	168	117	13	97	137

Z = Dark-Key Selection

spectively. Latency increased from the correct response through higher step forward errors in most cases; however, the increase was not significant for serial position 1, first [$F(2,12) = 1.64$] or last [$F(2,12) = 2.33$] three sessions. The increase was significant for serial position two [first $F(1,6) = 27.45$, $p < .002$; last, $F(1,6) = 487.31$, $p < .0001$] and serial position three [first, $F(1,6) = 71.28$, $p < .0002$; last, $F(1,6) = 194.52$, $p < .0001$].

Table 7 gives a breakdown of errors for the first session of the three-stimulus and four-stimulus problems. Two subjects were correct on the first trial of the three-stimulus problem; the range for the other five pigeons was 2 to 78 errors before the first correct trial. The new color was pecked more frequently than any other as the first error of a new problem. During the total session one subject in the three-stimulus problem (205) and two subjects in the four-stimulus problem (202, 206) pecked the next-to-last color more frequently than the last color on error trials (data not presented). Only Bird 206 in the four-stimulus problem made a high proportion of errors in the last serial position (A B C); for all subjects most errors in the last serial position were repeat errors (ABB and ABCC).

Phase I Array Difficulty

Errors should be equally distributed over the 10 arrays if there was no influence of the locations of the colors on the keys. The percentage of errors for each array is shown in Table 8 with the upper limits underlined and the total number of errors (N) listed.

Kendall's coefficients of concordance showed significant ($p < .001$) agreement among the subjects in ordering the arrays for the first three sessions of array-set 1 [$\omega = .56$, $\chi^2(9) = 35.30$] and the first three sessions of array-set 2 [$\omega = .65$, $\chi^2(9) = 49.71$] but not for the last three sessions of either array-set 1 [$\omega = .23$, $\chi^2(9) = 14.42$] or array-set 2 [$\omega = .26$, $\chi^2(9) = 16.10$].

Phase II Chamber Reversal

After reversal, asymptotic level of accuracy (last three session means) decreased by 15.5% for Group A and increased by 15.5% for Group B. A 2 (groups) by 2 (chambers) analysis of variance showed a significant effect of chamber, $F(1,6) = 7.66$, $p < .05$, but no main effect of groups and no interaction. The second chamber reversal resulted in a 14% increase in accuracy for Group A and a 6.5% decrease for Group B at asymptote; however, none of the effects was significant.

DISCUSSION

All subjects acquired the stringing behavior and performed at a high level of accuracy. The most conservative estimate of correctly completing a string by chance is once in 24 trials under the assumption that subjects peck only dimly lit keys. All subjects exceeded this level of accuracy.

Increasing string length caused errors and an increased number of sessions to asymptote, but only at the introduction of the two-stimulus problem did any subject stop responding. Two contingencies first presented during the two-stimulus problem may have caused the disruption. These were the possibility of repeat errors and the possibility of pecking a dimly lit key in error. Repeat pecks of the last color of a string had no programmed effect as the string was defined as correct when the last color was pecked once. The keys remained lighted during the two-sec food-cup cycle, and subjects were observed to peck the last color in the string repeatedly prior to going to the food cup.

The blocks-of-20-correct-trials analysis, where amount of training was not confounded with arrays, showed a gradual increase in accuracy over blocks. Thus, the subjects did not learn the arrays of the four-stimulus problem in one or a few trials. Few errors occurred in the last serial position during the first session of the three- or four-stimulus problem and most of the errors which did occur in the last serial position were repeat errors, perhaps because repeat pecks of that color had not resulted in an aborted trial under the prior string length, one of the two factors thought to be responsible for the disruption in performance at the introduction of the two-stimulus problem. Many of the errors during the first session of the three- and four-stimulus problems were forward errors of pecks to the newly added color.

Dark-key errors were possible because there were more keys than stimuli. The dark/lighted discrimination was readily acquired and maintained at a high level of accuracy. Repeat errors were, in a sense, backward errors, i.e., they

Table 8

Array difficulty: Percent of total errors to each array for first and last three sessions of array-sets 1 and 2 of the four-stimulus problem.

