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ALL-OR-NONE ACQUISITION IN MATCHING-TO-SAMPLE AND A TEST OF TWO MODELS

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Three pigeons learned to match three colors in a matching-to-sample procedure. The sample hue was presented on the center one of three keys, and the comparison hues were presented on the side keys. Forty responses on the center key produced the stimuli on the side keys and left the sample on the center key. A single response on the correct side key produced 3-sec access to grain, which was followed by a 25-sec intertrial interval. A correction procedure was employed when an error was committed. Before attaining asymptotic levels, there was no evidence of learning, responses were independent of the preceding response, and distributions of errors in four-trial blocks were binomial. Distributions of error runs, runs of various lengths, autocorrelations of errors of several lags, alternations of correct responses and errors, *etc.*, were shown to fit Bower's (1961) all-or-none model better than a gradual learning model of Bush and Sternberg (1959). A transfer test employing a novel color showed only transitory degradation of performance.

The purpose of this report is two-fold. First, through an analysis of trial-by-trial behavior, the acquisition of a matching-to-sample performance is shown to be consistent with an all-or-none learning interpretation. Second, Bower's (1961) one-element, all-or-none learning model is shown to be preferred to the gradual learning model proposed by Bush and Sternberg (1959) in accounting for the acquisition of matching. Bower's (1961) model has been successfully applied to another conditional discrimination performance (Rodewald, 1973), and the present study further extends the scope of this model.

It might be assumed when an animal learns to match a sample stimulus (ST), as evidenced by choosing from a pair of comparison stimuli (CO) the one that is physically identical to the ST, that the learner has formed a concept of "matching". However, Cumming and Berryman (1965) showed that after high levels of matching performance have been attained, introduction of a new color as an ST and as a CO disrupted the performance. The disruption was limited to trials where the new stimulus was the ST. The presence of the new stimulus in pairs presented with old STs did not reduce matching accuracy. They also showed that behavior in the presence of each of three STs before attaining high quality overall performance was unequally controlled by the several STs. One ST clearly controlled behavior but the other two did not.

The failure to transfer behavior to a situation involving a new ST suggests that in their procedure (Cumming and Berryman, 1965) the concept of matching was not acquired. This, along with the unequal control by STs in the early stages of the development of accurate performance, suggests that behavior is controlled separately by each ST.

The trial-by-trial, sequential record of correct and incorrect responding in the presence of each ST can be used to test the appropriateness of an all-or-none interpretation of the acquisition of control by the STs. Suppes and Ginsberg (1963) proposed four conditions that must be satisfied if a sequence of responding is to be judged as supporting an all-or-none interpretation of acquisition. First, there is no evidence of learning before the last error. The conclusion of no learning is supported if the number of correct responses in the first half of trials before the last error is equal to the number of successes in the second half. Second, the sequence before the last error is a set of Bernoulli trials. The independence of trial-by-trial performance before last error is supported when the probability of a success on trial n + 1 remains unchanged by the behavior

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on trial n. Third, responses and specific sequences of errors and successes exhibit binomial distributions. The binomial hypothesis is supported if the number of errors, say, in four-trial blocks before the last error fits a binomial distribution. Finally, specific sequences of errors and successes in each four-trial block must also fit a binomial distribution.

If all four criteria above are met, there is good evidence for an all-or-none process. Note, however, that these criteria are tested statistically and that each of them is stated as a null hypothesis. A result favorable to an all-or-none interpretation based on these criteria is actually a conclusion that the all-or-none hypothesis is not rejected. Additional evidence for an all-or-none interpretation could be obtained by comparing a mathematical model that assumes all-or-none acquisition, in the sense of the four criteria, with one that assumes a gradual acquisition process. The former is represented by Bower's (1961) one-element model, and the latter is consistent with a model developed by Bush and Sternberg (1959). Each model predicts several statistical properties of response sequences before the last error. A comparison of the respective predictions with obtained data can increase the power of the present analysis of the all-or-none learning proposition.

These particular models were chosen for three reasons. First, Bower's (1961) model has been useful in a similar experimental context (Rodewald, 1973). Second, each model is a simple statement of all-or-none or gradual learning hypotheses. Finally, both allow estimation of the same number of parameters. This makes comparison immediate, since the number of estimated parameters influences the chances of a fit to obtained data.

