INFORMATION TO USERS

This material was produced from a microfilm copy of the original document. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the original submitted.

The following explanation of techniques is provided to help you understand markings or patterns which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting thru an image and duplicating adjacent pages to insure you complete continuity.
2. When an image on the film is obliterated with a large round black mark, it is an indication that the photographer suspected that the copy may have moved during exposure and thus cause a blurred image. You will find a good image of the page in the adjacent frame.
3. When a map, drawing or chart, etc., was part of the material being photographed the photographer followed a definite method in "sectioning" the material. It is customary to begin photoing at the upper left hand corner of a large sheet and to continue photoing from left to right in equal sections with a small overlap. If necessary, sectioning is continued again — beginning below the first row and continuing on until complete.
4. The majority of users indicate that the textual content is of greatest value, however, a somewhat higher quality reproduction could be made from "photographs" if essential to the understanding of the dissertation. Silver prints of "photographs" may be ordered at additional charge by writing the Order Department, giving the catalog number, title, author and specific pages you wish reproduced.
5. PLEASE NOTE: Some pages may have indistinct print. Filmed as received.

University Microfilms International
300 North Zeeb Road
Ann Arbor, Michigan 48106 USA
St. John's Road, Tyler's Green
High Wycombe, Bucks, England HP10 8HR

77-19,552

RICHTER, Ellen Marie, 1946-
ABSOLUTE JUDGMENTS OF LUMINANCE BY PIGEONS.

The City University of New York,
Ph.D., 1977
Psychology, experimental

Xerox University Microfilms, Ann Arbor, Michigan 48106

ABSOLUTE JUDGMENTS OF LUMINANCE BY PIGEONS

by

ELLEN MARIE RICHTER

A dissertation submitted to the Graduate Faculty in Psychology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York.

This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

May 13, 1977
date

Sheila Chase
Chairman of the Examining Committee

May 16, 1977
date

Florence L. Denmark
Executive Officer

Sheila Chase

Eric G. Heinemann

Robert L. Thompson
Supervisory Committee

The City University of New York

Abstract

ABSOLUTE JUDGMENTS OF LUMINANCE BY PIGEONS

by

Ellen Marie Richter

Advisor: Professor Sheila Chase

Pigeons were required to peck one of a row of four choice keys. The correct key choice was cued by the luminance of a centrally located display key. This task is analogous to one in which humans are asked to make absolute judgments of stimuli presented individually by assigning each stimulus to a category. All experiments in the series show that the accuracy with which two stimuli are discriminated decreases as the range of stimuli to which the subject is exposed increases. This pheonmenon, the range effect, until now has been demonstrated only in humans.

Techniques derived from signal detection theory (SDT) were used to examine the subjects' sensitivity in discriminating between two stimuli differing from each other by .2 log ft.L. These stimuli were always in the center of a series consisting of four stimuli. The overall stimulus range was manipulated by increasing the separation of the brightest and dimmest stimuli in the series from the two central stimuli. According to SDT, this situation should result in equal sensitivity (<u>d</u>') measures regardless of the range condition. The results, however, clearly indicate

that _d'_ _does_ vary with range. Since input- and sensory-system noise should remain constant across ranges, this change in _d'_ was attributed to the subjects' maintaining less stable criteria between the two central stimuli.

In the narrow-range condition in Experiment 1, three pigeons identified four stimuli which were equally spaced over a narrow (.6 log unit) range. In the moderate-range condition three pigeons identified the same two central stimuli located in the center of a 1.4 log unit range. In all cases the narrow-range birds were better at identifying the central stimuli than the moderate-range birds.

In Experiment 2, twelve pigeons were trained for 160 days, six on the narrow range (.6 log unit) and six on a wide range (3 log units). Again the narrow-range birds showed greater sensitivity on the discrimination between the two central stimuli.

In Experiment 3, which lasted 25 days, the birds trained on the narrow-range condition in Experiment 2 were switched to the wide range and those trained on the wide range in Experiment 2 were switched were switched to the narrow range. Every bird switched to the wide range showed a decrease in sensitivity and every bird switched to the narrow range showed an increase in sensitivity.

It has been assumed that as the number of criteria which a subject is required to hold increases, criterion variability also increases. Experiment 4 was designed to

test this assumption and to see if the range effect would endure when pigeons were required to hold only one criterion. Eight pigeons, four on each range, were trained for 160 days using the same stimuli used in Experiment 2. The procedure was exactly the same as that used in Experiment 2 except that here the birds were required to peck one key when the brighter two stimuli were presented and another key when the dimmer two stimuli were presented. The range effect was again clearly demonstrated. Contrary to the assumption, sensitivity was lower for both groups in this experiment than for the comparable groups in the 3-criterion situation in Experiment 2.

Sequential data were analyzed but the preceding stimulus was found to have no clear effect on the probability of the birds' making any particular response on a given trial. Similarly, examination of the response latencies did not indicate any consistent trends.

Possible explanations of the range effect are reviewed and an explanation of the range effect in terms of the "relative value" of attending to the central stimuli is suggested.

Acknowledgements

Most of all I would like to thank Sheila Chase, my mentor. She generously gave many hours of her precious time working with me on this project. She guided me throughout, providing support and friendship in my times of desperation and encouraging me to constantly improve the final product.

I would also like to express my gratitude to Eric G. Heinemann who served on my dissertation committee and who was involved in this project from its inception for his many helpful suggestions and comments. I also offer thanks to Robert L. Thompson, my third committee member, whose continued support and advice were appreciated.

I would also like to thank Stanley Novak and Mitchell L. Kietzman who served as outside readers for their helpful comments on this manuscript. In addition, I thank the people at the Queens College computer center without whose help the sequential and latency data analysis would have been impossible. I also thank Kathy Landry for her help during the final months of these experiments.

More personally, I thank my father, Henry Richter, for the many tedious hours he spent preparing many of the figures included in this dissertation.

Table of Contents

Page

Abstract.......... iii

Acknowledgements.......... vi

List of Tables.......... viii

List of Illustrations.......... ix

INTRODUCTION.......... 1.

GENERAL METHOD.......... 26.

- Subjects.......... 26.
- Apparatus.......... 26.
- Procedure.......... 30.
- Pretraining.......... 31.

SPECIFIC EXPERIMENTS.......... 33.

- Experiment 1 - Narrow and Moderate Ranges.......... 33.
  - Method.......... 33.
  - Results.......... 34.
- Experiment 2 - Narrow and Wide Ranges.......... 59.
  - Method.......... 59.
  - Results.......... 63.
- Experiment 3 - Ranges Switched.......... 93.
  - Method.......... 93.
  - Results.......... 94.
- Experiment 4 - Single Criterion.......... 109.
  - Method.......... 111.
  - Results.......... 112.

DISCUSSION.......... 135.

APPENDICES.......... 153.

- Appendix A.......... 153.
- Appendix B.......... 165.
- Appendix C.......... 178.
- Appencix D.......... 184.

REFERENCES.......... 196.

List of Tables

Page

1. Experiment 1. d' for the last 25 days of... training.. 58.

2. Experiment 2. d', C and RBI for the last... 25 days of training......................... 86

3. Experiment 2. C on trials immediately...... following each of the 4 stimuli for the..... last 25 days of training.................... 90.

4. Experiment 2. Mean latency of display key.. pecks preceding R2 and R3 for the last 25... days of training............................ 92.

5. Experiment 3. d', C and RBI for the last... 25 days of training......................... 106.

6. Experiment 3. C on trials immediately...... following each of the 4 stimuli for the..... last 25 days of training.................... 107.

7. Experiment 3. Mean latency of display key.. pecks preceding R2 and R3 for the last 25... days of training............................ 110.

8. Experiment 4. d', C and RBI for the last... 25 days of training......................... 130.

9. Experiment 4. C on trials immediately...... following each of the 4 stimuli for the..... last 25 days of training.................... 132.

10. Experiment 4. Mean latency of display key.. pecks preceding R2 and R3 for the last 25... days of training............................ 134.

11. Experiments 1, 2 and 3. d' between all..... adjacent stimuli for all subjects in the.... narrow-range conditions..................... 146.

List of Illustrations

Page

1. Schematic representation of the decision problem.................................... 6.

2. Illustration of the intelligence panel..... 27.

3. Experiment 1. Percent correct first choices by 5-day block throughout training.................................. 35.

4. Examples of the 4-response choice curves and how they are combined................. 38.

5. Examples of the 4-response choice curves showing little or no stimulus control and a strong key preference.................... 41.

6. Experiment 1. 4-response choice curves for the narrow-range birds by 25-day block...................................... 43.

7. Experiment 1. 4-response choice curves for the narrow-range birds by 5-day block for the first 25 days of training.......... 45.

8. Experiment 1. 4-response choice curves for the moderate-range birds by 25-day block...................................... 47.

9. Experiment 1. 4-response choice curves for the moderate-range birds by 5-day block for the first 25 days of training.......... 49.

10. Experiment 1. z-ROC points for all birds based on the last 25 days of training...... 53.

11. Experiment 1. *d'* for each bird throughout training by both 5- and 25-day blocks...... 55.

12. Experiment 1. Comparison of *d'* for the two ranges throughout training by 5-day block...................................... 60.

13. Experiment 2. Percent correct first choices by 5-day block throughout training.................................. 64.

Page

14. Experiment 2. 4-response choice curves for the narrow-range birds by 25-day block.. 67.

15. Experiment 2. 4-response choice curves for the wide-range birds for the first and last 25 days of training.............. 70.

16. Experiment 2. 4-response choice curves for the wide-range birds for the first 10 days of training by 5-day block......... 72.

17. Experiment 2. *d*' for each of the wide-range birds throughout training by both 5- and 25-day blocks...................... 75.

18. Experiment 2. *d*' for each of the narrow-range birds throughout training by both 5- and 25-day blocks...................... 77.

19. Experiment 2. Comparison of *d*' for the two ranges throughout training by 5-day block.. 79.

20. Experiment 2. z-ROC points for all narrow-range birds based on the last 25 days of training................................... 82.

21. Experiment 2. z-ROC points for all wide-range birds based on the last 25 days of training................................... 84.

22. Experiments 2 and 3. Bar graph comparing *d*' in the narrow- and wide-range conditions for each bird............................. 95.

23. Experiment 3. z-ROC points for all birds switched to the narrow range based on the 25 days of training....................... 98.

24. Experiment 3. z-ROC points for all birds switched to the wide range based on the 25 days of training....................... 100.

25. Experiment 3. 4-response choice curves for a representative bird from each range condition for the 25 days of training by 5-day block.............................. 102.

Page

26. Experiment 4. Percent correct first choices by 5-day block throughout training....... 113.

27. Experiment 4. Proportion of R3 first choices in the presence of each stimulus for the narrow-range birds throughout training....... 115.

28. Experiment 4. Proportion of R3 first choices in the presence of each stimulus for the wide-range birds throughout training....... 117.

29. Experiment 4. d' for each of the narrow-range birds throughout training by both 5- and 25-day blocks....... 121.

30. Experiment 4. d' for each of the wide-range birds throughout training by both 5- and 25-day blocks....... 123.

31. Experiment 4. Comparison of d' for the two ranges throughout training by 5-day block....... 125.

32. Experiments 2 and 4. Comparison of d' for the two narrow-range conditions and for the two wide-range conditions by 5-day block throughout training....... 127.

33. Schematic representation of the changes expected in C if (a) sensory adaptation or (b) assimilation occurred....... 137.

34. Illustration of how d' is obtained using the ROC method and using the Thurstonian method....... 154.

35. Illustration of the logical equivalence of the ROC and Thurstonian methods....... 158.

The purpose of this research was to examine some of the factors influencing the accuracy of absolute judgments of luminance by pigeons.

In the method of absolute judgment (Wever & Zener, 1928) also known as the method of single stimuli (Woodworth & Schlosberg, 1954, p. 217), subjects are required to identify stimuli varying along a single physical dimension without reference to a comparison stimulus. Much of the early work in information theory used this procedure to determine how many unidimensional stimuli could be accurately identified by a human observer and what factors might influence this number. George Miller (1956) described the problem as follows:

> "If the human observer is a reasonable kind of communication system, then when we increase the amount of input information the transmitted information will increase at first and will eventually level off at some asymptotic value. This asymptotic value we take to be the channel capacity of the observer; it represents the greatest amount of information that he can give us about the stimulus on the basis of an absolute judgment. The channel capacity is the upper limit on the extent to which the observer can match his responses to the stimuli we give him." (p. 82)

Some examples of attempts to assess human channel capacity follow.

In 1952, Pollack carried out a series of experiments in which he had subjects identify tones varying in frequency from 100 to 8000 Hz by assigning a number to each. The number of tones and the physical range over which they extended varied from experiment to experiment, but the tones in each experiment were always equidistant from one another in logarithmic steps. After the subject made his judgment, he was informed as to the correct response. Subjects could perfectly identify two or three tones and they still did quite well with four tones. Five or more tones led to frequent confusion, and fourteen tones resulted in the subjects making many mistakes. When these results were analyzed in terms of transmitted information, the channel capacity of the human observer for absolute judgments of pitch was found to be about six equally likely alternatives or 2.5 bits[1].

The total stimulus range in which any two stimuli appear has been found to influence the accuracy of identification of two stimuli within that range. It is reasonable to expect that as the distance between adjacent stimuli is increased subjects will confuse adjacent stimuli less often. Pollack, in his 1952 study, tested this hypothesis under two experimental conditions each using eight tones equally spaced on a logarithmic (log) frequency scale. In one condition the range over which the stimuli varied was 800 Hz and in the other 8000 Hz. Holding the lowest frequency of the series constant at 100 Hz, he varied the upper limit of the frequency range. He found only minimal increases in the accuracy of judgments despite this large increase in the physical difference between adjacent stimuli. In fact, if

---

[1] number of bits = $\log_2 \underline{n}$, where $\underline{n}$ is the number of equally likely alternatives or choices.

we evaluate performance in terms of physical units (Hz), increasing the separation between adjacent stimuli leads to poorer performance in that the difference threshold is greater under the "easier" (wider-range) condition. This phenomenon has come to be known as the range effect.

In a subsequent study, Pollack (1953) began with a series of nine tones equally spaced logarithmically over a 100 to 8000 Hz range. He then increased the input information by adding on a stimulus to each end of the display. The new range extended from 60 to 14000 Hz and consisted of eleven stimuli. This increase in input information resulted in a very small increase in transmitted information.

In a similar experiment, Garner (1953) varied the loudness of tones over a range of 15 to 100 dB SPL (.0002 dynes/cm^2) requiring subjects to identify 4, 5, 6, 7, 10 and 20 different intensities. Subjects were given practice sessions in which each intensity was identified for them until they reported that they believed no further improvement would result from additional practice. He found that the human observers' channel capacity for loudness is about 2.3 bits (approximately five perfectly discriminable categories).

The low channel capacity of human observers is not limited to the transmission of auditory information. In

1955, Beebe-Center, Rogers and O'Connell asked subjects to make judgments concerning the concentration of salt in solutions using 3, 5, 9 and 17 different concentrations ranging in equal subjective steps from .3 to 34.7 gm. NaCl per 100 cc. tap water. They found that only about four distinct categories could be utilized accurately, a channel capacity of only 1.9 bits.

