PATTERN DISCRIMINATION LEARNING
WITH RHESUS MONKEYS

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Abstract

Rhesus monkeys were trained to criterion on a two-stimulus and a five-stimulus pattern discrimination task. The probabilities of response to the various stimuli throughout learning are examined for individual subjects, and it is found that the subjects exhibit consistency in the order and manner in which incorrect stimuli are eliminated. This suggests a simple mathematical description of the process, which is used to deepen the analysis of the data, permitting estimation of individual learning parameters and construction of more meaningful summaries of the group data.

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Introduction

Despite the number of studies devoted to pattern discrimination learning in primates, there has been conspicuously little attention given to careful analysis of the changes in response probabilities throughout the course of learning for individual subjects. This is particularly true if one considers discriminations among more than two patterns presented simultaneously to the subject. There are a number of reasons for this lack of attention. First of all, the investigators have often been interested in questions about the nature of the stimulus factors affecting problem difficulty, generalization, transposition, and so on. Generally the effects of these factors can be conveniently assessed by comparing "gross" measures such as mean trials to criterion, total errors, etc., from various groups of animals. Secondly, much of the work on primate pattern discrimination has been done in connection with studies of brain function in learning, and here too, such measures as mean trials to criterion have been a convenient way of exhibiting a deficit in learning of brain injured subjects relative to normal animals.

A final reason for the lack of attention to the details of changes in response probabilities has been the tendency of experimenters to deal primarily with group learning curves. This has been based on the assumption that results from individual subjects exhibit such marked fluctuations that only group analysis is feasible. The position taken here is that considerable regularity in individual data can be uncovered and that in this case, at least, much can be discovered about the learning process. To support this assertion, data will be presented from Rhesus monkeys trained to discriminate among 2 and 5 stimulus alternatives. In addition, a simple mathematical description of the learning will be offered, and will be used to further analyze the results.

The data reported here were collected in the laboratory of Dr. K. H. Pribram as part of a larger study concerned with the effects on discrimination ability of two types of lesions in the inferotemporal neocortex (Pribram, Blehert, and Spinelli, 1965).

Method

Subjects. The subjects were 8 Rhesus monkeys 12-18 months old at the start of training. They comprised the Normal (nos. 160, 162, 165, and 170) and Crosshatch (nos. 158, 159, 161, and 166) groups of the study dealing with the inferotemporal cortex. Prior to discrimination training the Crosshatch subjects underwent surgery in which a net of small vertical subpial cuts was made bilaterally in the inferotemporal cortex (see report for details). No differences could be detected between the Crosshatch and Normal groups on any of the tasks, and they will be treated together in this report.

Apparatus. All testing was carried out in the DADTA machine (Pribram, et al., 1962), an apparatus for programmed presentation of stimulus patterns and automatic response recording. The subject sat in a traveling cage facing an array of 16 plastic panels (4 × 4 array), onto which the stimulus patterns were projected from the rear. When the subject pressed any panel on which a pattern appeared, a microswitch was activated and the discriminanda disappeared for 6 sec., after which they reappeared on another randomly chosen set of panels. If the stimulus chosen was the correct one, a peanut was delivered into a cup in the center of the array. If an incorrect stimulus was pressed, nothing happened during the intertrial interval. Responses to panels on which no pattern was displayed produced no change in the display. Presentation of stimuli was controlled automatically from an adjacent room and the responses (position and identity of the stimulus chosen) were recorded on punched tape. An overhead light provided illumination in the testing cage, and the noise of a blower masked extraneous sounds.

Pretraining. Subjects were trained to enter traveling cages from their home cages and were gradually shaped in the testing apparatus to press any panel on which an illuminated pattern appeared. The pattern used for pretraining was the number 1. The number of lighted 1's was gradually reduced from 12 to 1, and shaping continued until the subject responded about 60 times over 2 consecutive days to presentation of a single 1.

Throughout training (except just prior to surgery and during the 2 weeks allowed for recovery) subjects were fed 8-10 standard lab pellets per day and an occasional orange in addition to the peanuts they obtained during testing. Surgery for the Crosshatch subjects followed pretraining. After recovery, retention of the pretraining responses was checked for all of the animals and then training began.

Training. Fifty trials were given per day. The only exceptions were the 30 trials of the first day and the few times when a subject refused to test. All discrimination training was continued until the subject reached a criterion of 90% correct on 2 consecutive days. The discriminations which the subjects learned were as follows:

Two-stimulus discrimination: The discriminanda were the numbers 3 and 8. The positive stimulus was 3. On each trial the following sequence of events occurred. The 3 and 8 appeared on 2 panels chosen randomly from among the 16 panels available. The subject made a choice by pressing one of the 2 panels; if the choice was correct he was rewarded. In the event of either a correct or an incorrect response the stimuli disappeared for the 6 sec. intertrial interval and then reappeared on 2 more randomly chosen panels.[2]

Multiple-stimulus discrimination: The 5 stimuli for this discrimination were the capital letters A, H, K, N, and M. The M was rewarded the stimulus pattern. The sequence of events on each trial was identical to that of the previous discrimination except for the number of patterns displayed.

Results and Discussion

The trials to criterion, N_c, on the two discriminations (Table 1) indicate that the 3-8 discrimination was considerably easier than the multiple discrimination and that there was no significant difference between the Crosshatch and Normal groups.[3]

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[2]A very simple discrimination between a Red and a Green circle was presented between the two-alternative and the five-alternative discriminations. The results are not relevant to this paper. They can be obtained from the report of the inferotemporal lesions.

[3]Subject 170 will be dropped from the rest of the analysis. The taped records of his performance on 3 days of the multiple discrimination are incomplete, and only the number of correct responses could be determined.

Table 1

Total Trials to Criterion, N_c, for Each Subject on Two-Stimulus and Multiple-Stimulus Discriminations

Subject	N_c 3 vs. 8	N_c Multiple
N-160	380	800
N-162	280	400
N-165	380	550
N-170	450	700
C-158	480	400
C-159	280	575
C-161	680	750
C-166	230	450
Ave. including Subject 170	395.0	578.1
Average	387.2	560.7

The individual learning curves of Fig. 1 show that the probability of a response to the correct cue in the 3-8 discrimination, Pr(3), does not rise gradually from the beginning of training. For all of the subjects except one there are at least 2 days during which no change occurs in Pr(3). This period is succeeded by a gradual increase in Pr(3) to the criterion level. The one exception, subject 162, starts to discriminate by the second block of 25 trials. In contrast to these individual learning curves, the mean learning curve (obtained by assuming each subject to be responding perfectly after criterion) rises gradually throughout with only a small initial negative acceleration to hint at what is occurring in the individual subject's data (Fig. 2a).