METHOD

Subjects

Three White King pigeons, obtained from Palmetto Pigeon Plant, Sumter, S.C., were experimentally naive and were maintained at 80% to 85% of their free-feeding weights.

Apparatus

A Lehigh Valley Electronics pigeon chamber was housed in an acoustical chamber (Industrial Acoustics Company, Model 102311). One wall of the pigeon chamber contained a line of three response keys. The keys were 2.5 cm clear plastic disks set 8.25 cm center-to-center and 24.1 cm from the floor. The feeder was located directly below the center key at a distance of 14 cm. Behind each key was an in-line projector (Industrial Electronics Engineering, one-plane readout, Model 0010-01-xxxx-1820) also supplied by Lehigh Valley. The projectors were used to illuminate each of the three keys with white, red, yellow, and green light. A small white light located in the roof of the acoustical chamber was illuminated at all times. Since the roof of the pigeon chamber was opaque, this light provided soft reflected light as a houselight. Control of the projectors, schedules, and data retrieval was accomplished by a Lehigh Valley Interact System employing a PDP 8/I 8k computer. The system is described fully elsewhere (Rodewald, 1972).

Procedure

Several 20-min sessions were devoted to adapting the birds to the apparatus. They were placed in the operant chamber, and the empty food magazine was activated on a random-interval schedule averaging 10 sec. They were then trained to eat from the feeder, and the key-pecking response to the white center key was shaped. Each key-peck response was followed immediately by the reinforcer, 3-sec access to grain, until 50 reinforcers were delivered. During the next two sessions, the number of responses necessary to produce a reinforcer was adjusted upward until a final requirement of 40 responses (fixed-ratio 40 or FR 40) was reached. At least 20 reinforcers were earned on the FR 40 schedule. Each of these two sessions delivered 100 reinforcers.

Responding on all three keys was then established. The keys were illuminated with white light in random fashion. The center key was illuminated twice as often as either side key. The FR 40 was in effect on the center key and FR 1 on the side keys. After the reinforcer was presented for responding to any lighted key, a 25-sec intertrial interval (ITI) was begun, and any key-peck responses during the ITI started it over again. If a peck occurred on a black key when a lighted one was available, the ITI was reinstated. Fifty reinforcers occurred on this schedule. The following session maintained the previous contingencies, but the red, yellow, and green lights used in the matching-to-sample sessions replaced white. Each color appeared randomly on all keys. The session terminated after 100 reinforcers had been delivered.

Matching-to-sample training began in the next session. The sample stimulus was presented on the center key. When the FR 40 requirement was met, the center key remained lighted and the two side keys were illuminated. One of the side keys displayed the same color as the center one, and the other side key showed one of the two remaining colors. Which side key contained the matching stimulus was a random event with both positions equi-probable. The non-matching color was randomly selected from the remaining stimuli. A single response to the matching CO resulted in reinforcement. Following reinforcement, a 25-sec ITI was begun, and a response on any key repeatedly reset the interval to 25 sec. Following a 25-sec response-free period, the next sample color was randomly selected from the three colors, and a new trial started. If an error was made, a 5-sec blackout occurred. Following the blackout, the sample stimulus was repeated. When the FR 40 requirement was met, the two side keys were presented again in the same configuration employed when the error was made. This recycling, correction procedure continued until the animal crossed over to the correct CO. The cross-over response was reinforced, and the ITI was produced for the next trial. Five matching-to-sample sessions, 100 reinforcers per session, were presented. For purposes of data analysis, the cross-over response (*i.e.*, the reinforced response following an error) was not counted as a correct response. The structure of the schedule was based on previous work by Sacks, Kamil, and Mack (1972) and by Holt and Shafer (1973). The schedule parameters were selected to maximize stimulus control.

A sixth session was used to check for transfer of matching behavior to a novel stimulus, blue. Blue replaced one of the original colors in the schedule: green for Animal 1, red for Animal 2, and yellow for Animal 3.

RESULTS

Acquisition occurred rapidly. The proportion correct across the five sessions for Birds 1, 2, and 3, respectively, were: 0.57, 0.83, 0.94, 0.98, 0.97; 0.44, 0.83, 0.94, 0.95, 0.99; and 0.61, 0.77, 0.91, 1.00, 0.99. The sequences of responding in the presence of each ST, called a subject-item sequence or SI, were examined according to the four criteria of Suppes and Ginsberg (1963).