Miller (1956) reviewed the work on absolute judgments of unidimensional stimuli done prior to that time and concluded:

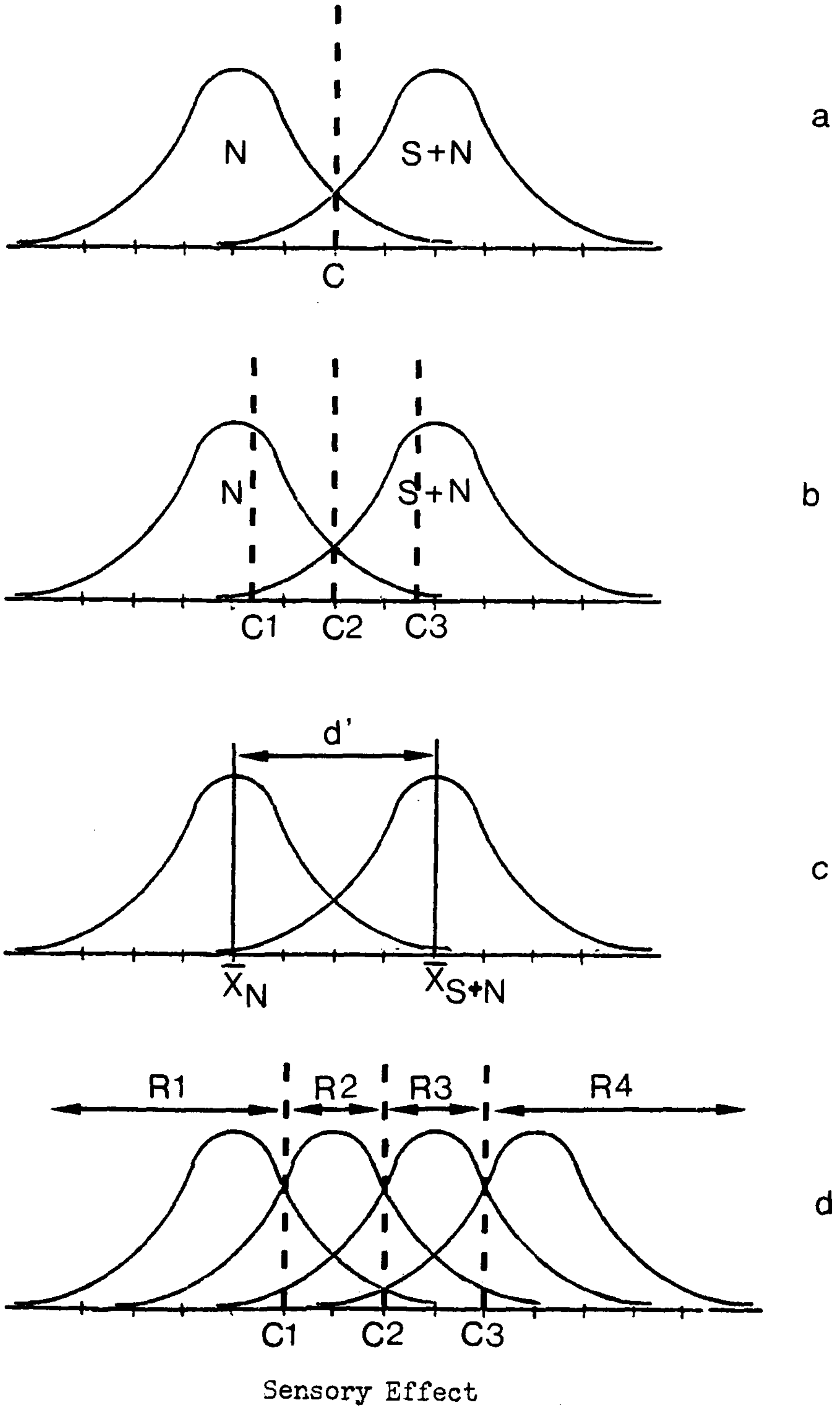
> "There seems to be some limitation built into us either by learning or by the design of our nervous systems, a limit that keeps our channel capacity in this general range. On the basis of the present evidence it seems safe to say that we possess a finite and rather small capacity for making such unidimensional judgments and that this capacity does not vary a great deal from one simple sensory attribute to another." (p. 86)

Since then, substantial work has been done, but most of the questions raised in the 1950's remain unanswered.

Recently signal detection theory (SDT) has been used to investigate human performance on absolute judgment tasks. This approach has the advantage of enabling investigators to evaluate performance in terms of two sets of processes: (1) sensory processes which deal with the representation of stimuli within the perceptual system; and (2) decision processes dealing with the assignment of responses to perceptual events. The theory assumes that sensory processes fluctuate randomly and thus are best represented by distributions rather than as discrete events or points on a sensory continuum. It has been assumed that one or more criteria are used in the decision stage to partition the sensory continuum into two or more regions corresponding to the response categories.

For example, a subject may be required to discriminate between those trials on which a near-threshold stimulus is presented and trials on which it is absent. This situation can be represented by two normal distributions as illustrated in Figure 1a. The momentary fluctuations of noise within the sensory system may be represented by the left-hand distribution. The right-hand distribution is Figure 1a represents the effects attributed to the signal plus the noise. In this illustration the distributions overlap. Since the identical sensory effect may be produced by either event, some errors are inevitable. Errors, however, may be minimized by setting a criterion (C) midway between the two distributions as shown in Figure 1a. The subject's decision rule is to say a signal was presented whenever the sensory effect exceeds his criterion (falls to the right of it). Such a response is correct, a <u>hit</u>, when the signal is presented. However, the sensory effect produced by noise alone will also on some trials exceed the criterion. In this case the subject will respond "yes" when a signal is

Figure 1. Schematic representation of the decision problem.


N
S+N
C
a
N
S+N
C1
C2
C3
b
d'
$\bar{X}_N$
$\bar{X}_{S+N}$
c
R1
R2
R3
R4
C1
C2
C3
d
Sensory Effect

not presented, i.e., a _false alarm_. The decision that noise alone occurred, a "no" response, is made when the sensory effect falls below (to the left of) the criterion. A "no" response when the stimulus has not been presented is called a _correct rejection_; a "no" response when the stimulus has been presented is called a _miss_.

The subject may be induced to shift his criterion by altering the consequences of his correct and incorrect responses (the _payoff matrix_), by changing the probability of the stimulus occurring (e.g., from 50% to 25% or 75%), or simply by instructing him to avoid making false alarms or alternately that he not miss. For example (see Figure 1b), a subject may minimize his false alarms by shifting his criterion from its original position (C2) to the right (C3). This, however, would also result in fewer hits. A subject may minimize his misses by shifting his criterion to the left (C1). At each of these criteria we can observe the proportion of hits to that of false alarms, and these observations can be plotted on a graph on which the ordinate represents the proportion of hits and the abcissa the proportion of false alarms. The function thus produced is known as the Receiver Operating Characteristic (ROC) curve.

SDT gives us a measure of sensitivity, _d'_ which is independent of the position of the subject's criterion. The _d'_ measure is the distance between the means of the two normal distributions divided by their common standard deviation (see Figure 1c). Thus the smaller the standard deviation, or the greater the difference between the means, the higher will be _d_'. If the distributions are assumed to be normal and or equal variance, _d_' may be obtained from tables of the area under the normal curve for any pair of hits and false alarms, and, of course, from the ROC curve which represents a number of such pairs (Green & Swets, 1966). Even if the assumption of equal variance cannot be made, alternate measures of sensitivity may be obtained from such data (Green & Swets, 1966; Simpson & Fitter, 1973).

Subjects can rate the confidence they have in their judgments that the stimulus was present or absent on each trial. Each confidence rating may be viewed as bounded by simultaneously held criteria such as those shown in Figure 1b. If C1, C2 and C3 in Figure 1b are regarded as simultaneously held criteria for four ratings of certainty (4 indicating the greatest certainty of presentation of the signal and 1 indicating the greatest certainty of non-presentation) then points on an ROC curve may be obtained by combining response categories as follows: The data resulting from the subject's certainty ratings can be described in terms of the probability of his responding "4" (hit and false alarm rates are obtained for this "high criterion"), the probability of his responding either "3" or "4" (hit and false alarm rates are obtained for this "slightly lower criterion"), and so on. As each successive category is added, the probability of both hits and false alarms rises thus generating a ROC curve from which _d_' may be obtained.

An adaptation of this rating scale method of obtaining _d_', referred to as the _ROC method_, has been applied to data obtained in absolute judgment tasks (Durlach & Braida, 1969; Cuddy, 1970; Shipley, 1970). Here the subject is usually required to identify two or more stimuli by number. In the simplest case there are an equal number of stimulus and response categories (R). This is illustrated for four stimuli and four responses in Figure 1d. The number of simultaneously held criteria is equal to the number of response categories minus 1. For any pair of stimuli, _d_' may be obtained by treating the responses made in the presence of these stimuli exactly as described above. In this case, however, the numbers used by the subject are not confidence ratings but represent attempts to identify each stimulus correctly.

A second but similar measure of sensitivity which has been applied to absolute judgment data (Graveter & Lockhead, 1973) is based on Thurstone's method of category scaling as extended by Torgerson (1958) and will henceforth be referred to as the _Thurstonian method_. Using this procedure, data are treated as one would those obtained using the method of constant stimuli. A psychometric function may be drawn for R1 vs. all remaining responses, R1 + R2 vs. the remaining responses, and for R1 + R2 + R3 vs. R4. Instead of obtaining *d'* directly for a pair of stimuli, the standard deviation (SD) of the psychometric function is obtained. To obtain *d'* for the pair of stimuli the difference between the two stimuli is divided by SD. The point of subjective equality for each of the psychometric functions may be taken as an estimate of the category boundary or criterion position (Gravetter & Lockhead, 1973; Woodworth & Schlosberg, 1954, pp. 217-218).

Both procedures assume that the underlying distributions are normal and of equal variance. If these assumptions are met and the criteria are placed midway between the means of the adjacent stimulus distributions, both methods yield identical estimates of *d'*. Lee (1969) has pointed out the similarity between signal detection's ROC curve and the curve obtained using Thurstone's category scaling method. A full description of the ROC method and the Thurstonian method described above demonstrating their logical equivalence appears in Appendix A.

Interestingly enough, while a major contribution of SDT is its recognition of the fact that criterion position is sensitive to changes in the payoff matrix and the a priori probability of signal presentation, it is generally assumed that the criterion remains *fixed* in an appropriate position. If, however, criteria vary from moment to moment, as well as from condition to condition, *d'* will be decreased. This is true since a subject's response on any given trial is determined by both the specific sensory effect and the momentary placement of the criterion on the sensory effect axis. In the past, momentary changes in criterion position were treated as merely a minor source of noise which could be added to the noise in the sensory stage without seriously distorting the measures of sensitivity to stimulus differences (McNicol, 1975). More recently changes in d' in situations in which stimuli remain unchanged have been attributed to changes in criterion position and such changes have become a topic of interest to those investigating the operation of decision processes.

Factors such as (1) the physical range over which the stimuli are distributed, (2) the number of criteria that must be held simultaneously by the subject, and (3) the preceding stimuli and feedback have been shown to influence d'. A number of investigators have suggested that these changes in sensitivity reflect changes in criterion variability. Some relevant studies will be reviewed below.

1. Physical range. As clearly demonstrated by Pollack (1952, 1953), the total stimulus range in which any two stimuli appear can influence the discriminability of the two stimuli. As range increases, discriminability decreases. This inverse relationship between range and discriminability has more recently been observed by Gravetter and Lockhead (1973). They had two groups of human subjects make absolute judgments of the loudness of three 1000 Hz, 0.5 second tones under three conditions. The conditions varied the physical range in dB of the stimuli by separating either the lowest

or the highest of the stimuli from the other two by 1, 3, or 7 dB. As in the previously reported range experiments, the discriminability of the two unchanged stimuli deteriorated with expanded range. They concluded that the range over which the cirteria are spread and response variability are positively related. They suggested that these findings are due to the human observer functioning much in the manner of a physical measuring device such as a voltmeter with the scale on which the instrument is set determining the precision of the reading. Expanding the range to which the subject must attend is analogous to setting the voltmeter to a larger scale; both result in poorer resolution. While this analogy is not unreasonable, it does little to explain <u>how</u> range exerts its effect.

In 1969, Durlach and Braida also postulated a variance component proportional to stimulus range to explain the range effect. According to their model, noise in stimulus identification (absolute judgment) experiments arises from two sources: <u>sensation noise</u> and <u>memory noise</u>. Sensation noise is that noise not attributable to memory. Moment-to-moment variation within the sensory system itself and in the stimulus as presented are examples of sensation noise. Sensation noise is considered to be primarily responsible for errors in experiments requiring discrimination of two stimuli separated by relatively short periods of time. Memory noise is considered to be primarily responsible for errors in experiments requiring the identification of many stimuli. Durlach and Braida's model further assumes two types of memory noise: sensory-trace noise and context-coding noise. In the sensory-trace mode the subject "rehearses" the sensory experience in an attempt to maintain the image or trace of the sensation. Noise in this mode will arise from interference and the tendency of the trace to wander over a period of time. In the context-coding mode, Durlach and Braida assume that "the subject attempts to compare the sensation with the general context of sounds in the experiment, and to remember an imprecise verbal representation of this comparison." Noise in the context-coding mode is assumed to be independent of time; the subject makes his comparison immediately following the sensation and verbally encodes and perfectly remembers that which he has encoded. The width of the context is considered to lead to greater noise and this width is determined by the total stimulus range. As the range is increased and the number of stimuli held constant, sensory-trace noise remains constant while context-coding noise increases. Thus increasing range results in an increase in the proportion of noise from the context-coding mode which counters the increase in resolution which would be expected due to the increased physical separation of the stimuli. The question of precisely how increased range increases context-coding noise remains unanswered.

2. Number of criteria required. It has also been suggested that requiring a subject to hold more than one criterion simultaneously may lead to an increase in criterion variability and a corresponding decrease in *d'* (Nachmias, 1968; Shipley, 1970; Wickelgren, 1968).

Wickelgren (1968) presented an extensive theoretical explanation of how criterion variability can be inferred. In short, if two different methods which require a different number of criteria to be held yield data indicating different *d'* values despite the fact that stimulus values have been constant and, therefore, have had constant variances as well, this difference in *d'* tells us that the data yielding the lower *d'* reflect greater criterion variance. Wickelgren (1968) cites several experiments in which requiring subjects to use a larger number of response categories resulted in more variable criteria.

Nachmias (1968), however, did not find an increase in criterion variability when he required subjects given a visual detection task to hold three criteria as compared to having them hold only one criterion. However, he stressed that the small number of simultaneous criteria, the narrow range of presentation probabilities (.25 to .75), the narrow range of detectability of signals (*d'* ranged from .6 to 2.0) and the permissive nature of his instructions to subjects may limit the generalizability of his results.

Shipley (1970) required subjects to use three, five, and nine response categories and thus to set up two, four, and eight criteria. On an auditory task requiring subjects to make absolute judgments of the loudness of 1000 Hz tones without feedback, she found that an increase in the number of possible responses led to a clear decrease in sensitivity.

3. Preceding stimuli and feedback. Other factors which can influence choice performance on an absolute judgment task are the sequence of stimuli and responses preceding a specific trial as well as the presence or absence of feedback as to the correct response. Garner (1953), in the absolute-judgment-of-loudness study described above, tested subjects without feedback after training them with feedback. He found that there was a tendency for subjects to give a higher rating to stimuli when the previous stimulus was higher than the one currently being judged and a lower rating when the preceding stimulus was lower. This phenomenon has been called assimilation. The assimilation effect Garner (1953) observed, however, was barely discernable when six or fewer stimuli were used, although visible when the number of categories approached his upper limit of twenty.

Speeth and Mathews (1961) found evidence of sequential dependencies in a forced-choice signal detection experiment in which four subjects were required to judge in which of four temporal intervals (signaled by lights) a 1000 Hz stimulus was presented. Intensities of the tone were varied over conditions. They used an intertrial interval of five seconds and feedback supplemented by monetary reward for correct identification of the signal. They found sequential dependencies extending as far as three or four trials back with many individual differences in the form of these dependencies. The magnitude of the sequential effects decreased as the signal level and, therefore, its discriminability increased. Thus, it appears that sequential effects are more likely to be found when near-threshold discriminations are called for.

Holland and Lockhead (1968) investigated sequential effects in absolute judgments of ten, 0.5 second, 1200 Hz tones varying in loudness over a range of 25 dB. Subjects initiated stimulus presentation and always received feedback. They found consistent sequential dependencies of two types as a function of the preceding stimuli. The first type, assimilation, refers to the tendency of a response on a given trial (N) to vary directly with the stimulus on the immediately preceding trial (N-1). The second type, contrast, refers to the tendency for those stimuli two or more steps back (eight in this study, trials N-2 through N-8) to inversely affect the response on trial N with the magnitude of the effect being greater for the more recent stimuli.

Ward and Lockhead (1970) found that the elimination of feedback resulted in a decrease in sequential effects in a study very similar to Holland and Lockhead (1968). They required subjects to judge ten loudness levels centered around approximately 60 dB SPL with adjacent stimuli separated by 1 dB and a total range of 9 dB. They added a condition under which no feedback as to the accuracy of the response was given and used a 3.5 second intertrial interval. In their feedback condition they found both assimilation to the stimulus immediately preceding a given trial and contrast to stimuli as far as five trials back. Without feedback the assimilation effect was still clearly present but to a lesser extent; contrast was not evident three trials prior to a response. If, as Ward and Lockhead suggest, extreme stimuli exert a greater influence on subsequent judgments than do less extreme stimuli, then the presence of such extreme stimuli should produce greater criterion variability and show up in poorer discrimination performance. Such sequential dependencies may reflect the manner in which humans estimate probabilities and use numbers (Ward & Lockhead, 1970) or may reflect a nonsequential process common to both verbal and nonverbal organisms.

Larkin (1971) also proposed a variable criterion model which assumes that a subject's criterion will shift on trials following those on which feedback indicates that an error has been made. Such criterion shifts are less likely to occur on trials following correct responses with feedback. The variable criterion models are comparable to the win-stay/lose-shift strategy which has been reported in the animal literature (e.g., Williams, 1972).

Carterette, Friedman and Wyman (1966) investigated the effects of feedback on performance on a two-alternative, temporal-forced-choice auditory signal detection task in which the stimulus was a 1000 Hz tone against a continuous background of noise. They varied the signal-to-noise ratio and the proportion of trials on which correct feedback was given (incorrect feedback was given on the remaining trials). Their findings led them to suggest that feedback indicating that an error has been made causes the subject to shift his criterion thus inducing criterion variability which is reflected in a decrease in d'. They also found that on trials immediately following trials on which subjects' responses and feedback agreed, hit rates were higher and false alarm rates lower than on trials following disagreement between response and feedback. These findings are in support of Larkin's (1971) model.