That this long initial period during which there is no change in the response probabilities is not peculiar to the two-choice situation and is not due to the monkey's lack of familiarity with the discrimination procedure, is demonstrated by the individual learning data from the multiple stimulus problem (Fig. 3). All of the cues are chosen with equal probability before the A, H, and K as a group are discriminated from the M and N. As the AHK group drops out, the remaining responses are divided between the M and the N until they are discriminated from each other. Because there appeared to be no discrimination among the A, H, and K by any subject, the mean choice probabilities of these 3 cues are shown in each graph and are labeled $\overline{\mathrm{Pr(A)}}$. That is, $\overline{\mathrm{Pr(A)}}$ in the figures is equal to 1/3 of the sum of Pr(A), Pr(H), and Pr(K). As in the 3-8 discrimination, the mean learning curve for all of the subjects (Fig. 2b) does not reflect accurately what is happening in the individual curves. The initial period of equal choice among the cues is evident,

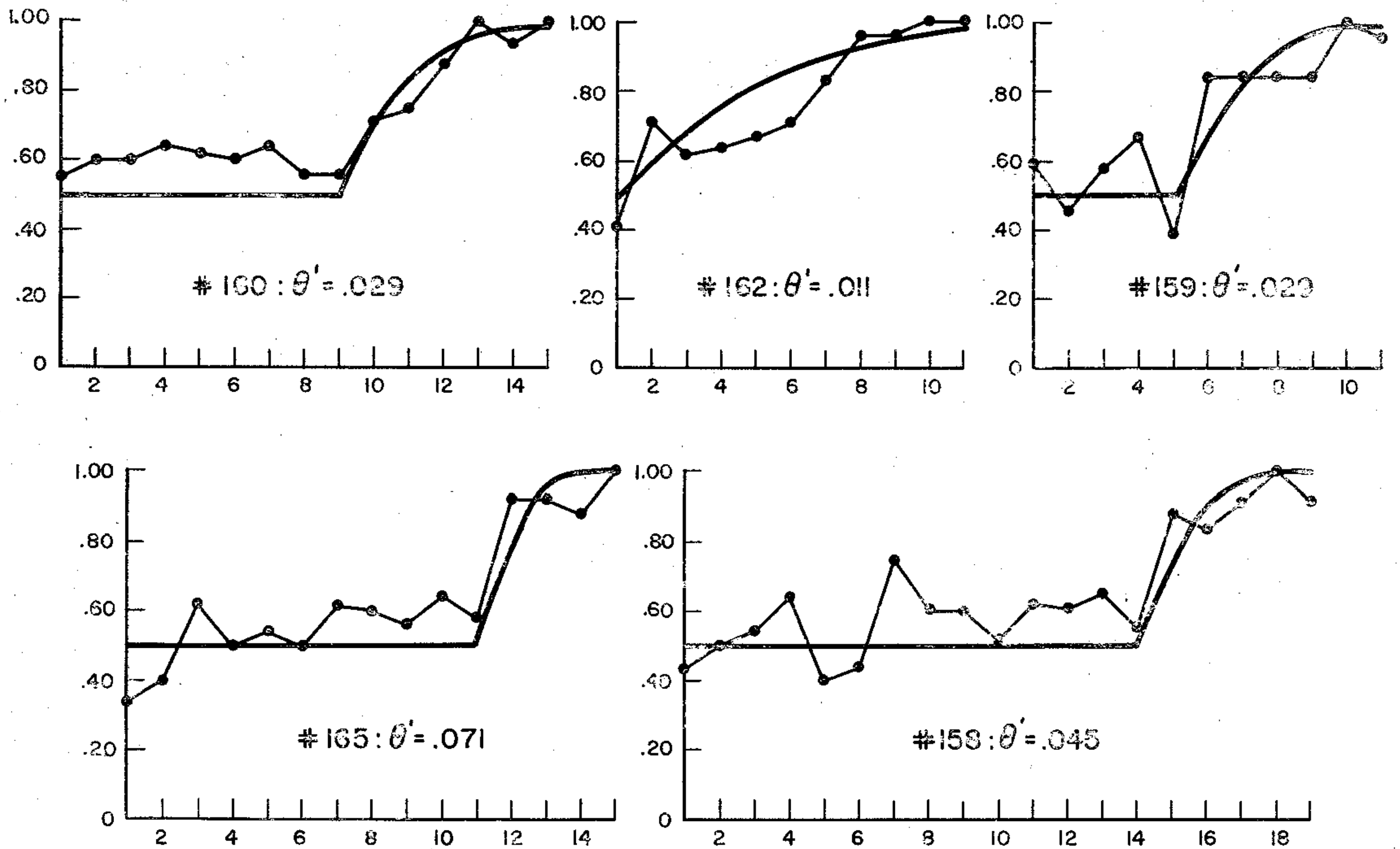

Figure 1: Observed and predicted proportion correct responses for individual subjects on the two stimulus discrimination. Each point is the mean for a 25-trial block (the first point has 30 trials). The values of N' and θ' used in constructing the theoretical curves are those given in Table 2.