For purposes of analysis, an SI was a string of zeros and ones representing successes and errors, respectively, on successive trials. For example, the SI corresponding to the behavior of an animal when confronted with the red ST might be displayed as follows: 111001010001100...., the trailing dots indicating no more errors. Each animal's behavior, therefore, is coded as three SIs. In four-trial blocks before the last error there are one of three errors, one of two, and one of one. Specific sequences within blocks show one of 1110, one of 0101, and one of 0001.

Since the notion of all-or-none learning implies the existence of a final error followed by consistently correct responding in each SI, the trial of last error must be specified. It seems unreasonable at the present level of development of behavior control technology to expect that even a well-conditioned response will be completely controlled by the scheduled discriminative stimuli. However, it is reasonable, on the notion of all-or-none acquisition, to expect that at some point in an SI there will be a precipitous rise in the probability of a correct response following one of the errors. Inspection of the data indicated that final, stable performances were at the level of about 90% correct. Therefore, a criterion was established as follows. Whenever an error was followed by a correct response in an SI, the 20 trials following the error were examined. If 18 of these 20 trials were correct, the error preceding the 20-trial block was considered the "last error". For all animals, this procedure divided SIs into two segments with radically different probabilities of correct responses. The probabilities of a correct response obtained by pooling the pre-criterion segments of SIs for each bird were 0.55, 0.49, and 0.64, for Animals 1, 2, and 3, respectively. Pooling in the same manner 50 post-criterion trials resulted in probabilities of 0.91, 0.92, and 0.95 for Birds 1, 2, and 3, respectively. Results of pooling across all three birds, 12 SIs, showed the probability of pre-criterion correct at 0.57 and post-criterion at 0.93. This method of sectioning SIs into pre- and post-criterion segments clearly seems adequate for determining a point of transition from poor to very good performance.

The first of the four criteria for all-or-none learning states that the expected number of correct responses in the first half of pre-criterion trials is equal to the number in the second half. Equality of performance in these halves was evaluated by a paired t-test (see Atkinson, Bower, and Crothers, 1965, p. 44). For Animals 1, 2, and 3 the values were $t = 2/2.08 = 0.9615$, $t = 5/2.65 = 1.8868$, and $t = 3.33/4.06 = 0.8202$, respectively. With $df = 2$, none of these was significant at the 0.05 level, two-tailed. Results of pooling over all animals produced $t = 3.44/1.68 = 2.0476$ which, with $df = 11$, was also not significant at the 0.05 level, two-tailed. A two-tailed test was employed because a change in either direction would cause rejection of equal performance in first and second halves. The hypothesis of equality of performance in halves of pre-criterion sequences was not rejected. No evidence of learning was found at the 0.05 level.

Trial-by-trial independence of pre-criterion responses was evaluated with χ^2 according to the procedure presented by Atkinson *et al.* (1965, pp. 45-49). This required tabulating the occurrences of errors and successes on trial $n + 1$ given the response on trial n. The obtained values based on the three SIs for each animal were 0.6198, 1.9544, and 0.9207 for Birds 1, 2, and 3, respectively. Data pooled over all birds resulted in $\chi^2 = 1.9465$. With $df = 1$, none of these was significant at the 0.05 level. Therefore, the hypothesis of independence, of Bernoulli sequences of responses, could not be rejected.

Tests of the binomial distribution of the number of errors in four-trial blocks were conducted with χ^2, $df = 4$. The parameter of the distribution was established by setting p, the probability of an error, equal to the proportion of errors on trials in the pre-criterion segments of the pooled SIs for each animal. The expression for the binomial was evaluated for 0, 1, 2, 3, and 4 errors. These values served in generating expected values against which observed frequencies were compared. The χ^2s and their associated p-values were: 7.4119, $p > 0.100$; 3.0113, $p > 0.500$; 0.9020, $p > 0.900$; 0.8522, $p > 0.900$, for Animals 1, 2, 3, and pooled data, respectively. Binomial distribution of errors was not rejected.