McNicol (1975) further investigated the effects of feedback reliability upon performance in a five-category, absolute judgment of loudness task. Subjects were required to identify five 500 Hz tones differing in 1dB steps from about 75 to 80 dB. After making a judgment, the correct answer was presented to the subject visually via a slide with a number from one to five on it. Forty-five subjects were divided into five groups. Three groups received accurate feedback on 100%, 50% and 20% of all trials and random feedback on the remaining trials. These subjects were told that feedback would be unreliable on some trials. Another group received 100% correct feedback and was so instructed. The fifth group received no feedback. He found that feedback increased the amount of information transmitted, but also resulted in more criterion variability than the no-feedback condition. These data indicated that unreliable feedback groups had more variable criteria than those receiving 100% accurate feedback. McNicol's data support the variable criterion model which predicts that criteria will be shifted to reduce the probability of again making the error which was made on the preceding trial.

In summary, the literature thus far reviewed shows performance on an absolute judgment task to be complexly determined. The ability of human subjects to accurately identify stimuli varying along a single dimension appears to be influenced by the presence of other stimuli (both their range and their order), the number of responses required and the nature of the feedback given to the subjects. The notion of criterion variability has been introduced by a number of investigators to account for these effects, but, as the above review has suggested, such explanatory mechanisms do not adequately explain the phenomenon.

The studies reviewed above have used only human subjects. Humans bring to the absolute judgment task a long history of using numbers, of estimating probabilities, and of formulating expectations regarding the experimenter's expectations. For example, both Parducci (1965) and Ward and Lockhead (1970) suggest that their human subjects' responses on absolute judgment tasks may have been biased by their expectations of a "low" stimulus following a sequence of "high" stimuli and vice versa. Parducci (1965) found that his subjects also had a tendency to use all categories equally often. Such influences upon the judgments of human subjects may, therefore, unnecessarily complicate the research findings and may even account for some of the inconsistencies and the complexities encountered in attempts to analyze sequential dependencies, the effects of feedback and of stimulus range. Blough (1966) has pointed out that the interpretation of such psychophysical data becomes more difficult, and the flaws attached to this interpretation more and more serious, as investigators "depart from simple operant situations and animals, like the pigeon, that are dominated by external stimuli" (p. 347). Basic decision processes present in both man and animals may best be studied first in the simpler organism. My dissertation research represents an attempt to sort out some of the factors influencing choice accuracy in an absolute judgment situation using pigeons as subjects.

Data obtained from experiments in which pigeons are required to make one of two equivalent responses (such as a peck on the left or right key in a Skinner box) may be treated as one would data obtained using the psychophysical method of single stimuli with two response classes. One application of this technique was that of Heinemann, Avin, Sullivan and Chase (1969) who trained pigeons to peck one key in the presence of a higher intensity white noise and the other key in the presence of a lower intensity. The physical separation of the stimuli to be discriminated was 2.3 dB, 7 dB or 29 dB for different groups of birds. When the birds' performance was asymptotic, key choice was observed in the presence of white noise at 13 different intensity levels including those used in training. They found that the birds' choice data in this generalization test situation yielded psychometric functions not unlike those obtained with human subjects required to classify sounds as loud or soft. The proportion of trials on which the pigeons chose the key correct for the higher intensity stimulus rose monotonically with stimulus intensity. The choice curves differed systematically with the training conditions; training with the more widely separated (more easily discriminated) stimuli yielded flatter curves. This is not what one would expect if, as suggested by SDT, pigeons establish a fixed criterion on the sensory effect axis and make a given response whenever the sensory effect produced by a stimulus exceeds this criterion. If this were true, curves identical in shape should have been obtained regardless of the initial training. To account for the flatter curves obtained following training with widely separated stimuli, Heinemann, et al. suggested that the criterion position varies normally about a mean and that the variance of this distribution is greater following training on the easy discrimination. Criterion variability has also been used to "explain" changes in <u>d</u>' observed in some of the human absolute judgment experiments reviewed above. If, indeed, these changes in <u>d</u>' are due to increased criterion variability, the means by which this variability is increased remains to be explained. The human data suggest that criterion variability is strongly affected by the range of stimuli to which the subject is exposed and that range may exert its effect on criterion variability through sequential dependencies.

Sequential dependencies have not yet been clearly demonstrated in animals. Boakes (1969) found no sequential dependencies nor significant tendency to use each category equally when he tested pigeons on a two-response task using eight stimuli varying in luminance (7.4, 15, 29, 59, 74, 150, 290 and 590 ml). The birds had previously been trained to respond on two different keys in the presence of the stimuli at the extreme ends of the series (7.4 and 590 ml) with an 8-second intertrial interval.

Similarly, Heinemann (1974) found no sequential dependencies in response latencies when pigeons were trained on a ten-stimulus, two-response sound discrimination in which a correct response was a peck on one key for stimuli equal to or greater than 76 dB SPL and on the other key for stimuli equal to or less than 72 dB. Latency was measured from the time at which the sound was initiated by a peck on a center key until a choice was made.

It is possible that a systematic examination of response latency in the absolute judgment situation may help to explain the observed effects of range upon performance if range directly affects the difficulty of the discrimination called for. Reaction time may be a function of the overall difficulty of the discrimination. For example, Heinemann et al. (1969), in the study discussed above, found some evidence of systematic differences in latencies as a function of the overall difficulty on the discrimination. Pigeons trained on the most difficult discrimination (2.3 dB) not only showed a steeper choice curve but also had longer latencies than birds trained on the easiest discrimination. These latency differences were clear <u>across</u> conditions for pigeons, i.e., more difficult discrimination tasks were characterized by longer latencies to all stimuli presented while easier discrimination tasks were characterized by shorter latencies to all stimuli presented. Within any particular task for any particular subject, Heinemann (1974) found no indication of longer response latencies in the middle of the stimulus range where the discrimination should have been most difficult. However, Flagg, Medin and Davis (1974) found the reaction times of monkeys in a particular discrimination task to be greatest in the center of the range.

In summary, the intent of this research is to throw light upon the yet poorly understood changes observed in measures of discriminability which occur in absolute judgments. Attention here will be focused upon the influence of the range of stimuli to which the subject is exposed. Pigeons will be used as subjects, in part to determine whether the range effect is a purely human phenomenon since it has previously been demonstrated only in humans. Particular attention will be paid to two factors which may in part account for the range effect: sequential response dependencies as described above and the latency of responding which may reflect decision time. As discussed earlier, either or both factors may influence the degree of criterion variability observed. Other factors which may influence criterion variability will also be examined.

General Method

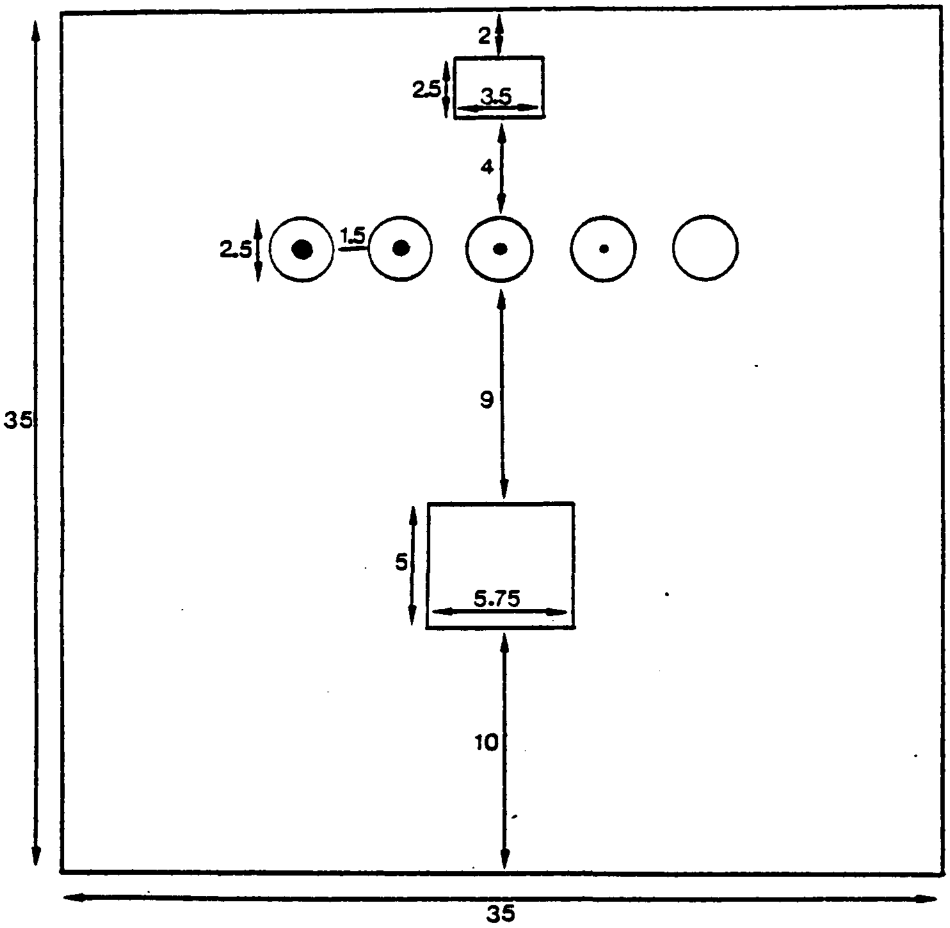
Subjects. The subjects in all experiments were adult White Carneaux pigeons without prior experience in an experiment in which reinforcement was contingent upon a response. The six birds used in Experiment 1 served previously in an autoshaping experiment; the remaining birds were experimentally naive. The birds were maintained at 80% to 85% of their free-feeding weights. Water and grit were always available in their home cages.

Apparatus. Two BRS/LVE (Beltsville, Md.) pigeon chambers were modified for these experiments. The dimensions of the intelligence panel used in these chambers are given in Figure 2.

White light could be projected from behind upon a translucent rectangular pecking key, the display key. In these experiments the discriminative stimuli were different intensities of this light. Luminance of the display key was varied by placing various Kodak Wratten Gelatin Neutral Density Filters (#96) in the beam of a Kodak Carousel projector.

In Experiment 1 the current through a General Electric CBA 120V bulb was checked frequently during each session and adjusted if necessary to 3.8 amps by means of a potentiometer provided on a control panel (LVE 111-10) used with a Kodak Model 800 slide projector modified by LVE (BRS/LVE SCP-001/111-10).

Figure 2. Illustration of intelligence panel.



(dimensions in cm.)

In the remaining experiments a Kodak Carousel slide projector (Model #750H) was used with quartz iodide projector bulbs (Sylvania Tungsten Halogen ELH Quartz TruBeam, 300W, 120V). A voltage regulator (Charles Beseler Co., Florham Park, N. J., Line Voltage Stabilizer, Cat. No. 8248) was used to minimize voltage fluctuations.

Five circular choice keys were located below the display key. The key on the far right was inoperative. The remaining keys, to be referred to as Keys 1 through 4 from left to right, could be illuminated from behind by green light. To make the keys more visually distinct from each other, the center of each key was marked with a black disk of 1/2, 3/8, 1/4 and 1/8 in. (1.27, .95, .64 and .32 cm.) diameter for Keys 1 through 4 respectively.

The chamber was continuously illuminated by a 28 volt pilot light (G.E. 1829) located in the center of the chamber ceiling. The luminance of the display key was -3.1 log ft.L. (.00085 ft.L.) when it was illuminated only by this pilot light. Ventilation was provided by a fan, and white noise at approximately 75 dB SPL (re .0002 dynes/cm^2) was continuously present in the chamber to mask any noise in the laboratory.

All experimental contingencies were controlled by standard relay equipment. The slides used to present the stimuli for all experiments were made from pieces of black oaktag cut to fit LinDia slide mounts (K. Heitz, Inc., New York, N. Y.). The appropriate filters were placed over openings cut in these pieces of oaktag so as to illuminate the display key. For purposes of programming, recording and controlling stimulus-response-reinforcement contingencies, all stimuli were identified by a specific combination of holes punched in the slide mounts for Experiment 1 or, in the remaining experiments, in parts of the oaktag through which the projector beam passed. Photocells mounted within the projector in Experiment 1 and on the outer surface of the pigeon chamber in all other experiments were used to code each stimulus presented.

The stimulus presented, choice made, and latency from stimulus onset to display key peck on each trial was punched on paper tape. These tapes were later read by the Xerox Sigma VII computer at Queens College, C.U.N.Y., and the data were sorted according to stimulus presented, response made, first vs. subsequent trials, preceding stimulus and latency of the response.

Procedure. For all experiments the onset of a trial was indicated by the illumination of the display key and the simultaneous onset of a 2800 Hz tone at 66 dB SPL (re .0002 dynes/cm^2). The display key was illuminated at one of four levels of light intensity. The specific intensity values will be given in the description of each experiment. The order of presentation of the stimuli was random with the restriction that each stimulus appeared an equal number of times within 40 trials. A session consisted of two repetitions of this 40-trial program. Programs were changed every two days.

On a first trial, a peck on the display key illuminated the four choice keys and terminated the tone; the display key remained lit. A peck at any choice, a first choice, was followed by a 10-second intertrial interval during which the choice and display keys were darkened and inoperative. A correct choice was followed by reinforcement which consisted of access to a food hopper filled with mixed grain for 1.5 seconds. On trials following incorrect responses the same stimulus in the presence of which the error occurred was repeated. A peck on the display key on the trial following an error illuminated only the keys not previously pecked in error. This procedure continued until the bird had made the correct response, received reinforcement, and the projector had stepped forward to present the next stimulus in the program. All data were analyzed in terms of first choices. A session continued until 80 correct responses had been made. Training was continued in Experiments 2 and 4 until performance appeared to be asymptotic (160 days), for 100 days in Experiment 1 and for 25 days in Experiment 3.

Pretraining. The birds in all four experiments were trained in the same manner. Each bird was first trained to eat from the food hopper and next trained to peck the continuously illuminated display key by the method of successive approximations. A peck at the display key during this phase of pretraining was reinforced by 2-second access to the feeder filled with mixed grain. This first phase of pretraining was continued until the bird had earned 40 reinforcements.

During the second phase of pretraining, the display key was not illuminated and pecks on it had no effect. The birds were trained by the method of successive approximations to peck the illuminated choice key. During this phase only one choice key was illuminated on each trial. A peck at the correct (illuminated) choice key was reinforced by 2-second access to the feeder during which time all choice keys were darkened. After reinforcement a choice key was again illuminated. Which choice key was illuminated during this phase of training was randomly determined with the restriction that each of the four keys was illuminated ten times per 40 trials.

When the birds completed 40 reinforced trials, the third stage of pretraining was begun. In this final stage the display key was again illuminated (luminance of the display key was not varied during pretraining). A peck on the display key illuminated one of the four choice keys; a peck on the illuminated choice key was reinforced and all keys were darkened for a 5-second intertrial interval. The sequence of choice-key illumination was quasi-random as described above. Pretraining was completed when the pigeon had received 40 reinforcements in this final stage.

Experiment 1

The purpose of Experiment 1 was to determine whether performance on an absolute judgment task is influenced by the range of stimuli to which a pigeon is exposed. In this experiment the two middle stimuli were fixed at their respective values and the difference between the extreme stimuli was varied. If the total range over which the stimuli are spread increases criterion variability, then the discrimination between the two central stimuli should be less accurate for the birds trained on the wider range than for those trained on the narrower range. That is, *d'* for the two central stimuli should be smaller for the wider range birds.

Method

Subjects. Six White Carneaux pigeons previously used in an autoshaping experiment were assigned to *narrow* and *moderate* range groups.