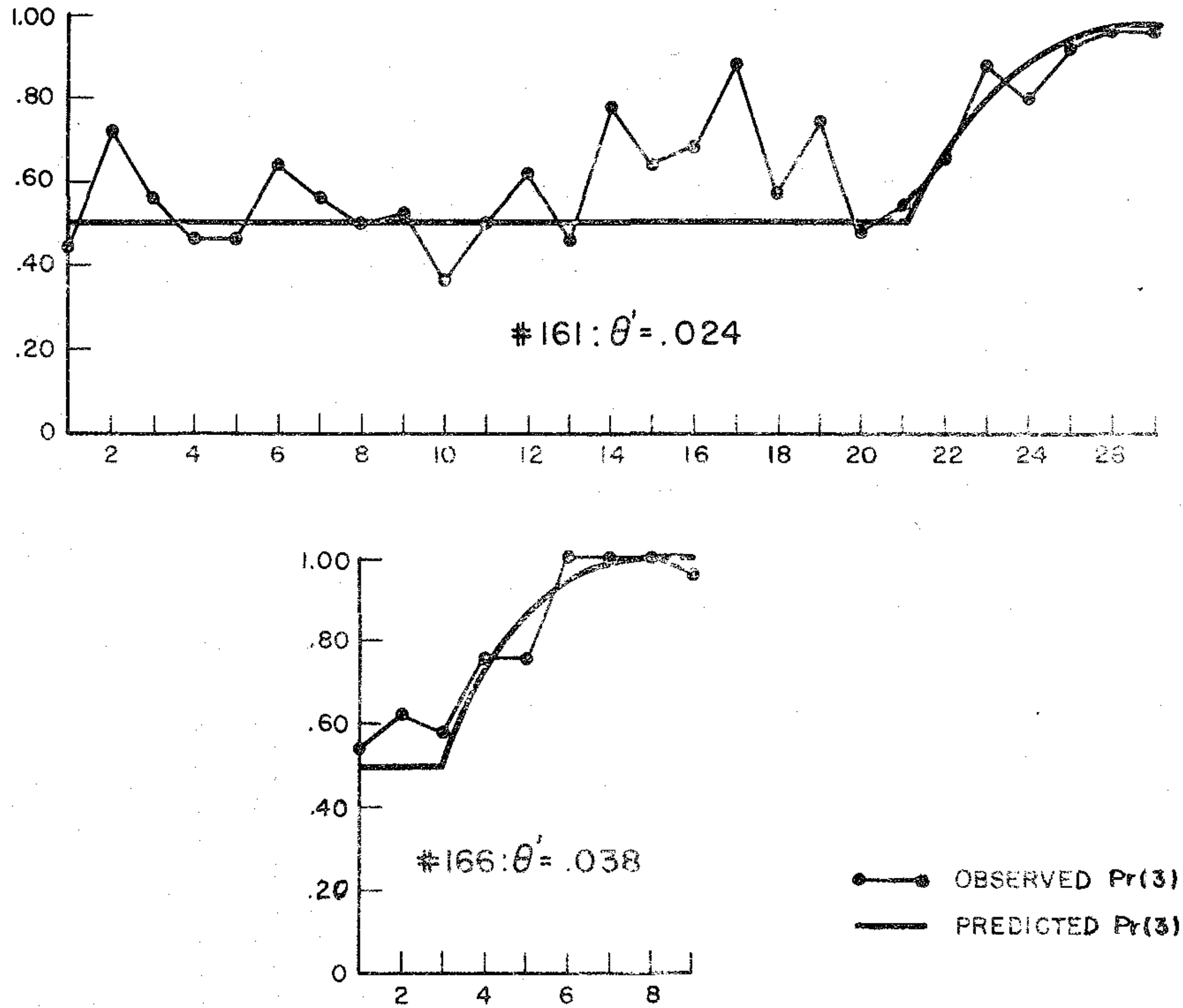

Figure 1 continued

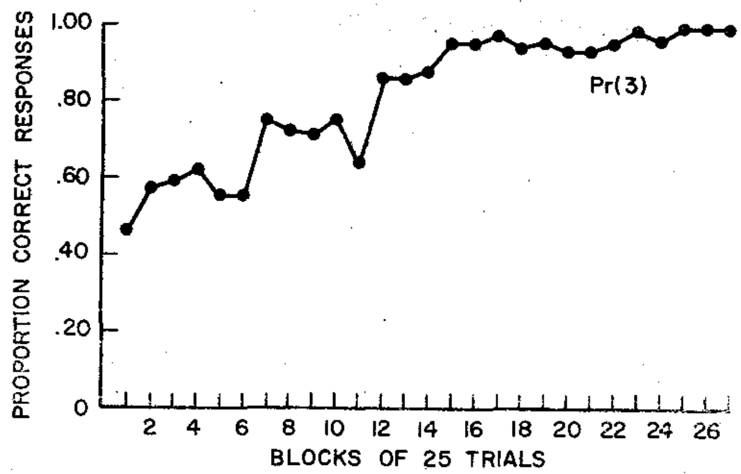

Figure 2a. Mean proportion correct responses, Pr(3), on two stimulus discrimination. Each point is the mean for a 25-trial block and includes all of the subjects by assuming no errors after criterion. N = 7.

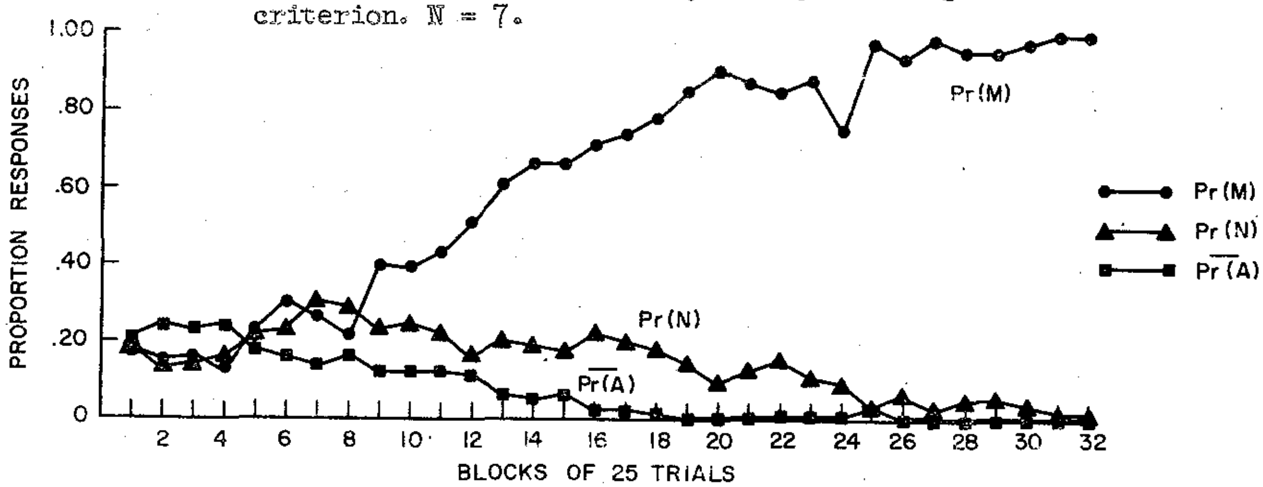

Figure 2b. Mean proportion responses to each stimulus on multiple discrimination in 25-trial blocks. N = 7.