Subject	*Array*										
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*N*
A. First three sessions (55 to 57) of array-set 1.											
201	5	5	23	5	9	15	3	9	16	11	358
202	5	3	14	1	22	6	2	7	6	33	624
203	1	11	23	7	7	10	10	19	7	6	455
205	2	5	41	2	4	5	7	18	12	5	564
206	1	4	35	7	9	6	11	8	13	15	342
207	4	8	18	4	16	4	12	13	15	7	258
208	2	5	11	5	12	7	3	30	16	11	509
B. Last three sessions (71 to 73) of array-set 1.											
201	11	4	13	15	7	6	24	10	6	2	97
202	5	5	13	11	11	11	1	24	8	11	118
203	10	13	13	5	4	10	11	12	10	12	119
205	10	12	18	7	8	6	10	16	8	6	105
206	13	6	13	6	8	13	2	11	2	16	126
207	11	8	11	17	1	9	14	8	7	8	117
208	2	7	15	7	7	6	9	10	32	4	349
C. First three sessions (74 to 76) of array-set 2.											
201	3	12	11	4	2	4	16	19	8	10	146
202	4	17	19	2	8	1	18	27	2	1	399
203	9	2	20	5	5	4	27	18	2	8	199
205	10	18	14	3	8	3	15	12	9	6	175
206	5	7	14	5	12	7	24	15	5	5	220
207	8	14	24	2	5	3	12	26	2	4	155
208	9	8	14	5	14	4	9	15	9	4	525
D. Last three sessions (95 to 97) of array-set 2.											
201	5	3	7	12	12	7	20	12	13	10	60
202	14	4	11	7	17	1	15	25	4	2	204
203	12	5	15	15	7	10	6	15	13	2	104
205	6	1	11	12	17	4	14	11	14	11	94
206	12	4	7	18	12	4	9	15	8	10	121
207	10	7	27	2	3	15	6	13	9	9	104
208	9	16	12	8	9	3	16	13	5	10	195

N = Number of sessions.
Upper limit is underlined.

were backward in the sequence relative to correct selections and were selections of a brightly lit key. As selections of brightly lit keys were never reinforced, why then was the probability of repeat errors approximately three times the probability of backward errors? We suspect that it has to do with the special status of pecking for pigeons. Pigeons frequently peck a stimulus several times in succession even when repetitive responses are never reinforced, as with the differential-reinforcement-of-low-rate schedule, whereas repetitive responses occur at a much lower level in pigeons under the same schedule when the treadle-press response is used (Richardson & Clark, 1976). Other responses by pigeons and other species might show a lower probability of repeat selections. Blough (1963, 1966) has argued that certain short-interresponse pecks are controlled by prior pecks and are not responsive to other variables. Schwartz and Williams (1972) have also argued that certain pecks are not a function of their consequences.

We found, as did Straub et al. (1979), (1) that under asymptotic performance on the four-stimulus problem forward errors predominated, (2) that there were more one-step forward errors than two- and three-step forward errors, and (3) that forward errors had longer latencies than correct pecks, repeat errors, and backward errors. We observed subjects "air peck" the correct stimulus, then peck the next stimulus in the sequence, producing a forward error. However, we also observed subjects correctly peck a stimulus immediately after having "air pecked" that stimulus, showing control by the experimenter-provided feedback for correct pecks. Thus, the effect of providing feedback for correct selections seems to be to raise the accuracy while leaving the pattern of errors and the latency effects intact.

The array-transfer tests produced a drop in accuracy followed by quick recovery. Under the assumption that the subjects had "learned the sequence" the only reason for this decrement would be that the new arrays were more difficult than the old arrays. However, asymptotic accuracy under the transfer arrays was, for all subjects except 202, at or above the level under the original arrays, indicating that the new set of arrays was not more difficult. The drop in accuracy in the first transfer session could result from initial low accuracy in the session followed by rapid learning. The only test of transfer which is not influenced by learning of the new arrays is the accuracy for the first trial of each of the new arrays in the first transfer session. This measure (see Table 4) did not show a decrement in accuracy, indicating that the subjects learned the sequence based on the color stimuli not on the specific arrays used. These data rule out explanation of the stringing behavior by a configuration model which would require learning a series of position responses for each separate array.

Subjects agreed in the rank order of difficulty of the arrays during the initial, lower accuracy sessions but not during the higher accuracy terminal sessions (see Table 8). The failure to find an array-difficulty effect during the terminal sessions was not due to a ceiling effect, as the initial sessions of the second set of four-stimulus arrays had only slightly lower accuracy than the terminal sessions. Extensive efforts to identify variables which would allow prediction of the relative difficulty of arrays were not successful. For example, in the first sessions with array-set 2, array 3 (A-BCD), which had the colors in the correct order from left to right, was one of the hardest arrays, whereas array 9 (BD-AC), which had the colors in mixed order, was one of the easiest.