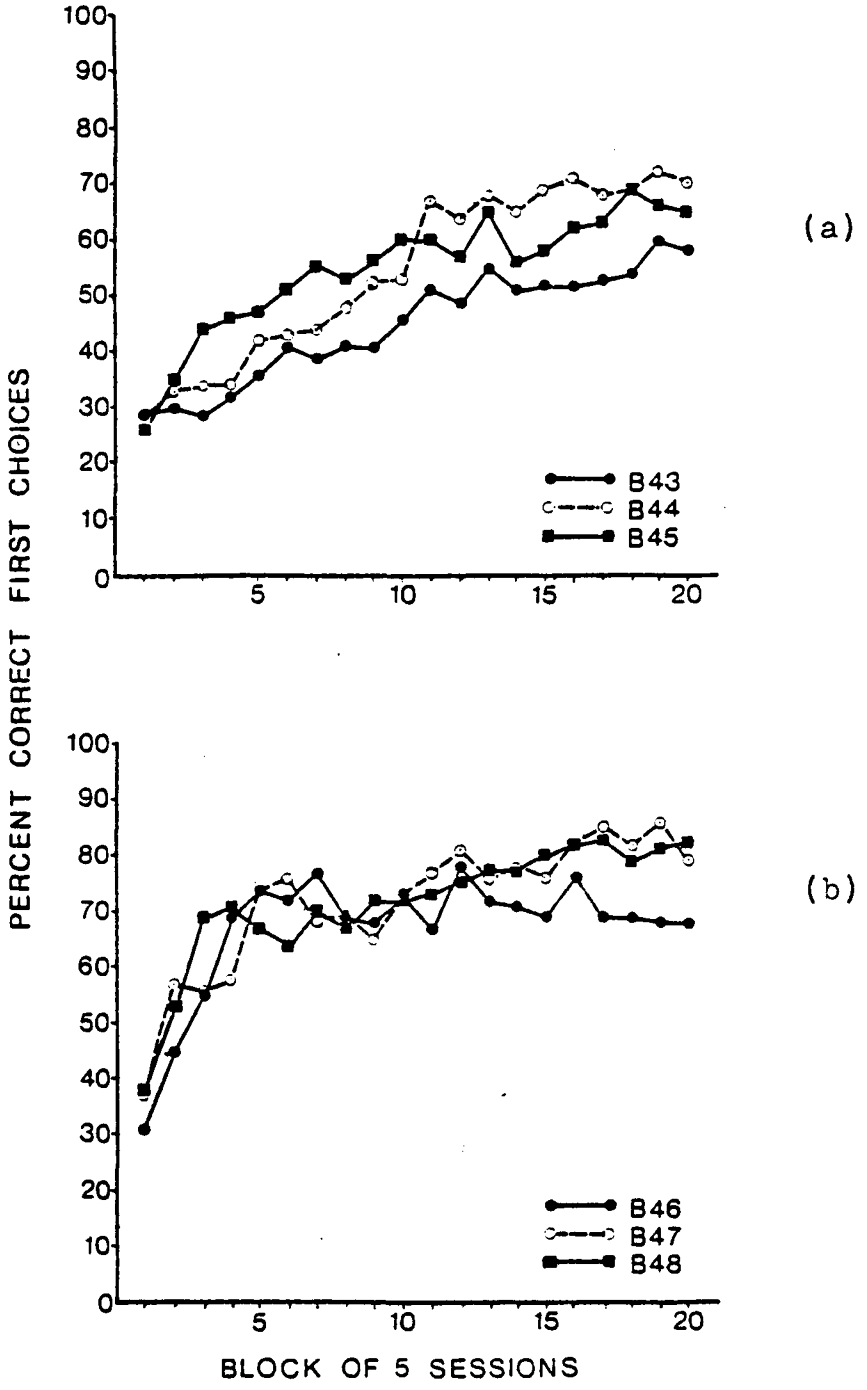
Apparatus. In this experiment the Model 800 Kodak Carousel slide projector as modified by LVE and the control panel referred to earlier were used with GE CBA 120V bulbs.

Stimuli. The stimuli used were the intensities of white light produced by passing the projector beam through neutral filters of densities .6, .8, 1.0 and 1.2 for the narrow range group (.6 log unit range) and densities .2, .8, 1.0 and 1.6 for the moderate range group (1.4 log unit range). The luminance levels thus produced were 1.7, 1.5, 1.3 and 1.1 log ft.L. for the narrow range group and 2.1, 1.5, 1.3 and .7 log ft.L. for the moderate range group as measured by a Spectra Brightness Spot Meter (Photo Research Corporation). Stimuli 2 and 3 were the same in both conditions (1.5 and 1.3 log ft.L.) differing from each other in both conditions by .2 log unit. For both groups the brightest stimulus (lowest neutral density filter value) was designated as Stimulus 1 (S1) and the correct choice was a peck on the key to the extreme left (Key 1 or R1), the next brightest (1.5 log ft.L. for both groups) was designated as Stimulus 2 (S2) with the correct response defined as a peck on the second key from the left (Key 2 or R2), the next brightest (1.3 log ft.L. for both groups) was designated as Stimulus 3 (S3) with the correct response defined as a peck on the third key from the left (Key 3 or R3), the dimmest stimulus (highest neutral density filter value) was designated as Stimulus 4 (S4) and the correct choice was a peck on Key 4 (R4). Thus for both conditions, whenever a stimulus was presented four choices were possible; the correct choice was cued by the luminance of the display key.

Results

The six birds were given 100 sessions of training at which time their performance appeared to be approaching asymptote. Figure 3 shows the percent correct first choices per session averaged over five-day blocks (100 presentations of each stimulus). These data show that the most dramatic

Figure 3. Percent correct first choices for each bird. Data are shown in five-day blocks for the 100 sessions of Experiment 1. Data for the birds trained on the narrow range are shown in panel a. Data for the birds trained on the moderate range are shown in panel b.

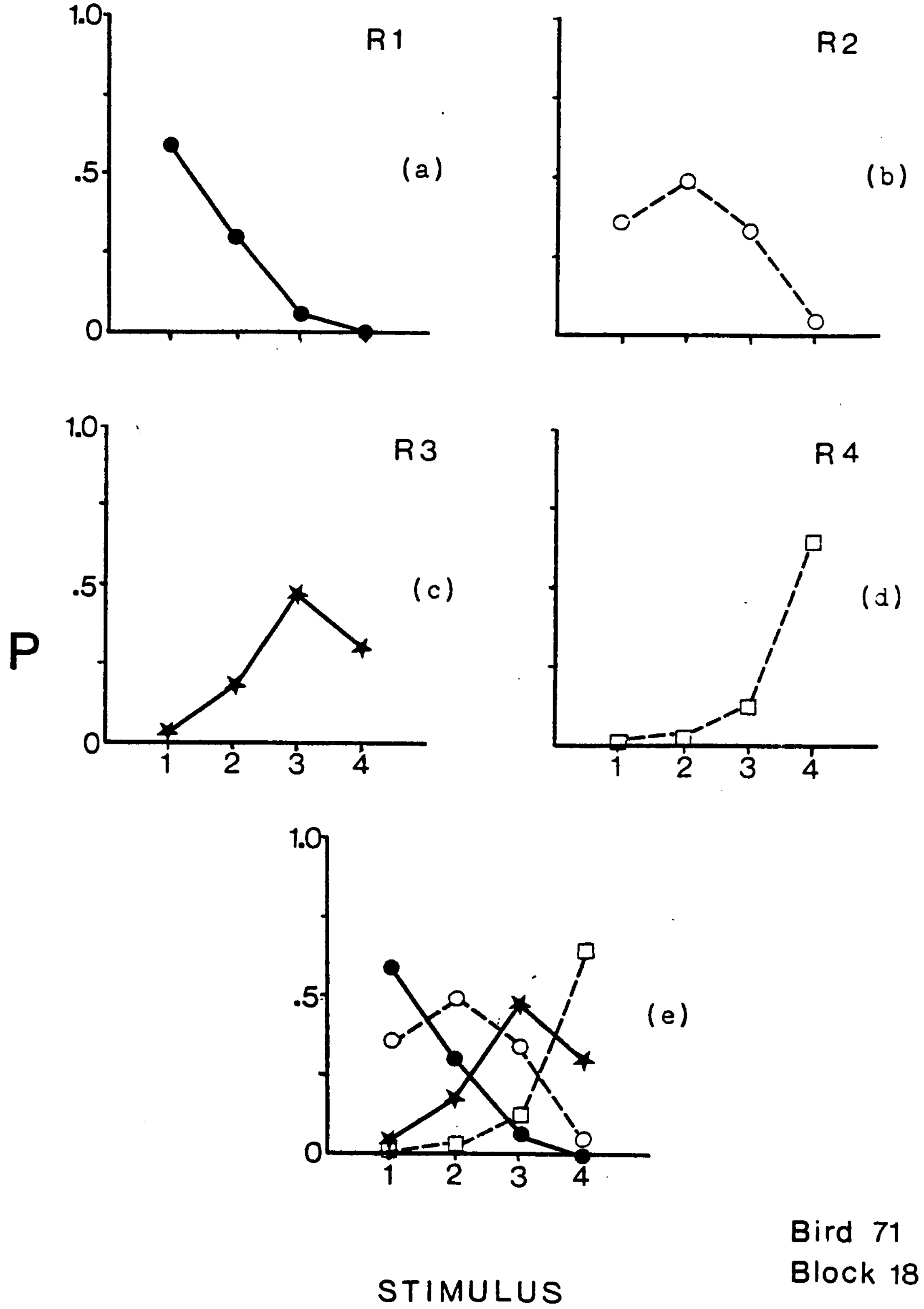

PERCENT CORRECT FIRST CHOICES
(a)
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
B43
B44
B45
(b)
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
B46
B47
B48
BLOCK OF 5 SESSIONS

increases in accuracy occurred during the first five blocks (25 sessions) for the moderate-range birds followed by a leveling off. The moderate-range birds reached a higher level of correct first choices than the narrow-range birds although the narrow-range birds continued to improve throughout the experiment.

The mean number of correct first choices is influenced by factors such as the range of stimuli to be identified as well as the number of criteria held and the position and variability of these criteria. To better understand the development of the discrimination and final level of performance, changes in the number, position and variability of the criteria were examined separately. Choice curves, one curve for each of the four responses, were plotted for each bird. These curves show the proportion of times each response was made in the presence of each stimulus.

As an example, Figure 4 shows a set of such curves for a subject who had established three criteria. Such curves reach their highest level (peak) at each of the stimulus values in the presence of which the response was reinforced. Choice curves for each of the four responses are shown in panels (a) through (d). These four curves are combined in panel (e). Combining the choice curves into a single graph has the advantage of showing the establishment of criteria and making possible rough estimates of criterion placment. For example, by observing the point at which the curves.

Figure 4. Examples of the four-response choice curves and how they are combined.



Bird 71
Block 18

intersect in Figure 4(e) it can be seen that the subject has established one criterion midway between S1 and S2, another criterion between S2 and S3 slightly closer to S2, and a criterion between S3 and S4 much closer to S2 than to S4.

Figure 5 (a and b) indicates how the four-response choice curves look when there is little or no stimulus control over responding. Panel (a) shows the results for a bird who made each of the four responses equally often, whereas panel (b) shows the results for a bird who had a strong key preference.

The acquisition process of each bird is shown in this manner in Figures 6 through 9. The data shown are based upon first trials only. From these figures the development of control over key choice by light intensity and the establishment of criteria can be followed throughout training. Choice curves for birds (B) 43, 44, and 45 representing the first 25 days of training (Figure 6) show some control over key choice by light intensity. Note, for example, that in the case of B43 R1 occurred in the presence of S1 more frequently than in the presence of any of the other three stimuli and that R4 was made in the presence of S4 more often than in the presence of any other stimulus. The curve for R2 is similar in form to that for R1, and the curves for R3 and R4 are practically identical. Curves such as these would be obtained if the subject had a single criterion dividing the sensory effect axis into two regions:

Figure 5. Examples of the four-response choice curves in two extreme cases. Panel a shows the curves when there is little or no stimulus control. Panel b shows the curves when there is little stimulus control and a strong key preference.

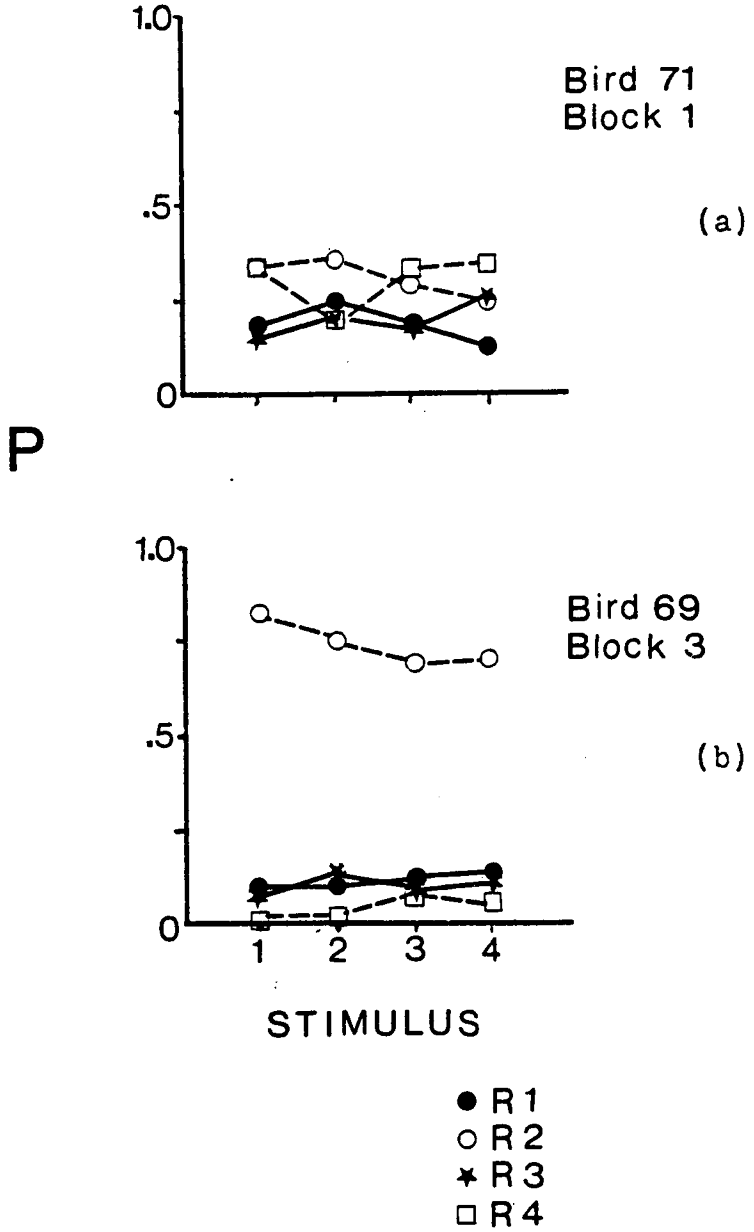

1.0
.5
0
Bird 71
Block 1
(a)
P
1.0
.5
0
Bird 69
Block 3
(b)
1
2
3
4
STIMULUS
● R1
○ R2
★ R3
□ R4

Figure 6. Four-response choice curves for the narrow-range birds in Experiment 1 by 25-day block. In this experiment S1, S2, S3 and S4 were 1.7, 1.5, 1.3 and 1.1 log ft.L. respectively for the narrow range condition.

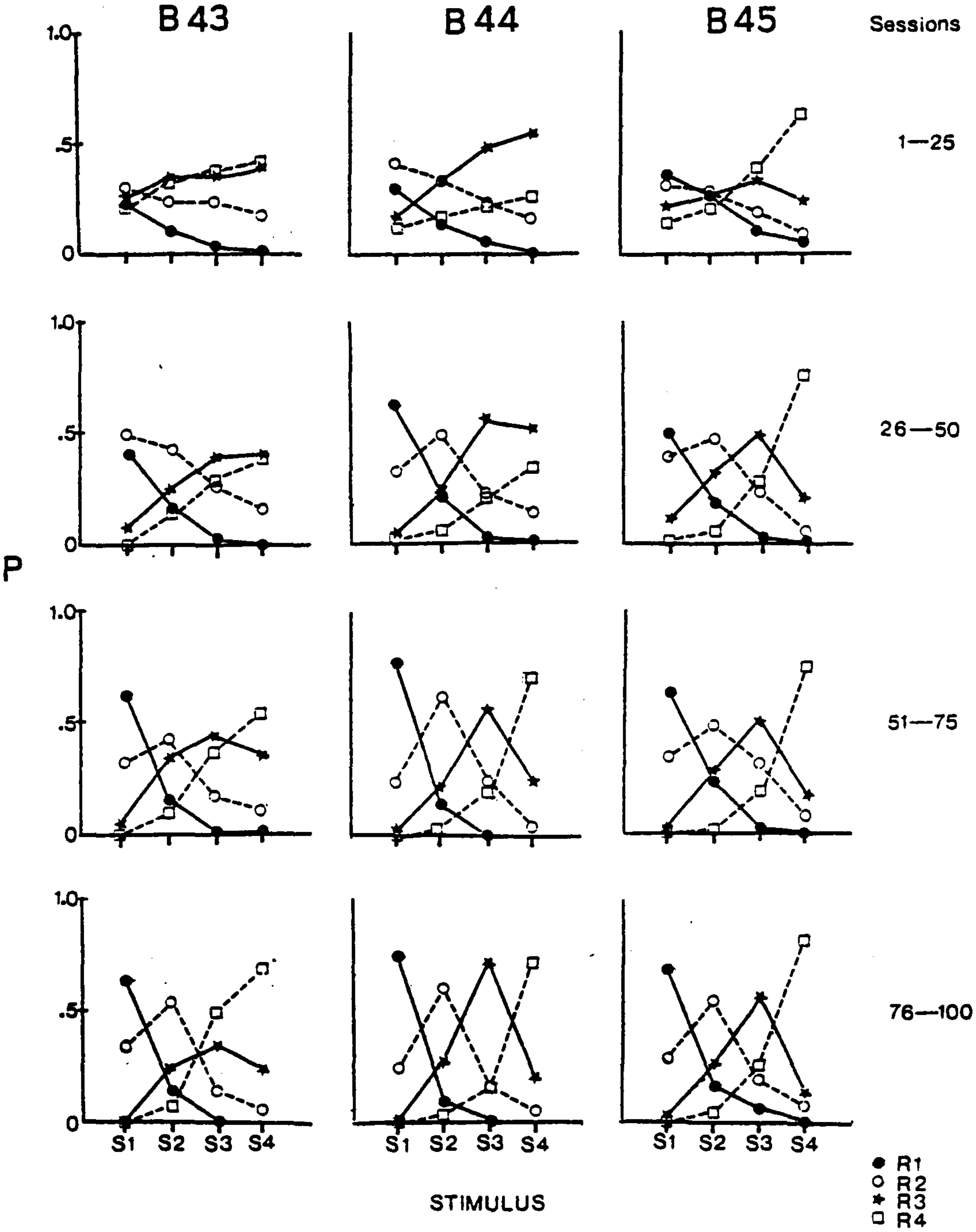

B 43
B 44
B 45
Sessions
1.0
.5
0
1—25
26—50
51—75
76—100
P
S1
S2
S3
S4
STIMULUS
● R1
○ R2
✱ R3
□ R4

Figure 7. Four-response choice curves for the narrow-range birds in Experiment 1. Data are shown by 5-day block for the first 25 days of training. In this narrow range condition S1, S2, S3 and S4 were 1.7, 1.5, 1.3 and 1.1 log ft.L. respectively.