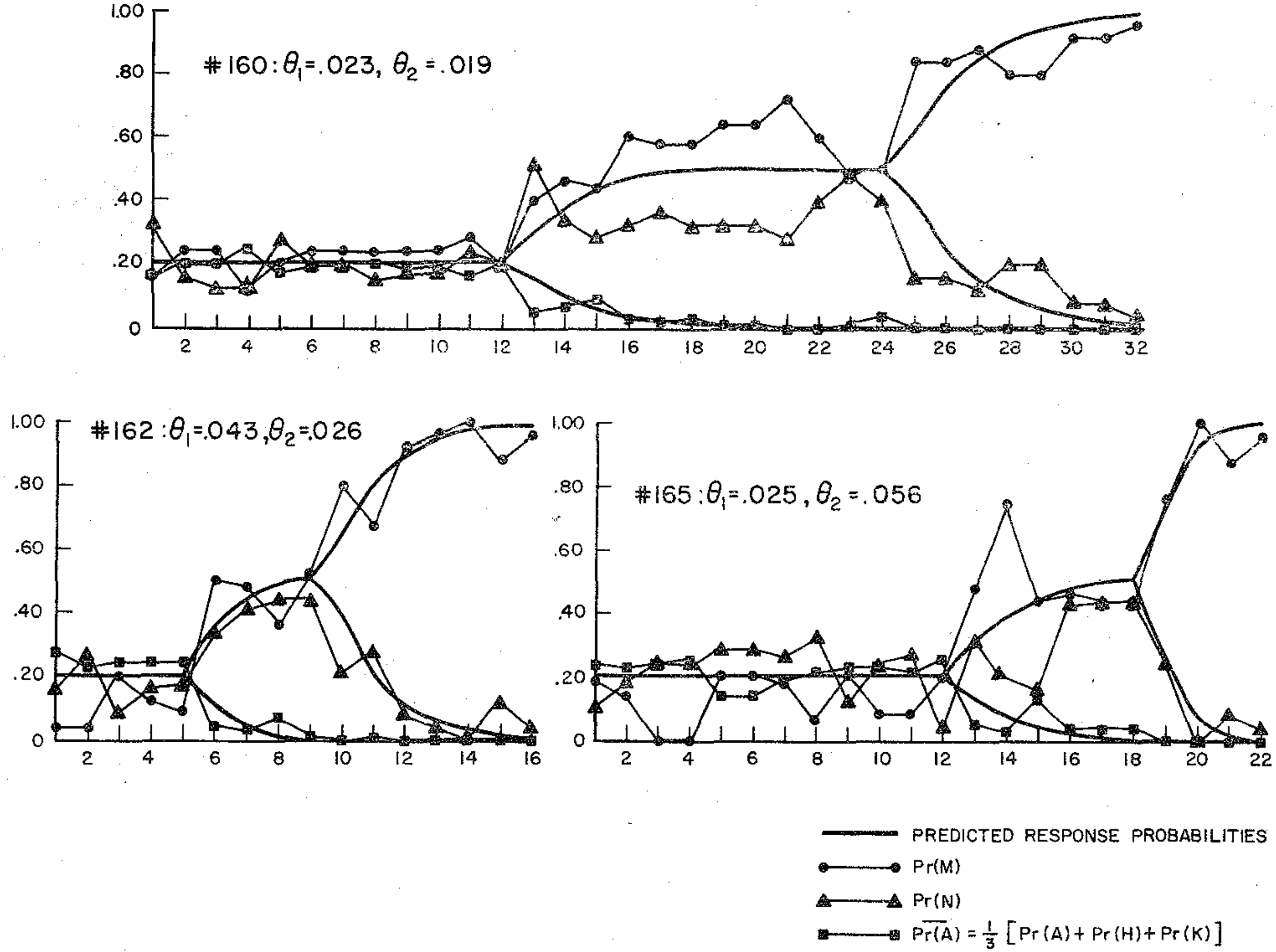

Figure 5: Observed and predicted proportion responses to each stimulus for individual subjects on multiple discrimination in 25-trial blocks. The values of N_1, N_2, θ_1, and θ_2 used in constructing the theoretical curves are those given in Table 2. $\overline{Pr(A)}$ is the mean proportion responses to the A, H, and K stimuli, i.e., $\overline{Pr(A)} = \frac{1}{3}[Pr(A) + Pr(H) + Pr(K)]$.