There are 16 possible specific sequences of errors and correct responses in four-trial blocks. Their distribution was also examined with a χ^2 test, $df = 15$, using parameters fixed above. The χ^2s and associated p-values were: 12.7502, $p>0.500$; 10.4886, $p>0.750$; 10.3402, $p>0.750$; 7.3052, $p > 0.900$, for Birds 1, 2, 3, and pooled data, respectively. Binomial distribution of specific sequences was not rejected.

Since the four distribution requirements suggested by Suppes and Ginsberg (1963) were fulfilled, the all-or-none character of matching-to-sample acquisition can be considered seriously. This does not mean the Bower's (1961) one-element, all-or-none model must fit the data because this is only one of several possible all-or-none theories. It is even possible to obtain good model fit when the underlying assumptions, as tested above, are not met. Comparisons of fit for Bower's (1961) model and for Bush and Sternberg's (1959) gradual learning model are, however, interesting because they contrast the two general approaches to theoretical interpretations of acquisition data.

Bower's (1961) model is represented by a two-state Markov chain. A stimulus element is either learned or it is not. If it is not learned on trial n, the probability of it becoming learned on trial $n + 1$ is c. In the unlearned state, the animal may emit a correct response in the presence of a stimulus with probability g. Once the learned state for a stimulus element is entered, no more errors in the presence of that element are expected. Bower (1961) considered g to be the reciprocal of the number of response alternatives. Since two COs were available on each trial, g would be 0.50. In Bower's (1961) test of the model, human subjects were required to learn a 10-item paired-associates list with two response alternatives. It is reasonable to assume that humans would not have pronounced response preferences under these conditions. Further, since Bower averaged data over 29 subjects, response biases should be largely balanced. It is also reasonable to assume that the single animals or the small group in the present study would exhibit some response bias. Weak color preferences might occur in choices in CO pairs. There might be a tendency to avoid the matching CO. Cumming and Berryman (1965) showed that oddity performances were superior to matching during early trials. A tendency to choose the odd, non-matching CO would result in a value of g different from 0.50. For these reasons, g was treated as an estimated parameter. It was set equal to the proportion of correct responses in the pooled pre-criterion SIs for each bird. The value of c was determined by Bower's (1961) method. c was set equal to $(1 - g)/u$, where u is the mean errors to criterion obtained by pooling SIs for each bird. The values of g and c for Animals 1, 2, and 3, respectively, were: 0.5505, 0.0275; 0.4851, 0.0224; 0.6383, 0.0160. Corresponding values for data pooled over animals were 0.5684 and 0.0209.

The Bush and Sternberg (1959) approach results in a linear operator model. The probability of an error on trial n is a proportion of the probability of an error on trial 1, $q_n = a^{n-1}q_1$. To make the comparison of the models immediate, Atkinson *et al.* (1965, p. 112) was followed, and q_1 was set equal to $(1 - g)$, and a was equated with $(1 - c)$.

The predictions of each model and the observed data for single animals and for averaged animals are shown in Table 1. An expression for mean successes between errors has not been reported for the Bush-Sternberg model. The present author was unable to obtain useful expressions for mean trials and standard deviation of trials for the linear model.

The observed values in Table 1 were obtained by averaging over the three SIs for each animal or the 12 SIs for the "average" animal. Errors to criterion is the mean number of errors before last error in the SIs for subjects and for pooled subjects. These values were used to obtain c in Bower's model and so were not predicted. The distribution of total errors before the last error in SIs is reflected by the standard deviation of errors. Note that the Bush-Sternberg model is superior to Bower's in predicting these values. Other comparisons in the table favor Bower's model. These statistics are now described.

Consider the following pre-solution SI: 1100101110.... There are three error runs of unspecified length. There is one run of length one, one of length two, and one of length three. Autocorrelations of errors of various lags are based on the number of times an error is followed k trials later by another error. In the SI above there are three of lag one, two of lag two, and two of lag three. Alternations of errors and correct responses are based on a tally of the transitions from errors to correct and *vice versa*. There are four alternations in the SI above. Successes between errors is the mean of the distribution of successes between adjacent errors. The values above are 0, 2, 1, 0, 0.

Table 1

Statistics observed (O) and those predicted by Bower (B) and by Bush-Sternberg (B-S) models.