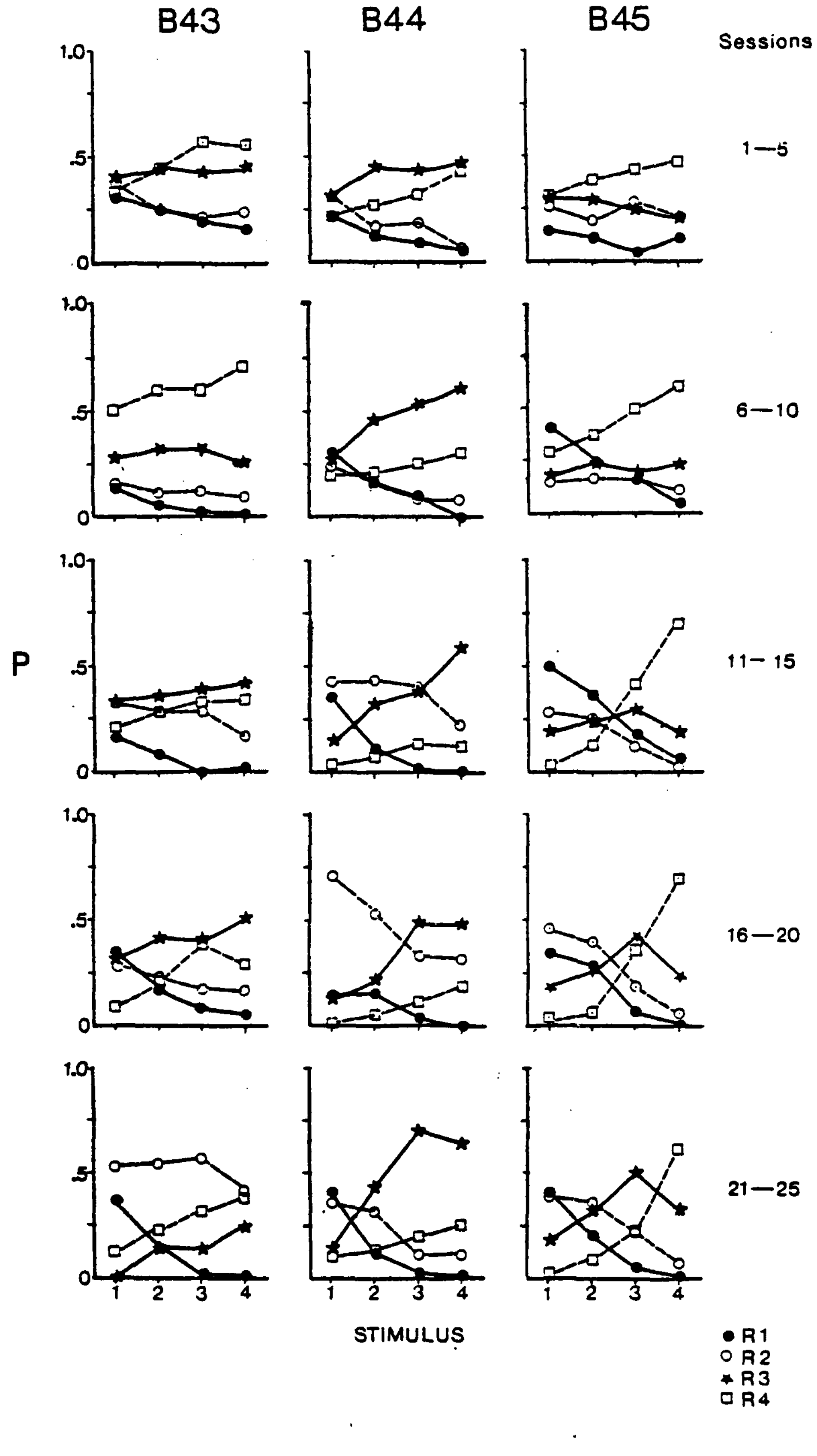

B43
B44
B45
Sessions
1—5
6—10
11— 15
16—20
21—25
P
1.0
.5
0
1
2
3
4
STIMULUS
● R1
○ R2
★ R3
□ R4

Figure 8. Four-response choice curves for the moderate-range birds in Experiment 1. Data are shown by 25-day block for the 100 days of training. In this moderate-range condition S1, S2, S3 and S4 were 2.1, 1.5, 1.3 and .7 log ft.L. respectively.

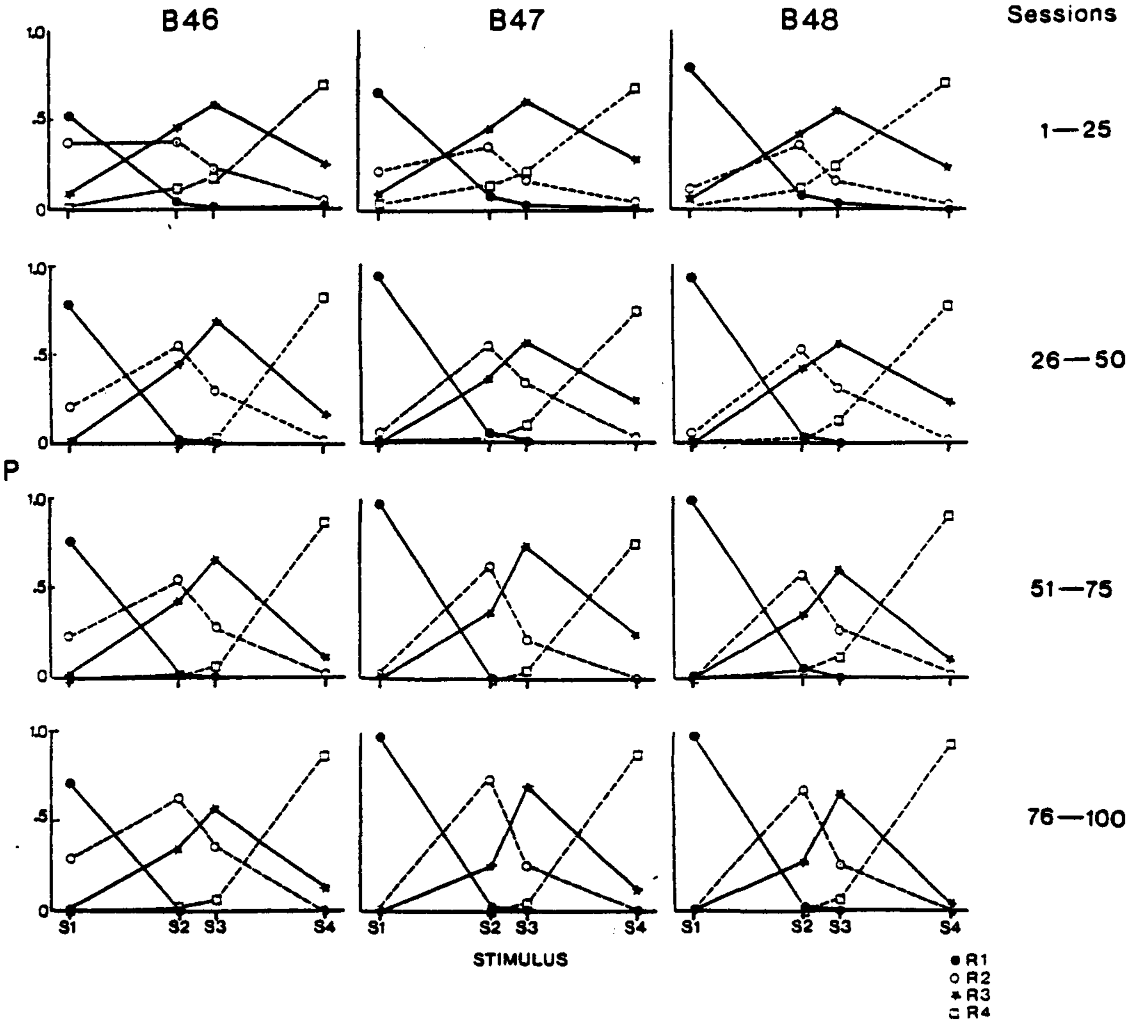
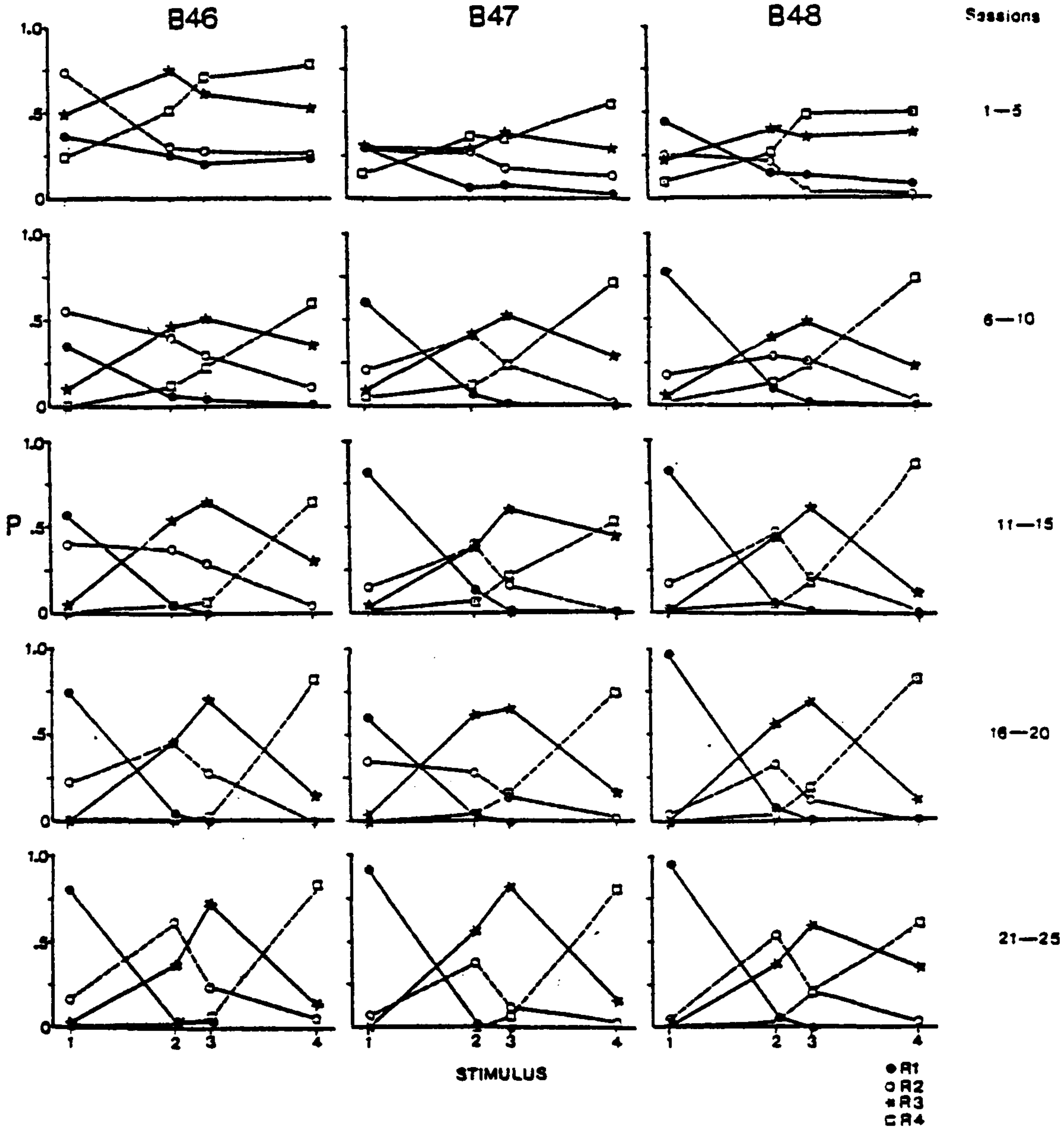

B46
B47
B48
Sessions
1.0
.5
0
P
1—25
26—50
51—75
76—100
S1
S2
S3
S4
STIMULUS
● R1
○ R2
✱ R3
□ R4

Figure 9. Four-response choice curves for the moderate-range birds in Experiment 1. Data are shown by 5-day block for the first 25 days of training. In this moderate range condition S1, S2, S3 and S4 were 2.1, 1.5, 1.3 and .7 log ft.L. respectively.


B46
B47
B48
Sessions
1.0
.5
0
P
1—5
6—10
11—15
16—20
21—25
1
2
3
4
STIMULUS
● R1
○ R2
✱ R3
□ R4

One in which R1 and R2 would be made and one in which R3 and R4 would be made. The point at which the choice curves cross suggests that this criterion lies near 1.6 log ft.L., between S1 and S2.

A single criterion was established by all narrow-range birds during the first 25-day block of training. The mean position of this criterion was near the high intensity end of the continuum, at approximately 1.5 log ft.L. for B43, slightly higher for B44, and slightly lower for B45. The two additional criteria were established during the second 25-day block (sessions 26-50) by birds 44 and 45. These criteria were evident in the choice curves of all three birds during the third and fourth 25-day blocks.

In Figure 7 the first 25 days of training are broken down into 5-day blocks. Additional information can be gained from the examination of these data. For example, a single criterion appears to have been established within the first five days of training by B43, 44 and 45. The five-day blocks reveal key preferences -- preferences which seem to change from block to block and were not obvious in the 25-day plot. Note, for example, the high frequency of R4 during days 6 to 10 and of R2 during days 21 to 25 for B43. In spite of these shifting key preferences, the trend shown in the 25-day block is repeated: the R1 and R2 curves tend to fall as stimulus intensity decreases and the R3 and R4 curves tend to rise.

For the moderate-range birds, the 25-day block analysis (Figure 8) indicates that all three criteria were established during the first 25 days of training. Each of the four responses occurred most frequently in the presence of the correct stimulus although the R2 and R3 curves did not intersect until the second 25-day block. Since three criteria were evident so early in training, the 5-day block graphs were examined (Figure 9) to get an idea of how the discrimination developed. The three criteria were clearly evident by the second 5-day block for birds 47 and 48. For bird 46, on the other hand, the four response curves did not clearly peak in the presence of the appropriate stimuli until the fourth block (days 16-20).

In Figure 10 the proportion (P) of hits and false alarms are plotted for each bird on normal deviate axes (z-ROC curves) for the discrimination between the two central stimuli during the last 25 days of training. Note that these points do not deviate substantially from a line with a slope of 1 indicating that the assumptions made in computing $\underline{d}'$, namely that the distributions of the decision variables are normal and of equal variance, were not seriously violated. The $\underline{d}'$ values for the 25-day period are also included in Figure 10.

The development of the discrimination between the two central stimuli was examined for all birds by plotting $\underline{d}'$ (ROC method) throughout training. Figure 11 presents these

Figure 10. Proportion of "hits" and "false alarms" for stimuli 2 and 3 for all birds in Experiment 1. All data points are based on the last 25 days of training and are plotted on normal deviate axes. The diagonal represents chance performance. Points further from the diagonal indicate higher _d_' values.