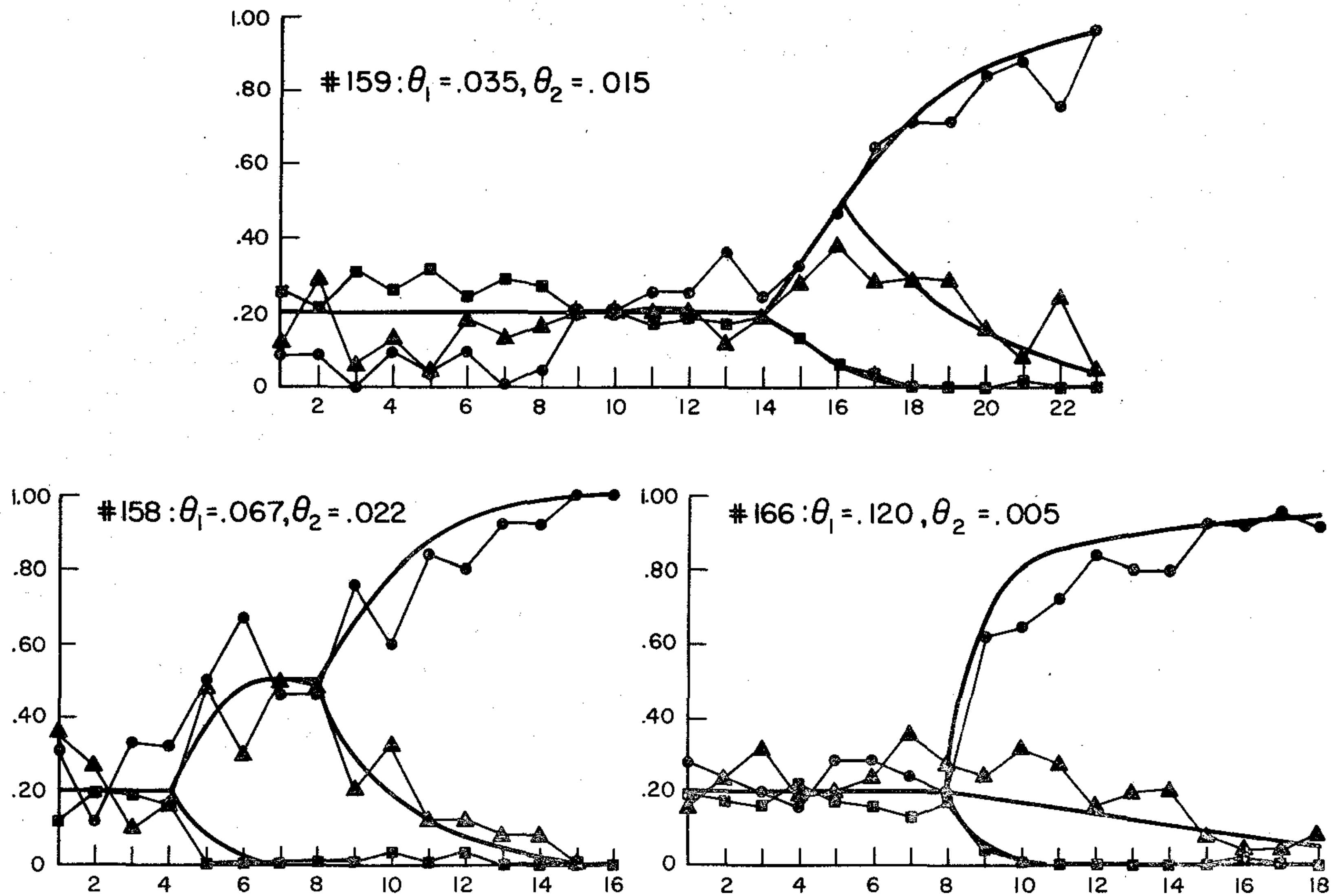

Figure 3 continued

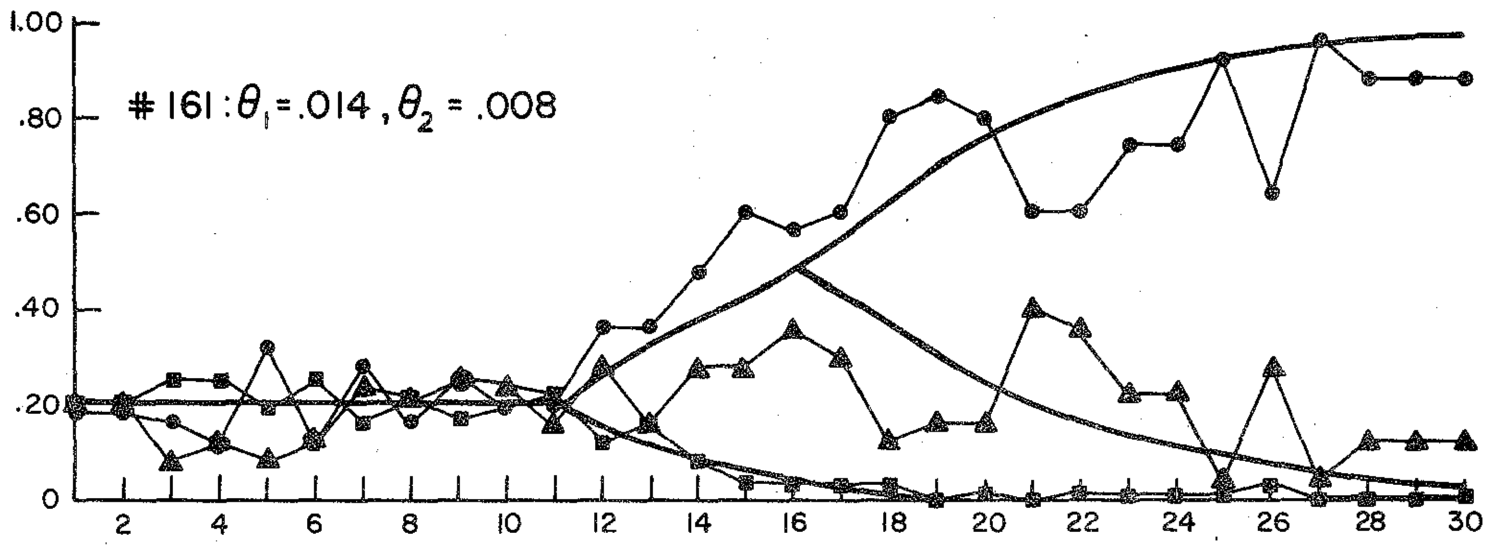

Figure 3 continued

but then learning seems to be very gradual with stimulus N dropping out at a somewhat slower rate than the AHK group.

A more detailed examination of this learning process can be achieved by translating the verbal description given above into a set of equations which specify the response probabilities throughout learning. Consider first the two-choice situation. Let n represent the trial number, and let N' be the trial on which discrimination between the two stimuli first begins. Then translating our verbal description of the behavior:

$$\Pr(3_n) = \begin{cases} \frac{1}{2} & , \text{ for } n \leq N' \\ 1 - \frac{1}{2}(1-\theta')^{n-N'} & , \text{ for } n > N' \end{cases}$$

where of course $\Pr(3_n) = 1 - \Pr(8_n)$.

The multiple-choice case can be formulated in a comparable manner, where N_1 represents the trial on which the AHK group begins to drop out, and N_2 represents the start of discrimination between the M and the N:

$$\Pr(M_n) = \begin{cases} \frac{1}{5} & , \text{ for } n \leq N_1 \\ \frac{1}{2}[1 - (1-\theta_1)^{n-N_1}] + \frac{1}{5}(1-\theta_1)^{n-N_1} & , \text{ for } N_1 < n \leq N_2 \\ 1 - \frac{1}{2}(1-\theta_2)^{n-N_2} & , \text{ for } n > N_2 \end{cases}$$

$$\Pr(N_n) = \begin{cases} \frac{1}{5} & , \text{ for } n \leq N_1 \\ \frac{1}{2}[1 - (1-\theta_1)^{n-N_1}] + \frac{1}{5}(1-\theta_1)^{n-N_1} & , \text{ for } N_1 < n \leq N_2 \\ \frac{1}{2}(1-\theta_2)^{n-N_2} & , \text{ for } n > N_2 \end{cases}$$

$$\Pr(A_n) = \begin{cases} \frac{3}{5} & , \text{ for } n \leq N_1 \\ \frac{3}{5}(1-\theta_1)^{n-N_1} & , \text{ for } N_1 < n \leq N_2 \\ 0 & , \text{ for } n > N_2 . \end{cases}$$

Figure 4 shows the learning curve generated for the multiple discrimination by these equations using illustrative values of the parameters N_1, N_2, θ_1, and θ_2. Prior to N_1 the cues are chosen equally. At N_1 the AHK group begins to drop out with a rate given by θ_1, and $Pr(M_n)$ and $Pr(N_n)$ rise together to 1/2. At N_2 the stimulus N begins to drop out with rate θ_2, and $Pr(M_n)$ rises to 1.[4] The form of the learning curve for the two-stimulus discrimination will be apparent from the preceding discussion.