Pigeons trained to peck a colored key and then tested with other colors on the key order the colors according to wavelength (Guttman & Kalish, 1956; Hanson, 1959). This phenomenon is robust and of large magnitude. We had expected, therefore, that a stimulus string of colors in sequence according to wavelength would be easier than a sequence in mixed-wavelength order. The data do not support such an effect at asymptote of the four-stimulus string.

A simple chaining model can explain the performance of correct strings. Trial onset is the discriminative stimulus for pecking dim-A, bright-A is the discriminative stimulus for pecking dim-B, etc. The bright-dim discrimination could account for the higher probability of forward errors while the high probability of repeat errors could be due to the nature of pecking in pigeons as previously discussed. "Air-pecking" could explain some of the difference between one and two-step forward errors in latency and number (Straub et al., 1979). The errors which occurred with an increase in string length were not consistent with a chaining model, however, which would predict correct performance on the elements previously learned with disruption in the newly added serial position. The data show most errors were an incorrect choice of the newly added stimulus as a forward error. This may simply be a preference for the new stimulus which overrides other variables. If so, then removing this factor might not only result in performance in accordance with the chaining model but would also result in near perfect transfer from string length N to $N + 1$.

Straub et al. (1979) rejected the chaining model for their data, as there was no identifiable differential stimulus change as a function of the color pecked; instead they postulated that the pigeons "learned a representation" and that this would account for the data. We suggest, rather, that the pigeon's behavioral state could differ after having pecked one color as opposed to another even though there was no experimenter-programmed differential-external-stimulus change. Any private stimulus which would allow the pigeon to "keep its place" in its "representation" could just as well serve as a discriminative stimulus for a chain.

REFERENCES

Blough, D. S. Interresponse time as a function of continuous variables: A new method and some data. *Journal of the Experimental Analysis of Behavior,* 1963, **6,** 237-246.

Blough, D. S. The reinforcement of least-frequent interresponse times. *Journal of the Experimental Analysis of Behavior,* 1966, **9,** 581-591.

Boren, J. J., & Devine, D. D. The repeated acquisition of behavioral chains. *Journal of the Experimental Analysis of Behavior,* 1968, **11,** 651-660.

Guttman, N., & Kalish, H. I. Discriminability and stimulus generalization. *Journal of Experimental Psychology,* 1956, **51,** 79-88.

Hanson, H. M. Effects of discrimination training on stimulus generalization. *Journal of Experimental Psychology,* 1959, **58,** 321-334.

Hulse, S. H. Cognitive structure and serial pattern learning by animals. In S. H. Hulse, H. Fowler, & W. K. Honig (Eds.), *Cognitive processes in animal behavior.* Hillsdale, N.J.: Lawrence Erlbaum Associates, 1978.

Hursh, S. R. The conditioned reinforcement of repeated acquisition. *Journal of the Experimental Analysis of Behavior,* 1977, **27,** 315-326.

Olton, D. S. Characteristics of spatial memory. In S. H. Hulse, H. Fowler, & W. K. Honig (Eds.), *Cognitive processes in animal behavior.* Hillsdale, N.J.: Lawrence Erlbaum Associates, 1978.

Premack, D. *Intelligence in ape and man.* Hillsdale, N.J.: Lawrence Erlbaum Associates, 1976.

Richardson, W. K., & Clark, D. B. A comparison of the key-peck and treadle-press operants in the pigeon: Differential-reinforcement-of-low-rate schedule of reinforcement. *Journal of the Experimental Analysis of Behavior,* 1976, **26,** 237-256.

Rumbaugh, D. (Ed.). *Language learning by a chimpanzee: The Lana project.* New York: Academic Press, 1977.

Schwartz, B., & Williams, D. R. Two different kinds of key peck in the pigeon: Some properties of responses maintained by negative and positive response-reinforcer contingencies. *Journal of the Experimental Analysis of Behavior,* 1972, **18,** 201-216.

Sidman, M., & Rosenberger, P. B. Several methods for teaching serial position sequences to monkeys. *Journal of the Experimental Analysis of Behavior,* 1967, **10,** 467-478.

Straub, R. O., Seidenberg, M. S., Bever, T. G., & Terrace, H. S. Serial learning in the pigeon. *Journal of the Experimental Analysis of Behavior,* 1979, **32,** 137-148.

Thompson, D. M. Repeated acquisition as a behavioral baseline. *Psychonomic Science,* 1970, **21,** 156-157.

Thompson, D. M. Transition to a steady state of repeated acquisition. *Psychonomic Science,* 1971, **24,** 236-238.

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