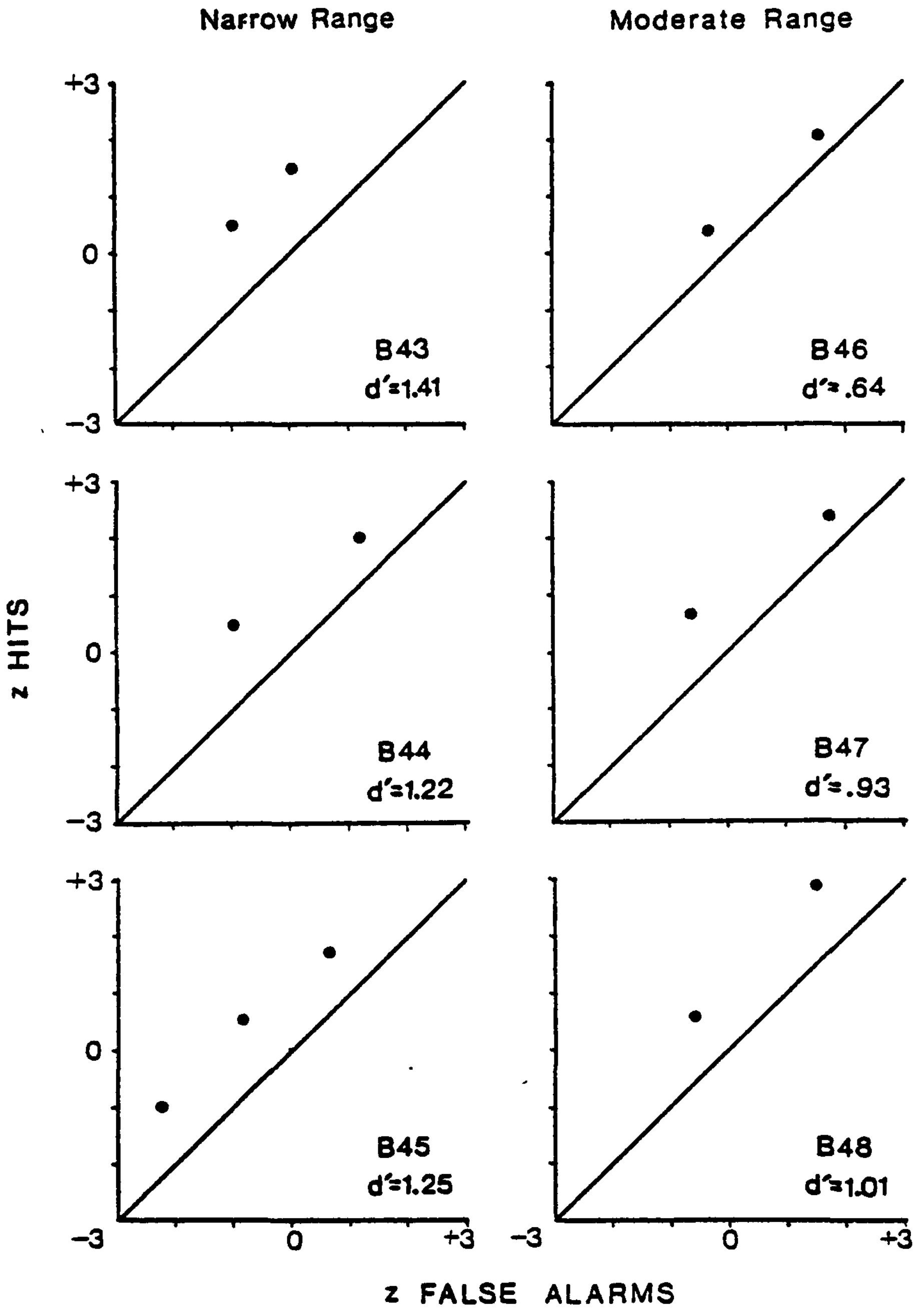
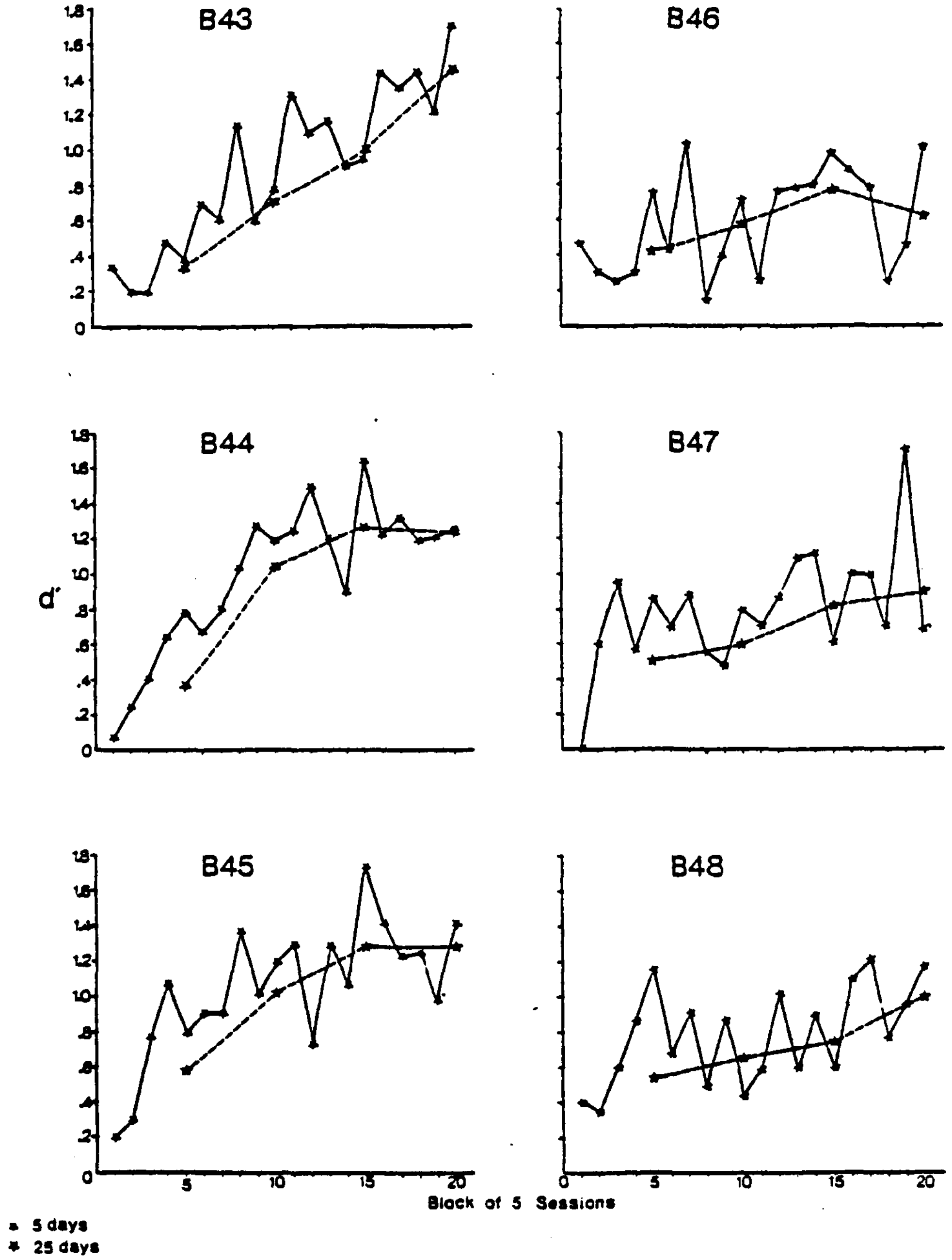

Narrow Range
Moderate Range
+3
0
-3
B43
d'=1.41
B46
d'=.64
B44
d'=1.22
B47
d'=.93
B45
d'=1.25
B48
d'=1.01
z HITS
-3
0
+3
z FALSE ALARMS

Figure 11. d' for S2 and S3 as a function of training for all birds in Experiment 1. The solid lines are for data shown in 5-day blocks; the dashed lines are for data shown in 25-day blocks.


B43
B46
B44
B47
B45
B48
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
d′
0
5
10
15
20
Block of 5 Sessions
5 days
25 days

data both by 5-day block (solid line) and by 25-day block (dashed line). It is clear from these plots that for birds 43 and 45 d' was asymptotic by block 15 (session 75). For bird 44, d' still appeared to have been increasing when the experiment was terminated. Of the moderate-range birds, B47 and 48 appear to have been improving on this discrimination slowly up to their last block of training while B46 did not improve after block 15 (session 75). These trends can be seen easily in the d' scores for the 25-day blocks.

Performance over the final 25 days of training was examined to determine whether range affects discrimination performance. The d' measures for the discrimination between the two central stimuli, S2 and S3, were obtained using both the ROC method and the Thurstonian method. Relatively small differences between the two methods were observed which are probably due to noise in the data. (See Appendix A for the specifics of the two methods.) These d' data are presented in Table 1. It can be seen that all d' values for the narrow-range birds are larger than those for the moderate-range birds regardless of which method of obtaining d' was used. The mean d' obtained by the ROC method was 1.31 for the narrow-range group and .84 for the moderate-range group. This difference was significant (t (4) = 3.29, $p < .05$). The Thurstonian method yielded similar though slightly higher estimates of d', 1.47 for the narrow-range group and 1.05 for the wide-range group. This dif-

Table 1. d' over the last 25 days of training in Experiment 1 as calculated by both ROC and Thurstonian methods.

Condition	Bird	d' ROC Method	d' Thurstonian Method
Narrow Range	43	1.45	1.43
	44	1.22	1.54
	45	1.27	1.43
	$\bar{x}$	1.31	1.47
Moderate Range	46	.61	.71
	47	.93	1.25
	48	1.01	1.18
	$\bar{x}$	.85	1.05

ference was not significant (t (4) = 2.420, $p > .05$). Thus, both methods of data treatment indicate that narrow-range birds form a sharper discrimination between these two stimuli.

The way d' (ROC method) changed during acquisition for the two groups is shown in Figure 12. Here the data shown in Figure 10 were averaged for the three birds in each condition, again by 5-day block. It is clear that after the first seven blocks (35 sessions) d' was consistently higher for the narrow-range birds.

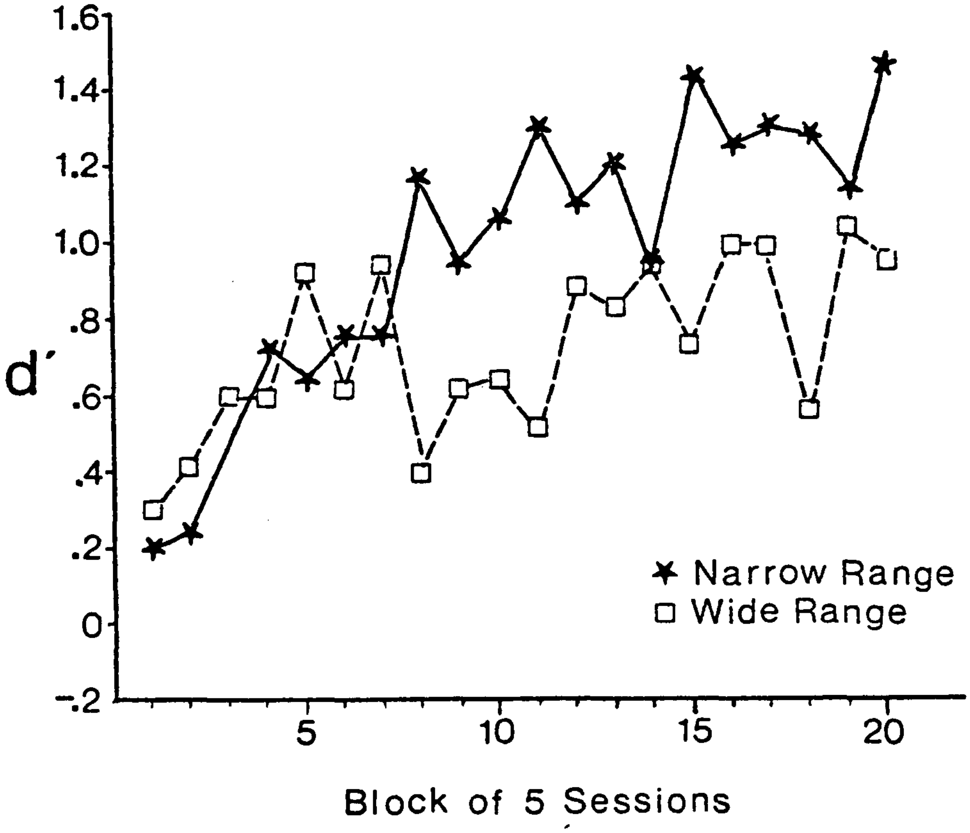
The results of Experiment 1 indicate that the range effect does indeed exist in the pigeon. Experiment 2 was undertaken to explore this phenomenon further. This was done by expanding the range over which the stimuli varied and increasing the number of subjects in each group. In addition, a paper-tape punch was used to record trial-by-trial results (including latencies). This made possible an analysis of possible sequential effects which, as discussed earlier, could be responsible for the range effect.

Experiment 2

Method

Subjects. Nine experimentally naive White Carneaux pigeons were assigned to two groups. Six were trained on a wide-range condition (3.0 log unit range) and three were trained on the narrow-range condition (.6 log unit range)

Figure 12. Comparison of d' between S2 and S3 throughout training for both range conditions in Experiment 1 (group data).


1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
-.2
d′
5
10
15
20
Block of 5 Sessions
Narrow Range
Wide Range

used in Experiment 1. In addition, the three narrow-range birds from Experiment 1 were given further training on the same, narrow, stimulus range after a lapse of approximately three months.

Apparatus. A new experimental chamber was used for this and subsequent experiments. The apparatus was similar to that used in Experiment 1 (see earlier description and Figure 2 for details). The major change consisted of the use of a Kodak Carousel #750H slide projector instead of the Model 800 used in Experiment 1 and the use of Sylvania Tungsten Halogen ELH Quartz TruBeam projector lamps instead of the General Electric CBA lamps.

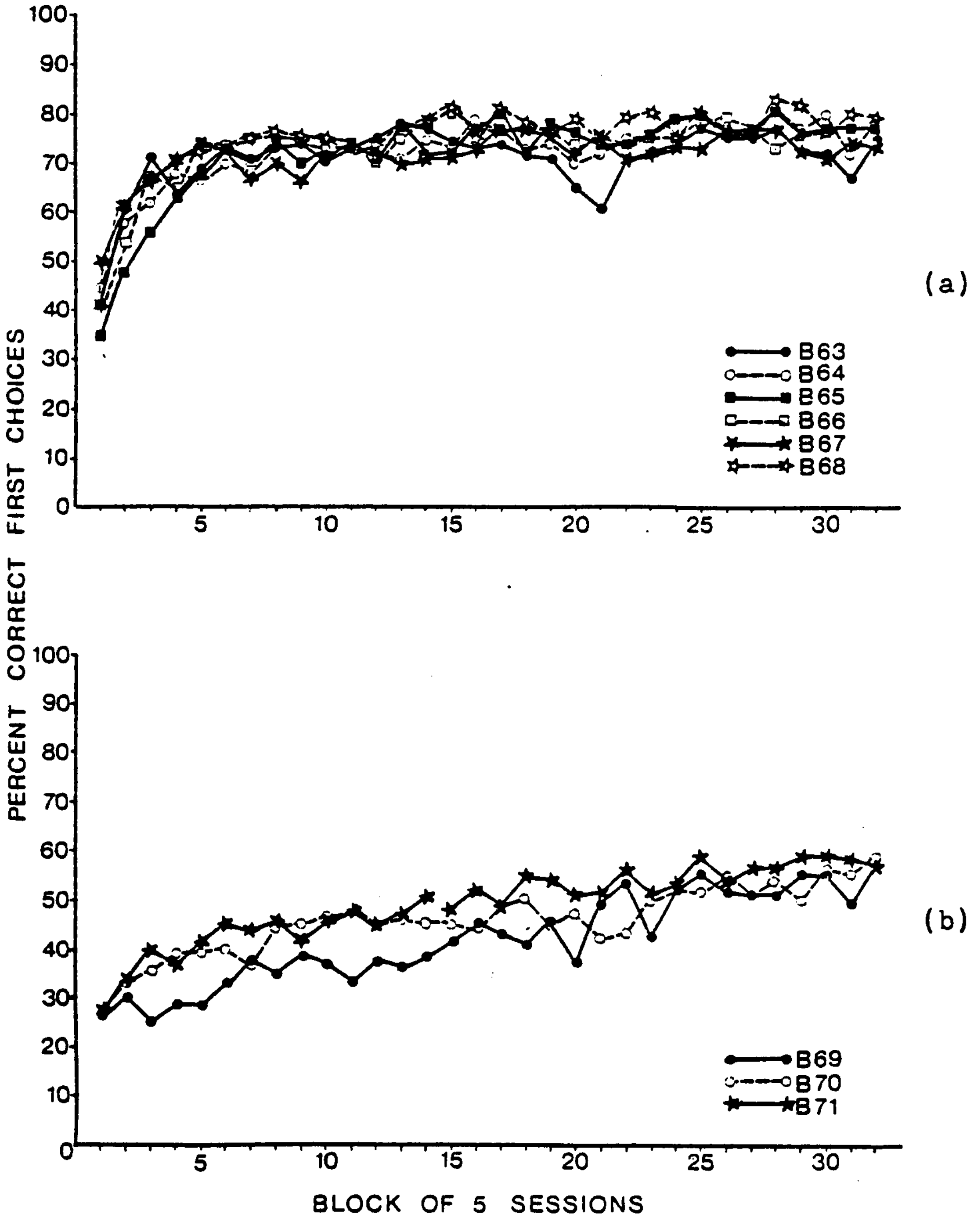
Stimuli. The model #750H slide projector was set on the "low" setting. The neutral filters used in Experiment 2 were of densities 1.4, 1.6, 1.8 and 2.0 for the narrow range. These filters attenuated the light source to .4, .2, 0 and -.2 log ft.L. for stimuli 1, 2, 3 and 4 respectively. The filters used for the wide range were of densities .2, 1.6, 1.8 and 3.2 which produced luminance levels of 1.6, .2, 0 and -1.4 log ft.L. for stimuli 1, 2, 3 and 4 respectively. As was the case in Experiment 1, stimuli 2 and 3 were the were the same for both conditions, however, these two stimuli were about 1.3 log units dimmer than the two central stimuli used in Experiment 1.