Estimates of N', N_1, and N_2 for each subject were obtained by setting them equal to the number of the last trial of the block preceding that block in which the appropriate probabilities appeared to separate (Table 2). More sophisticated methods of estimation could be used, but it was felt that these estimates obtained by visual inspection were sufficient for the purposes of this paper. The reader may determine whether or not significant biases seem to have been introduced by the values chosen. The means of the obtained estimates are: $\bar{N}' = 233.6$, $\bar{N}_1 = 205.7$, and $\bar{N}_2 = 353.6$. Thus, in the 3-8 discrimination it took an average of approximately 5 days for the subjects to reach N' and about 3 more days to reach criterion. In the multiple discrimination, N_1 was reached in about 4 days, N_2 in 3 additional days, and criterion after another 4 days.

These estimates permit the construction of meaningful summaries of the data for the whole group in the form of modified Vincent curves. The

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[4]Note that $Pr(A_n)$ for $N_2 < n$ is arbitrarily set equal to 0. This is not a necessary restriction in the model, but is done on the assumption that its actual value by trial N_2 will be small.

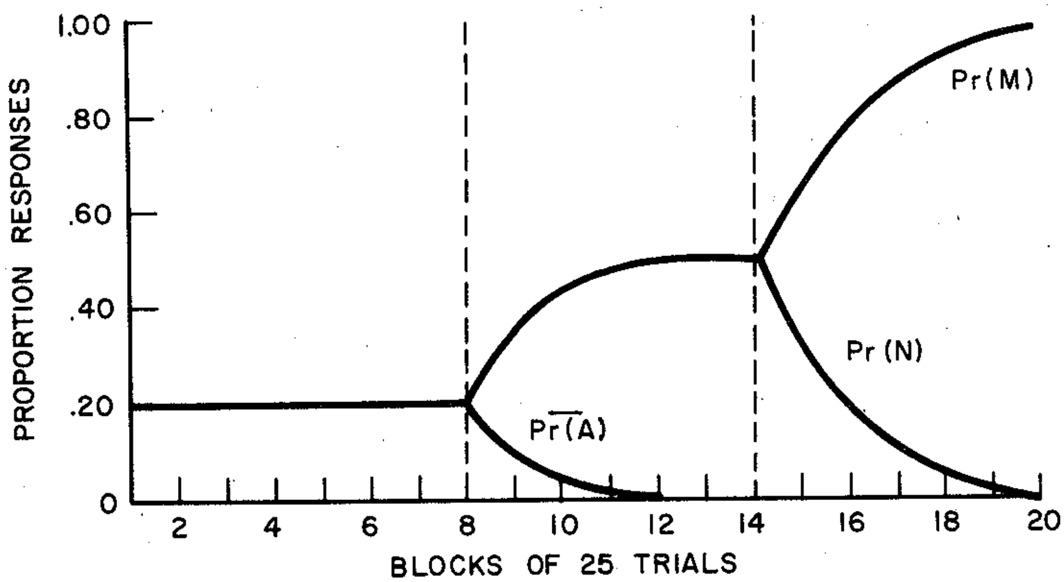

Figure 4: Example of predicted proportion responses to each stimulus in multiple discrimination. 25-trial blocks. $\overline{Pr(A)}$ is mean proportion responses to the A, H, and K. Parameter values used are the average values for the group: $N_1 = 205.7$, $N_2 = 353.6$, $\theta_1 = .047$, and $\theta_2 = .022$.

Table 2

Parameter Estimates for Each Subject on Two-Stimulus and Multiple Stimulus Discriminations. Estimates are Given for N', θ', N_1, N_2, θ_1, and θ_2, and for the Values of $N_c - N'$ and $N_c - N_1$ Resulting from These Estimates. Means and Standard Deviations Appear in the Last Two Rows.

Subject	N'	$N_c - N'$	$\hat{\theta}'$	N_1	N_2	$N_c - N_2$	$\hat{\theta}_1$	$\hat{\theta}_2$
160	230	150	.029	300	600	200	.023	.019
162	30	250	.011	125	225	175	.043	.026
165	280	100	.071	300	450	100	.025	.056
158	355	125	.045	100	200	200	.067	.022
159	130	150	.029	350	400	175	.035	.015
161	530	150	.024	275	400	350	.014	.008
166	80	150	.038	200	200	250	.120	.005
Average	233.6	153.6	.035	205.7	353.6	207.1	.047	.022
σ	160.6	30.2	.018	88.5	140.4	71.6	.034	.016

learning curves for each subject were aligned at trial N' and the 2 parts thus formed were each Vincentized in fifths (Atkinson, Bower, and Crothers, 1965). For example, subject 160 has 9 blocks of trials prior to N' and 6 blocks from N' to N_c. The first 9 blocks were collapsed into 5 parts by multiplying Pr(3) in each block by an appropriate fraction. Thus, Pr(3) in the first fifth is given by $(5/9)(.55) + (4/9)(.60) = .57$. This was done for both parts of the 3-8 discrimination and the resulting probabilities were averaged over the subjects. In the case of the multiple discrimination the same procedure was followed, this time aligning the subjects at N_1 and N_2 and Vincentizing in fifths between these points. The results--a two-segment Vincent curve for the 3-8 discrimination and a three-segment Vincent curve for the multiple discrimination--are shown in Figs. 5a and 6a. Each segment of the Vincent curve is drawn so that its length is proportionate to the mean number of trials spent by the group on that segment (e.g., in the ratio of 205.7:147.9:207.1 for the multiple discrimination).

For purposes of comparison, Vincent curves were constructed in the normal manner, that is, by dividing the <u>total</u> number of learning trials into 10 parts (3-8 discrimination) in the same manner as above, but without regard for trial N'. The data for the multiple discrimination was divided into 15 such parts. These Vincent curves appear in Figs. 5b and 6b. As would be expected, this averaging procedure tends to obscure the significant features of the data, although the initial period of random choice and the increase in Pr(N) as the AHK group is eliminated are still perceptible. And even though the normal (or unsegmented) Vincent curves are not as informative as those constructed using the parameter estimates,