	Animal											
	1			*2*			*3*			Average		
Statistic	*O*	*B*	*B-S*	*O*	*B*	*B-S*	*O*	*B*	*B-S*	*O*	*B*	*B-S*
Errors to Criterion	16.33	–	–	23.00	–	–	22.67	–	–	20.67	–	–
Standard Deviation	4.04	16.38	3.55	1.73	22.99	4.12	4.16	22.81	4.31	4.45	20.74	4.02
Trials to Criterion	36.33	35.15	–	44.67	43.75	–	62.67	60.95	–	47.89	46.61	–
Standard Deviation	4.93	35.82	–	6.03	44.17	–	12.34	62.16	–	13.75	47.38	–
Error Runs	10.00	9.19	12.71	10.67	11.42	17.15	13.67	14.60	18.60	11.44	11.93	16.26
Error Runs of Length:												
1	6.00	5.17	10.13	5.67	5.67	13.23	7.33	9.40	15.49	6.33	6.89	13.07
2	2.33	2.26	1.87	1.33	2.86	2.68	5.00	3.35	2.40	2.89	2.91	2.33
3	1.33	0.99	0.49	2.00	1.44	0.79	0.33	1.19	0.53	1.22	1.23	0.60
Alternations Errors and Correct	18.67	17.93	20.54	19.33	22.33	28.27	26.00	28.84	29.66	21.33	23.44	36.50
Autocorrelations of Lag:												
1	6.33	7.14	3.62	12.33	11.58	5.85	9.00	8.07	4.07	9.22	8.74	4.41
2	6.33	6.94	3.52	11.00	11.32	5.72	7.00	7.94	4.00	8.11	8.55	4.32
3	5.67	6.75	3.42	9.67	11.06	5.59	8.33	7.81	3.94	7.89	8.37	4.23
Successes Between Errors	1.24	1.15	–	0.95	0.90	–	1.83	1.69	–	1.35	1.25	–

Behavior in the transfer session was quite accurate. For Animals 1, 2, and 3, the proportions correct were 0.96, 0.92, and 0.94, respectively. However, when the first 20 trials under each ST of the transfer session are compared with data from Session 5, some performance decrements are observed. The performances of all birds for each ST in Session 5 showed proportions of at least 0.90 correct. Bird 1, with blue substituted for green, performed at 90% correct in the presence of the new ST during the first 20 trials of the transfer session with that ST. Behavior under the old STs, red and yellow, was 100% correct. The second animal, with blue substituted for red, dropped to 75% correct on the new ST but remained at 90% and 95% correct for green and yellow STs, respectively. Animal 3, with blue substituted for yellow, fell to 70% correct under the new ST but remained at 90% and 95% correct under red and green STs, respectively.

It should be noted also that during Sessions 1 through 5, neither color was consistently acquired sooner than others. An analysis of variance of trials to criterion for colors summed across animals resulted in $F = 124.11/44.45 = 2.79$, which with $df = 2/4$ was not significant at the 0.05 level.

DISCUSSION

The present results indicate the existence of an all-or-none learning process in the acquisition of a matching-to-sample performance. The criteria developed by Suppes and Ginsberg (1963) were met by all the animals and by the group. These criteria are useful because they involve several tests and are independent of the parameters of any mathematical model under consideration. The use of mathematical models may serve to improve understanding of various learning settings because they may help to uncover subtle differences in these settings, as well as to show fundamental similarities. However, several points suggest cautious appraisal of the present attempt to apply quantitative theory to matching-to-sample phenomena.

First, the schedule parameters were chosen in an effort to maximize the rate of acquisition, and the desired result was obtained. Was this particular setting, therefore, biased in favor of all-or-none acquisition? If a large number of trials had been required, and the criteria for all-or-none acquisition had been met, the present conclusions would have seemed to have stronger support. If an all-or-none interpretation could not have been entertained in rapid learning, it is doubtful that it would have been supported in a slow-learning situation.

The question of the adequacy of the present analysis can be brought into perspective from the point of view of a functional, experimental analysis of behavior. Since matching-to-sample performances may develop slowly (Cumming and Berryman, 1965) or may be achieved rapidly as in the present situation, a functional statement of the difference in procedures would argue that the conditions for control of behavior by scheduled stimuli are better in the latter experimental setting. Control by the scheduled stimuli might be greatly reduced by the transient effects of non-instrumental sources of control, such as position habits developed as a result of failure to make the appropriate observing response. Because the present study is devoted to a precise quantitative analysis of the development of control by scheduled stimuli, an attempt was made to employ a schedule in which the arranged stimuli would strongly affect performance, lest potential transient sources of control obscure the orderliness of the process of conditioning. In this sense then, the present experiment is not biased toward all-or-none acquisition; it only set the occasion for its appearance if, in fact, it exists.