Procedure. The procedure was the same as that used in Experiment 1 except that the nine naive birds were given 160 sessions of training. The three birds trained on the narrow range in Experiment 1 were given 100 days of training in the new apparatus under conditions that closely duplicated their original training.

Results

The nine new birds were given 160 sessions of training at which point the wide-range birds were asymptotic and all of the narrow-range birds had reached a point where their rate of improvement was minimal (i.e., an average increase of no more than 5% correct responses over 25 days or 500 presentations of each stimulus). Figure 13 shows the average percent of correct first choices per 5-day block for each bird. It can be seen that the wide-range group leveled off after approximately block 6 (30 sessions) at about 75% correct first choices. The narrow-range group, however, continued to increase their percent correct first choices until about block 24 (session 120). Birds 43 through 45, previously trained in Experiment 1 with the narrow range, appeared not to have made any noticable gains after block 6 (session 30) of retraining (retraining data in Appendix B). Birds 43, 44 and 45 never reached their earlier level of performance in the new apparatus (63% correct first choices in Experiment 1 vs. 51% in Experiment 2). The level that they did reach in Experiment 2, however, closely coincided

Figure 13. Percent correct first choices for each bird. Data are shown in five-day blocks for the 100 sessions of Experiment 2. Data for the birds trained on the narrow range are shown in panel **b**. Data for the birds trained on the wide range are shown in panel **a**.

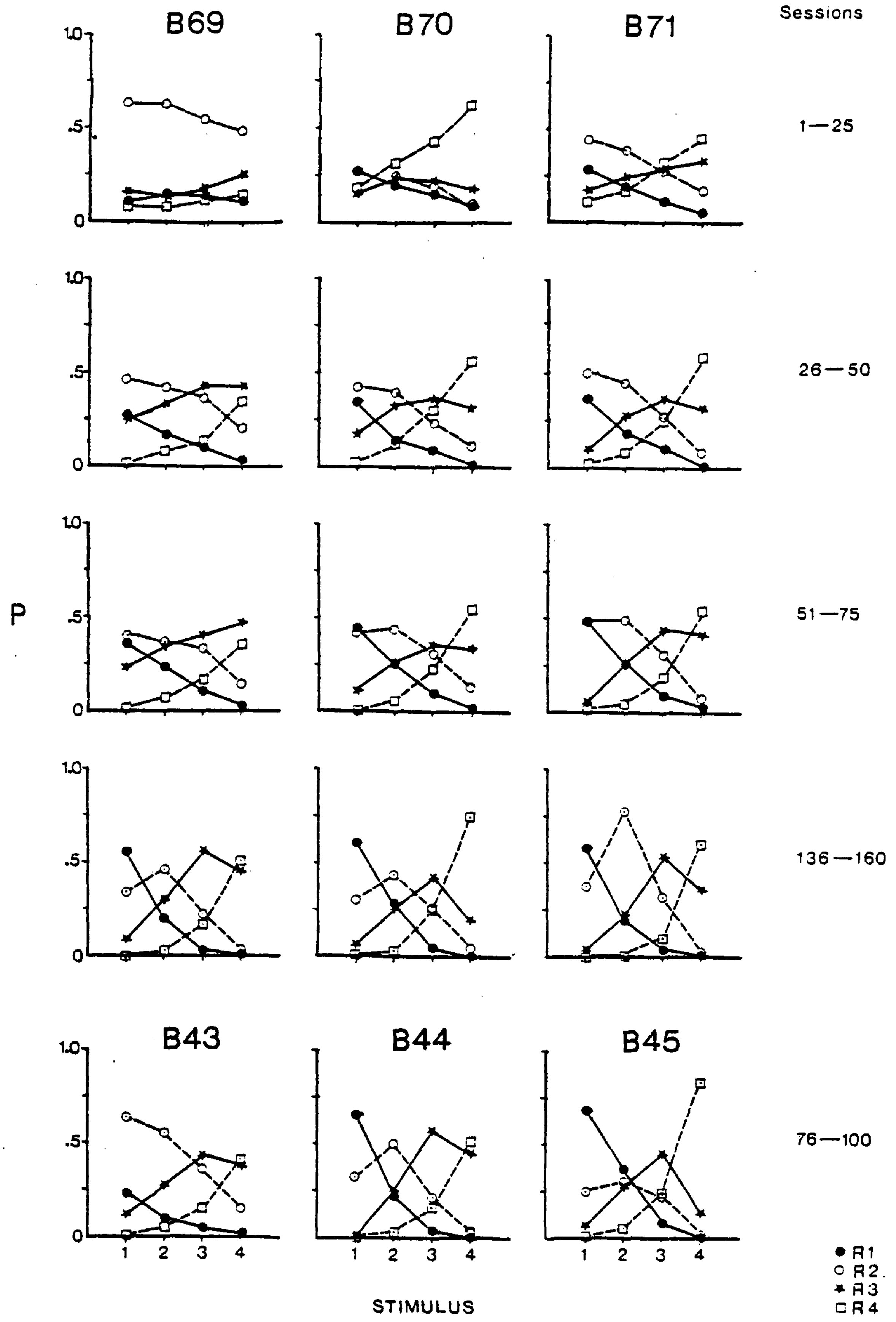

PERCENT CORRECT FIRST CHOICES
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
(a)
B63
B64
B65
B66
B67
B68
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
(b)
B69
B70
B71
BLOCK OF 5 SESSIONS

with the performance level of the birds (B69, 70 and 71) trained exclusively in the new apparatus. The lower level of performance may have been due to the absolute difference in luminance. Although the relative differences in luminance were the same in both experiments, the absolute luminance level in Experiment 1 was approximately 1.3 log ft.L. higher than that in Experiment 2.

Figure 14 shows the four response choice curves for the new narrow-range birds (B69, 70 and 71) for the first three and the last of the 25-day blocks. The data for each of the birds show some evidence of stimulus control (i.e., that at least one criterion had been established) during the first 25-day block. The second and third 25-day blocks show increases in stimulus control for all three birds. The plot for days 136-160 shows that all response curves reach their highest points in the presence of the appropriate stimuli.

An examination of the five-day block data (included in Appendix B) confirms the above observation that birds 70 and 71 established a single clear criterion early in training (certainly by the second 5-day block). These data show that bird 69 had a preference for R2 throughout the 25-day period. Despite this key preference which decreased as training progressed, there is some indication of control of R2 by the luminance dimension. R2 was made most frequently in the presence of the brighter of the two stimuli, S1 and S2, over the first 25 days.

Figure 14. Four-response choice curves for the narrow-range birds in Experiment 2. The first three 25-day blocks are shown for birds 69, 70 and 71 as well as the last 25-day blocks for birds 69, 70, 71, 43, 44 and 45. In this narrow-range condition S1, S2, S3 and S4 were .4, .2, 0 and -.2 log ft.L. respectively.


B69
B70
B71
Sessions
1.0
.5
0
1—25
26—50
51—75
136—160
B43
B44
B45
76—100
P
1
2
3
4
STIMULUS
● R1
○ R2
✱ R3
□ R4

The birds originally trained on the narrow range in Experiment 1 (B43, 44 and 45) showed some improvement over their 100 days of retraining. With the exception of B43, all three criteria were evident on the first 25-day block. Bird 43 tended not to make R1 as a first choice; however, when R1 was made, it was most often made in the presence of the appropriate stimulus, S1. This response bias may account for the fact that even by the last block of retraining (see Figure 14, bottom panel), R2 was made most frequently in the presence of S1. The other responses were made most frequently in the presence of the appropriate stimuli.

Choice curves for the first and last 25-day blocks for each of the wide-range birds are shown in Figure 15. Three criteria were established during the first 25 days of training. Note that with few exceptions the choice curve for each response peaks over the appropriate stimulus. An examination of these data for the first two 5-day blocks (Figure 16) indicates that all six birds established at least one criterion during the first five days. In addition, both of the outer criteria appeared within the first five days for birds 63 and 68. Both outer criteria were present by the second 5-day block (sessions 6-10) for birds 63, 64, 67 and 68. It is interesting to note that all birds developed the criterion between the two brightest stimuli, S1 and S2 first. As was noted, most of the birds in Experiment 1 also developed their first criterion between the two

Figure 15. Four-response choice curves for the wide-range birds in Experiment 2. Data are shown for the first and last 25 days of training. In this wide-range condition S1, S2, S3 and S4 were 1.6, .2, 0 and -1.4 log ft.L. respectively.

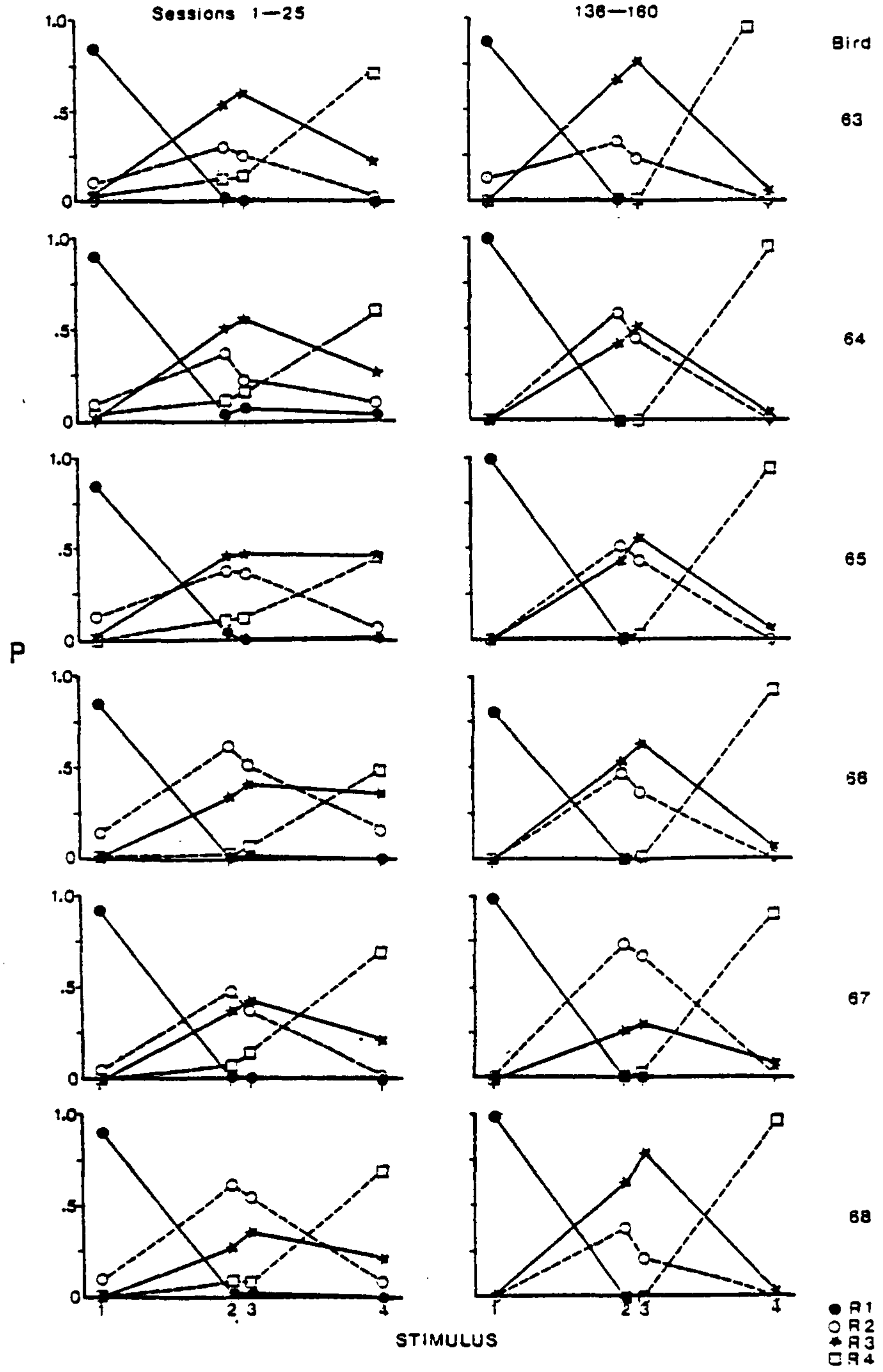
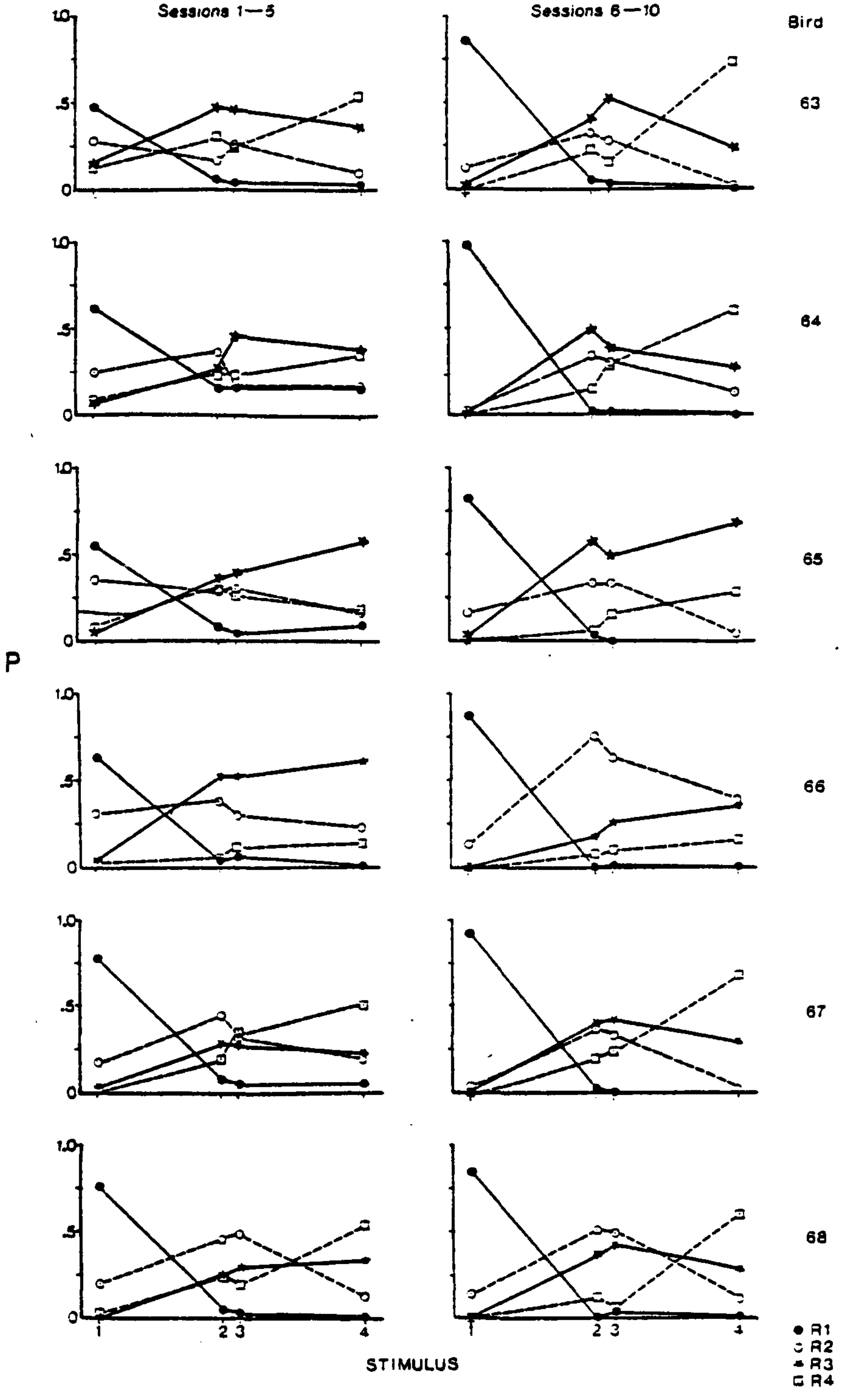

Sessions 1—25
136—160
Bird
63
64
65
66
67
68
1.0
.5
0
P
1
2 3
4
STIMULUS
● R1
○ R2
✱ R3
□ R4

Figure 16. Four-response choice curves for the wide-range birds in Experiment 2. Data are shown by 5-day block for the first 10 days of training. In this wide-range condition S1, S2, S3 and S4 were 1.6, .2, 0 and -1.4 log ft.L. respectively.


Sessions 1—5
Sessions 6—10
Bird
63
64
65
66
67
68
1.0
.5
0
P
1
2 3
4
STIMULUS
● R1
○ R2
* R3
□ R4

brightest stimuli. Evidence of discrimination between the two central stimuli was visible in the first 5-day block for one of the birds (B63), as indicated by R2 having occurred most frequently in the presence of S2 and R3 in the presence of S3. For three other birds (B66, 67 and 68) this control was apparent in the second 5-day block, and it was evident for all but B65 by the third block of five days (not shown). Once apparent, despite evidence of key preferences for several of the birds, R2 and R3 remained under control of the luminance dimension throughout the experiment.