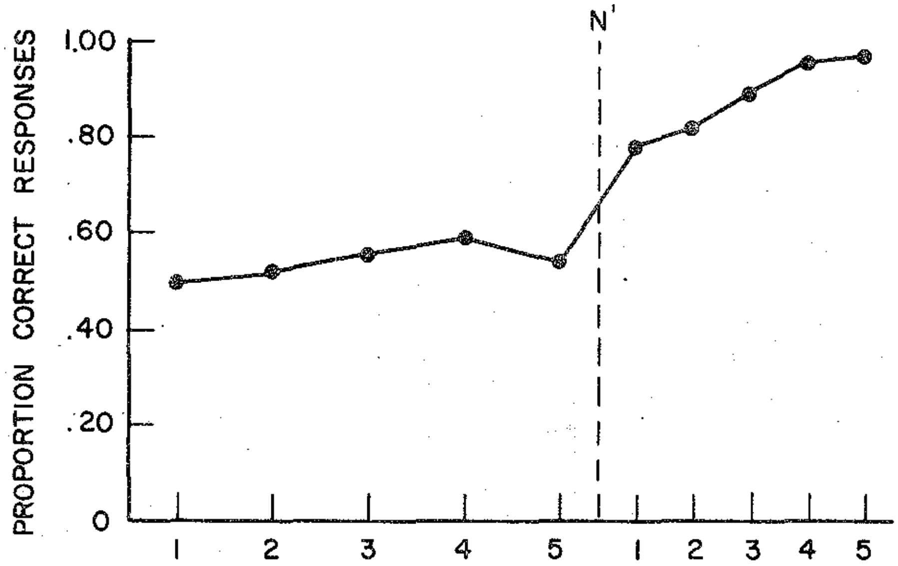

Figure 5a: Two-segment Vincent curve for two-stimulus discrimination. Each point within the segments before and after trial N' is the mean proportion correct responses for one-fifth of that segment (see text). N = 7.

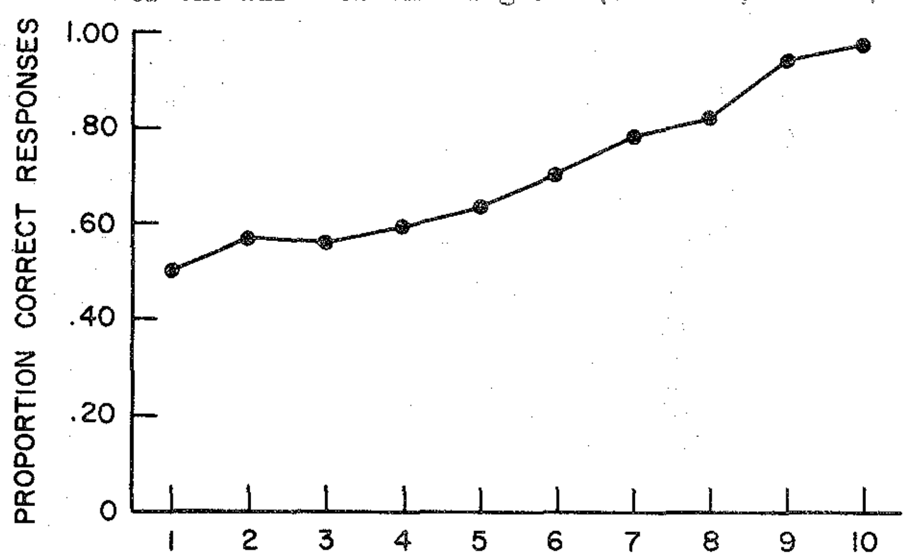

Figure 5b: Regular Vincent curve of proportion correct responses in two-stimulus discrimination. Each point is mean proportion for one-tenth of the total trials. N = 7.

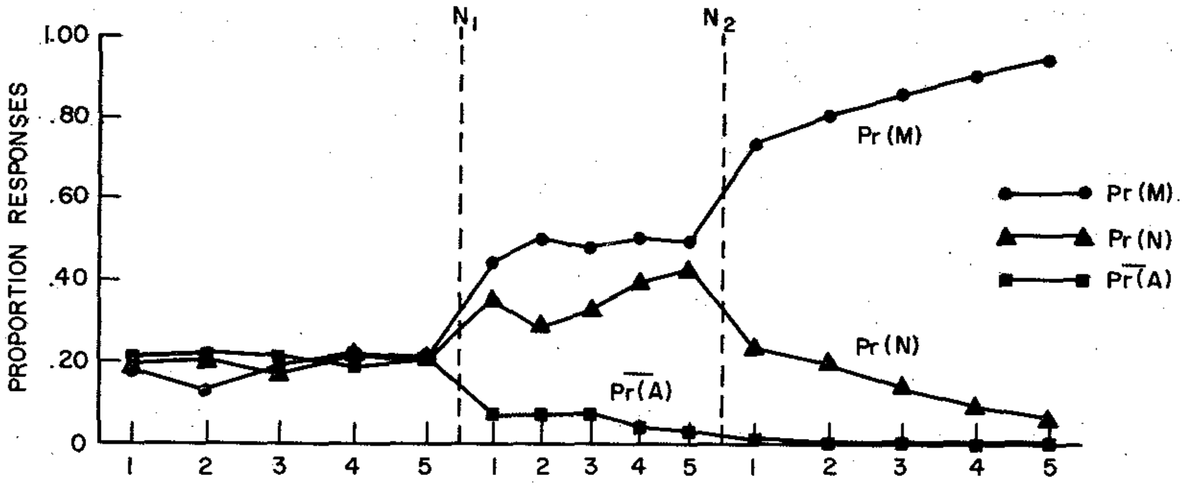

Figure 6a: Three-segment Vincent curve for multiple stimulus discrimination. Each point within the segments marked of by trials N_1 and N_2 is the mean proportion responses for one-fifth of that segment. N = 7.

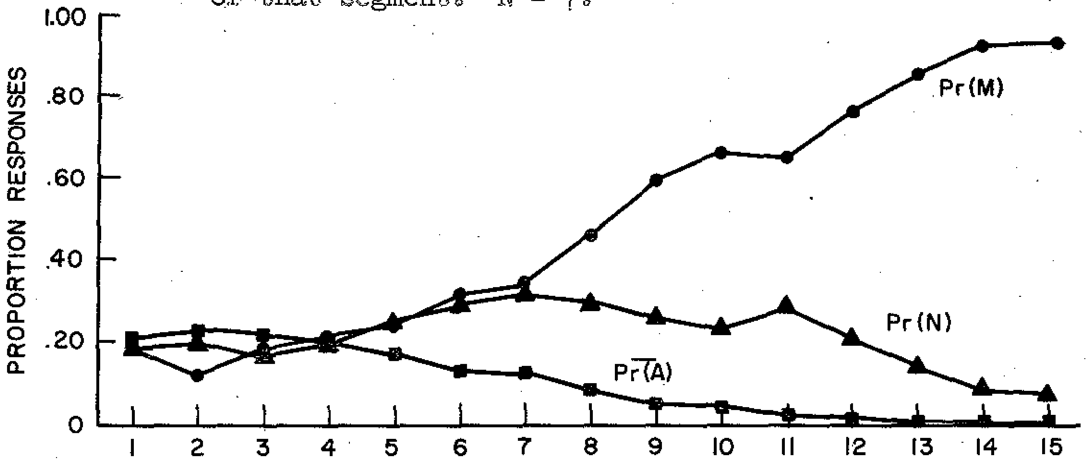

Figure 6b: Regular Vincent curve of proportion responses to each stimulus in multiple stimulus discrimination. Each point is mean proportion for one-fifteenth of the total trials. N = 7.

they still preserve more information than do the mean learning curves of Figs. 2a and b.