A second issue occurs in regard to the adequacy of the two models. Bower's (1961) model is generally superior to the Bush-Sternberg (1959) model in predicting sequential statistics, but Bower's clearly fails to predict the standard deviations of errors and trials to criterion. These failures are unexpected because the sequential statistics are a careful representation of the SIs. How could Bower's model predict so much data and still fail to predict the relatively gross summary statistics, standard deviations?

The predicted standard deviations under Bower's model are much too large. That is, the lengths of the pre-criterion SIs are more closely equal than the model expects, and the errors in SIs are more closely equal than predicted. It is as if mastery of one ST condition predisposes the animal to master the remaining STs with increased speed. This phenomenon could occur if the animal learns two things in this situation. First, it learns which CO to choose, given an ST. Second, having so learned the first ST condition, it acquires the rule or concept by which the general schedule requirements can be met. Bower's model was not developed to deal with rule or concept-learning situations; rather, it addresses rote learning of paired-associates tasks. Although there was some decrement involved when new STs were presented to two of the birds, it was not very great and was soon overcome. Perhaps they had learned the rule and did not simply start over with a novel stimulus. The existence of a rule for meeting schedule requirement may then impose a limitation on the general applicability of Bower's model in animal discrimination learning.

A potentially more troublesome possibility is that when relatively few stimuli are involved as STs or conditional stimuli, the animal simply learns to choose on a conditional basis once a discrimination task is mastered. This is not equivalent to learning a particular rule, such as physical identity of ST and CO, but is rather learning about an invariant aspect of the contingencies that can be used to meet the schedule requirements. This weaker assumption could also explain the failure to find lasting, marked decrements when new STs were substituted into the schedule. Similar failures to predict standard deviations were noted in an earlier study that employed four conditional stimuli (Rodewald, 1973). It is the case that Bower's model is a good first approximation to the underlying structure of the conditioning that occurs in matching-to-sample, but it will require modification if it is to be completely adequate. Perhaps a third conditioning state should be supplied, which is entered following mastery of an ST. A new transition probability could then be applied for the remaining ST conditions. Unfortunately, as more parameters are added and more of the raw data are used in estimating them, it is more difficult to reject the adequacy of a model. This could lead to the spurious conclusion that an ultimate model has been constructed for the acquisition of stimulus control.

Is it possible that the relatively better fit of the Bush-Sternberg model for standard deviations of errors to criterion should lead to its partial acceptance? The Suppes-Ginsberg criteria for all-or-none learning and the quality of Bower's sequential predictions in contrast to those of the Bush-Sternberg model clearly argue against it. Of course, as more states are added to a model such as Bower's, it begins to move toward a gradual learning model composed of many small discrete conditioning steps. A continued search for an adequate model may help further to clarify the subtle phenomena of discrimination learning.

A third point relates to the attempt to show an all-or-none process in stimulus control. Is the current quantitative approach simply forcing a conclusion that has little generality? Skinner (1938, pp. 66-71) reported that several reinforcers may be appropriately presented without a noticeable increase in response frequency. He noted that several factors might "affect the observed rate but not the rate of conditioning" (1938, p. 71). Since the frequency of responding did precipitously increase following one of the reinforcers, he concluded that an instantaneous change in frequency was common in original conditioning. Rodewald (1973) found evidence for an all-or-none process in a conditional discrimination. Bower (1961) developed his model in human paired-associate learning. The issue of all-or-none *versus* gradual learning is a major one in recent theoretical psychology. Of course, it is unreasonable to assume that all acquisition processes will appear to be all-or-none. The interesting problem is to specify the level of analysis at which the phenomenon occurs in a variety of experimental settings. In the present experiment, session-by-session data on overall performance would not appear to be generated by an all-or-none process. Averaging of overall performances across birds would produce the smooth, increasing, negatively accelerated learning curve. Only when performance in the presence of each ST is examined as above does the all-or-none character of acquisition appear. If one finds all-or-none or gradual acquisition at various levels of data treatment, then a more satisfactory working model of complex behavior can be developed.

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