Consideration of Table 2 reveals a very small variability among subjects in the number of trials between N' and criterion, N_c. The standard deviation of the length of this segment is 30.2 trs. as compared to 160.6 trs. for the standard deviation of N'. This would suggest that the total number of trials which a subject requires to learn the discrimination is primarily determined by the length of the initial segment, rather than by the rate at which discrimination is attained after it once begins. Additional support for this observation comes from the lack of correlation between N' and $N_c - N'$ ($\rho = -.48$), which suggests that there are not consistent individual differences leading to faster learning in both segments.

Such a notion would predict that the variability of N_1 and of $N_2 - N_1$ in the multiple discrimination would be greater than the variability in $N_c - N_2$. The observed are standard deviations, 88.5 trs. and 140.4 trs. compared to 71.6 trs. in the last segment. The second segment, $N_2 - N_1$, would be expected to have the greatest variability because it includes any variability which does exist in the number of trials taken to eliminate the AHK group. Although one would hesitate to attach too much significance to these values, they seem consistent with the idea that the most variable process is the initial elimination of responses to irrelevant cues before discrimination begins. It should be noted that one cannot conclude from this data that this variability depends on differences in the abilities of the subjects, and the idea discussed above does not require that it do so. In fact, there is a lack of correlation between the lengths of the initial segments, N' and N_1, on the two discriminations ($\rho = .13$).

The estimated values of N', N_1, and N_2 can also be used to obtain estimates of θ', θ_1, and θ_2 for each subject. For θ' this was done by setting the observed number of incorrect responses after N' equal to the theoretical value and solving for $\hat{\theta}'$, namely, $\hat{\theta}'$ is given by

$$\hat{\theta}' = \left[2 \sum_{n=N'}^{N_c} \Pr(8_n)\right]^{-1} .$$

In similar fashion, the observed number of AHK responses after N_1 and of N responses after N_2 were used to estimate θ_1 and θ_2 (Table 2). The mean values of these estimates are : $\hat{\theta}' = .035$, $\hat{\theta}_1 = .047$, and $\hat{\theta}_2 = .022$. The AHK group was not only eliminated first by all of the subjects, but with one exception (subject 165) it was eliminated at a faster rate than the stimulus N.

The individual learning curves generated by the model using the various parameter estimates are shown in Fig. 1 for the 3-8 discrimination and in Fig. 3 for the multiple discrimination. They can be compared to the observed learning curves to obtain an idea of the adequacy of the mathematical description. A statistical test of the correspondence of the model and the data could be performed, but it is obvious from the variability of the individual curves and the number of observations that such a test would lead to rejection of the model. What is emphasized here is the qualitative similarity between the behavior of the model and the data.

A few discrepancies between model and data deserve comment. In the 3-8 discrimination all of the subjects start with a slight bias toward the 3. This is probably due to the slight disadvantage of the 8 in brightness because of the lateral location of the bulb which illuminates it in the display units. The apparent fit of the equations could be improved if $Pr(3_n)$ for $n \leq N'$ were determined from the data. The effect of this would be to slightly lower the estimated $\hat{\theta}$'s. These new estimates have been examined, and the amount of change is quite small.

One other assertion of the model is not borne out in the data, and the reason for this is not entirely clear. During the trials between N_1 and N_2, $Pr(M_n)$ and $Pr(N_n)$ should be equal. Instead, $Pr(M_n)$ seems to be slightly higher than $Pr(N_n)$ for a number of the subjects. This difference, if anything, tends to decrease (in both the individual and the group curves), which makes it plausible that $Pr(N_n)$ is being depressed because of some generalization between the N and the AHK group that diminishes as these latter cues are eliminated. It might be suspected that the difference results from selecting a value of N_2 which is too large, that is, that the learning is much more gradual than the selected values would indicate. In this case, it is difficult to see why the difference between $Pr(M_n)$ and $Pr(N_n)$ would not increase.

Although it is not the primary purpose of this paper, it is interesting to speculate about the events occurring on individual trials which could generate the process described above. The finding that there are <u>long</u> periods of random responses among stimuli forces the conclusion that during these periods there is a gradual <u>increase</u> in the probability that the subject will begin to respond to the properties which are relevant in distinguishing one group of stimuli from another. The converse assumption, that this probability is constant (or decreasing), would imply that N', for example, should occur most often on trial 1, and progressively less often on later trials for various animals. This prediction is analogous to the geometric distribution of the trial of last error which is predicted by the simple one-element model (Atkinson, Bower, and Crothers, 1965).

One can now ask if this progressive, though not necessarily efficient, elimination of cues is taking place primarily on correct or incorrect responses, but here the data cannot provide any model-free information. It produces equivalent predictions about the qualitative pattern of elimination of incorrect relevant cues to assume either that an error leads to discrimination of some difference between correct and incorrect cues, or to assume that this occurs on successful trials, or both. Only if specific assumptions about the relative importance of successes and errors are made within the context of a learning model and this model is tested can the question be answered. The data from this study are felt to be too complex, because of the unanticipated grouping of the A, H, and K, to warrant the necessary analysis. This analysis will be attempted when data is obtained from a three-alternative problem with more control over stimulus similarity.

Conclusion

The individual subject data from both two- and five-alternative pattern discriminations supports the view that there is a progressive elimination of responses to irrelevant aspects of the discriminanda. At some point discrimination of one group of cues from another begins and the subject gradually learns to avoid the incorrect group. Choices are divided equally among any remaining cues until further discrimination begins. This process continues until the incorrect cues have all been eliminated and only the correct one is chosen. This successive elimination of cues was made particularly obvious in the five-alternative discrimination because the same group of stimuli was eliminated first by all of the subjects and because there were about 150 trials intervening before the last stimulus was dropped.

The consistency of behavior found among the individual subjects is encouraging. As we have shown, once this consistency has been described by a set of simple mathematical equations, it can be captured in appropriately constructed group learning curves and not be lost as it would be with the usual averaging procedures.

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