Despite this very early evidence of differentiation between R2 and R3 for the wide-range birds, d' (ROC method) between stimuli 2 and 3 for these birds increased little over the course of training (see Figure 17). Examination of the development of the discrimination between the two central stimuli by the narrow-range birds (Figure 18) clearly shows that d' increased over training. A comparison of d' under the two conditions can be seen in Figure 19 which shows the mean d's for each group by 5-day block. Note that d' is similar for both groups at the start of training, but the curve for the narrow-range group continued to climb during training more rapidly than that of the wide-range group. Comparison of Figure 19 to Figure 12, the comparable plot for Experiment 1, indicates that the larger difference between the ranges in Experiment 2 resulted in

Figure 17. d' for S2 and S3 as a function of training for all wide-range birds in Experiment 2. The solid lines are for data shown in 5-day blocks; the dashed lines are for data shown in 25-day blocks.

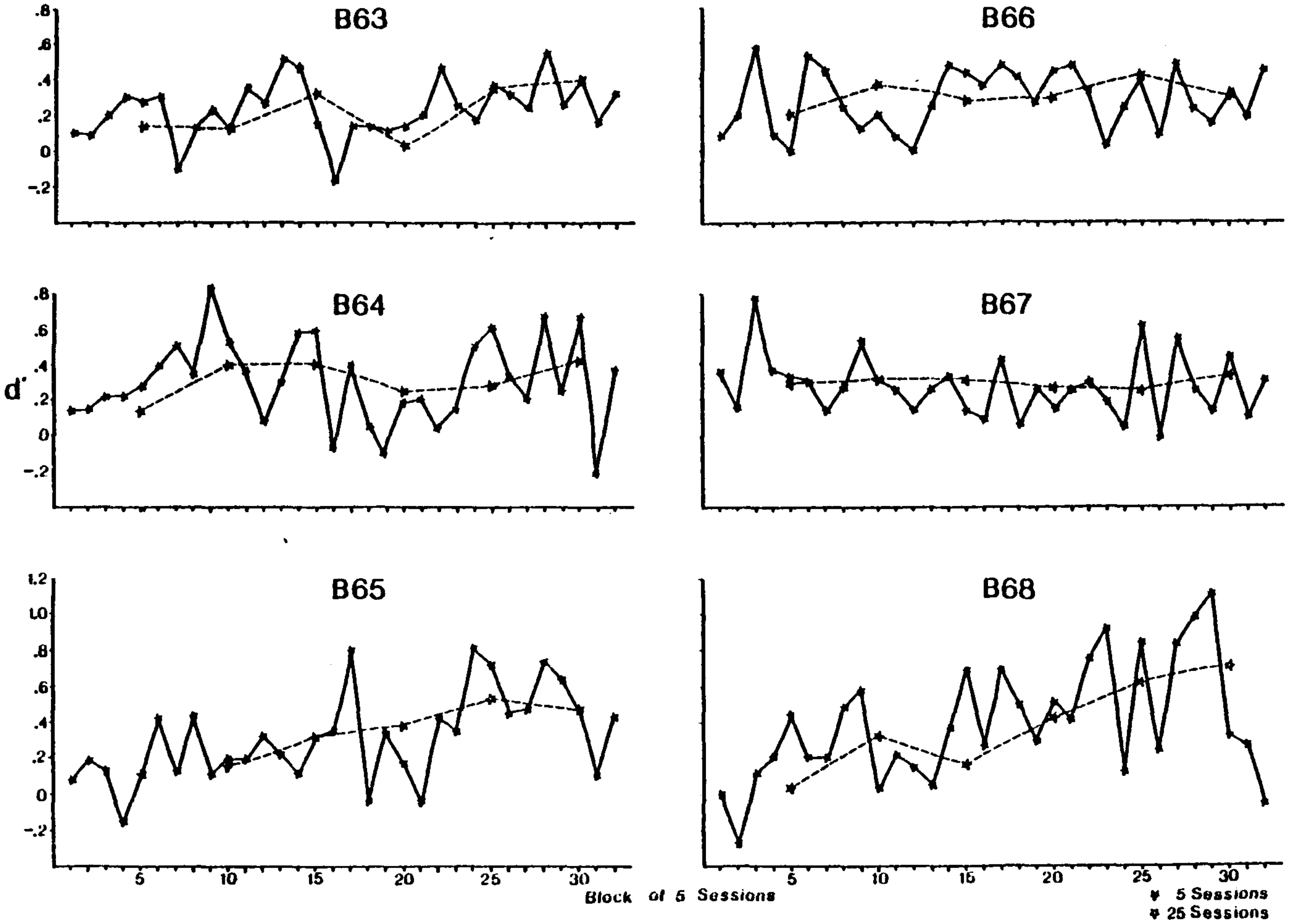

B63
B66
B64
B67
B65
B68
d'
.8
.6
.4
.2
0
-.2
1.2
1.0
5
10
15
20
25
30
Block of 5 Sessions
5 Sessions
25 Sessions

Figure 18. d' for S2 and S3 as a function of training for all narrow-range birds in Experiment 2. The solid lines are for data shown in 5-day blocks; the dashed lines are for data shown in 25-day blocks.

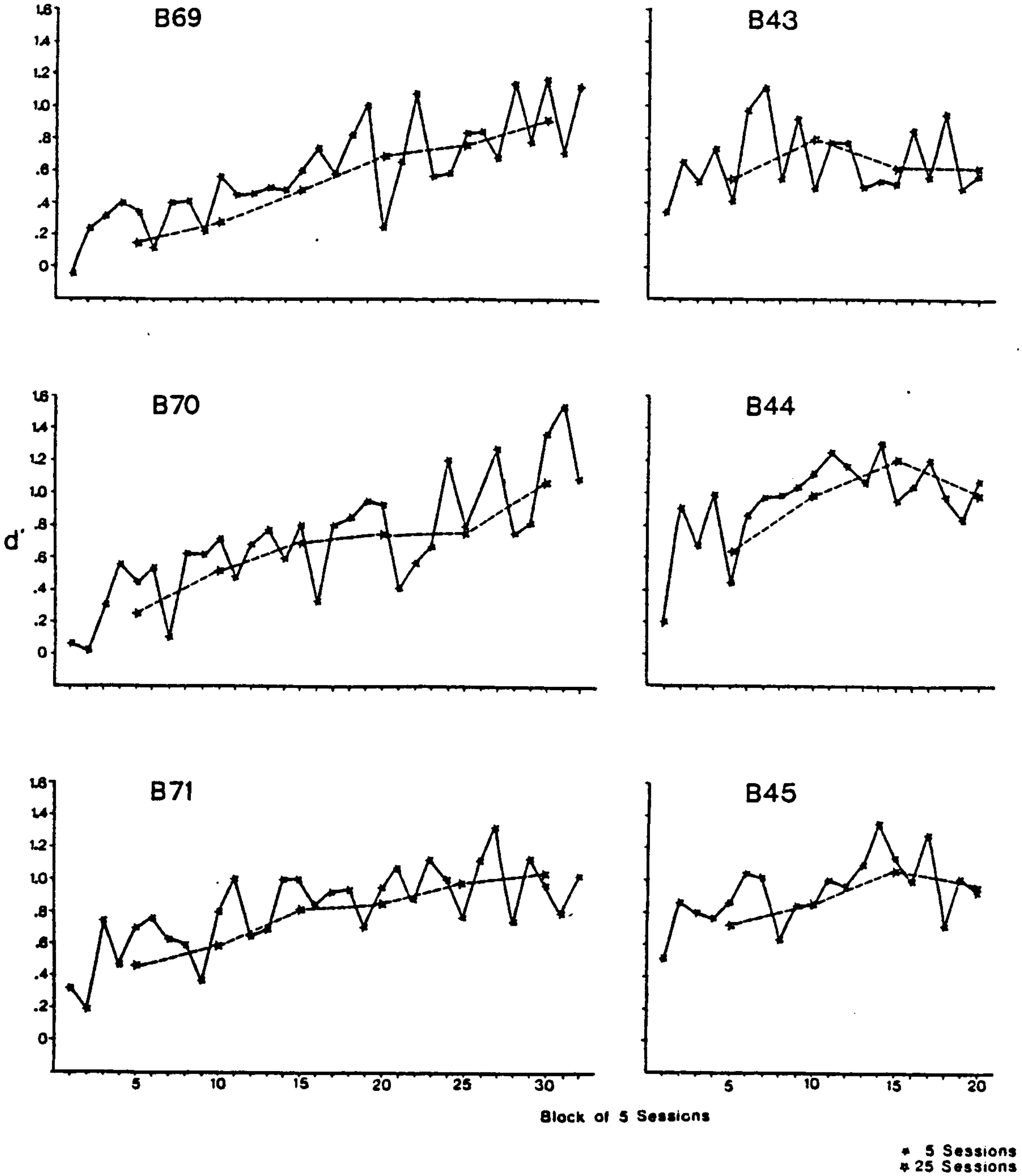
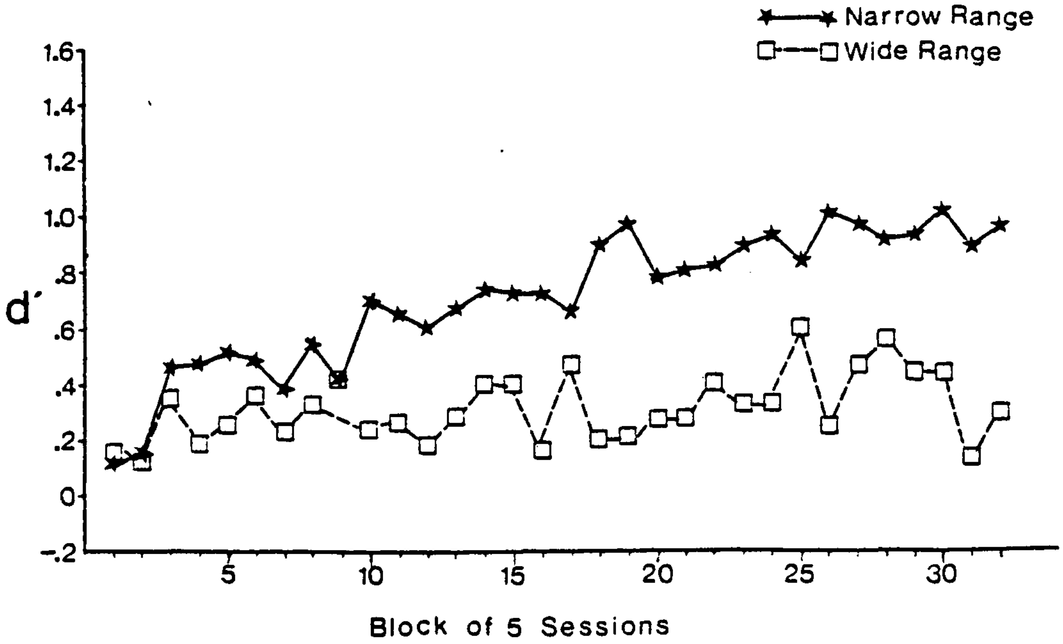

B69
B43
B70
B44
B71
B45
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
d'
5
10
15
20
25
30
5
10
15
20
Block of 5 Sessions
* 5 Sessions
* 25 Sessions

Figure 19. Comparison of d' between S2 and S3 throughout training for both range conditions in Experiment 2 (group data).


Narrow Range
Wide Range
d′
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
-.2
5
10
15
20
25
30
Block of 5 Sessions

more clearly divergent functions and thus a more conclusive demonstration of the range effect. Both in terms of d' and in terms of the percent correct first choices, the narrow-range birds in Experiment 2 never reached the level of the narrow-range birds in Experiment 1.

Figures 20 and 21 present the z-RCC curves for the discrimination between S2 and S3 generated during the last 25 days of training for all birds. Again the points for the narrow-range birds are further from the diagonal indicating greater sensitivity and they are well fit by a line with a slope of 1. Since in the wide range the stimuli being discriminated were exactly the same as those in the narrow range, it is reasonable to assume that the z-RCC curves for these birds also have a slope of 1. The perfect identification of S1 and S4 resulted in fewer data points.

Table 2 shows the mean d' for each of the birds in Experiment 2 over the last 25 days of training as calculated by both methods. The difference between the mean d's calculated by the RCC method (.93 for the narrow range and .37 for the wide range) is statistically significant (t (10) = 5.909, $p < .001$). The Thurstonian method of obtaining d' indicates a mean d' of 1.01 for the narrow-range birds and of .36 for the wide-range birds; this difference is also significant (t (10) = 7.054, $p < .001$).

For each bird, the mean criterion position separating R1 and R2 from R3 and R4 (C) is also presented in Table 2. If the birds followed the decision rule described in Figure

Figure 20. Proportion of "hits" and "false alarms" for stimuli 2 and 3 for all birds in the narrow-range condition in Experiment 2. All data points are based on the last 25 days of training and are plotted on normal deviate axes. The diagonal represents chance performance. Points further from the diagonal indicate higher *d*' values.

Narrow Range

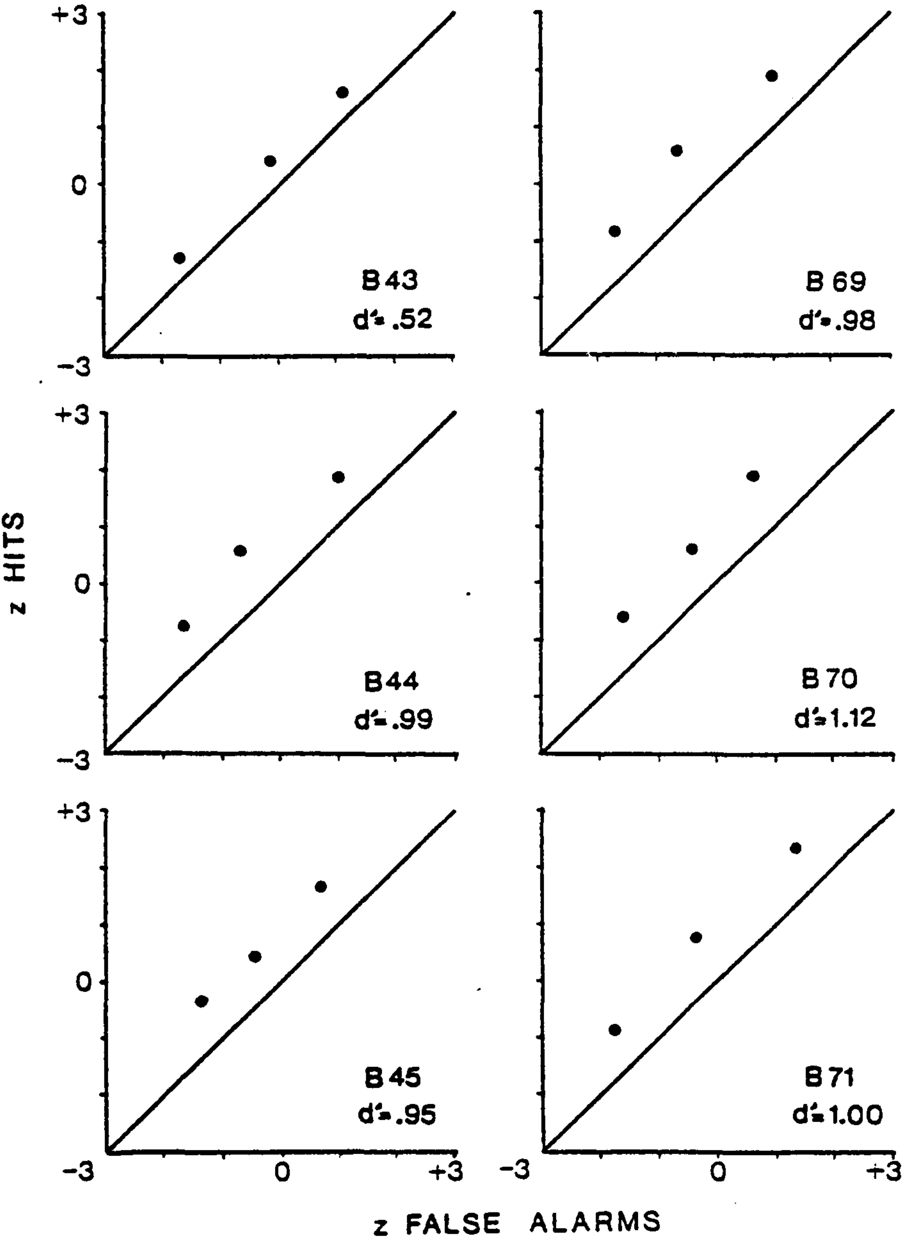


Figure 21. Proportion of "hits" and "false alarms" for stimuli 2 and 3 for all birds in the wide-range condition in Experiment 2. All data points are based on the last 25 days of training and are plotted on normal deviate axes. The diagonal represents chance performance. Points further from the diagonal indicate higher _d_' values.

Wide Range

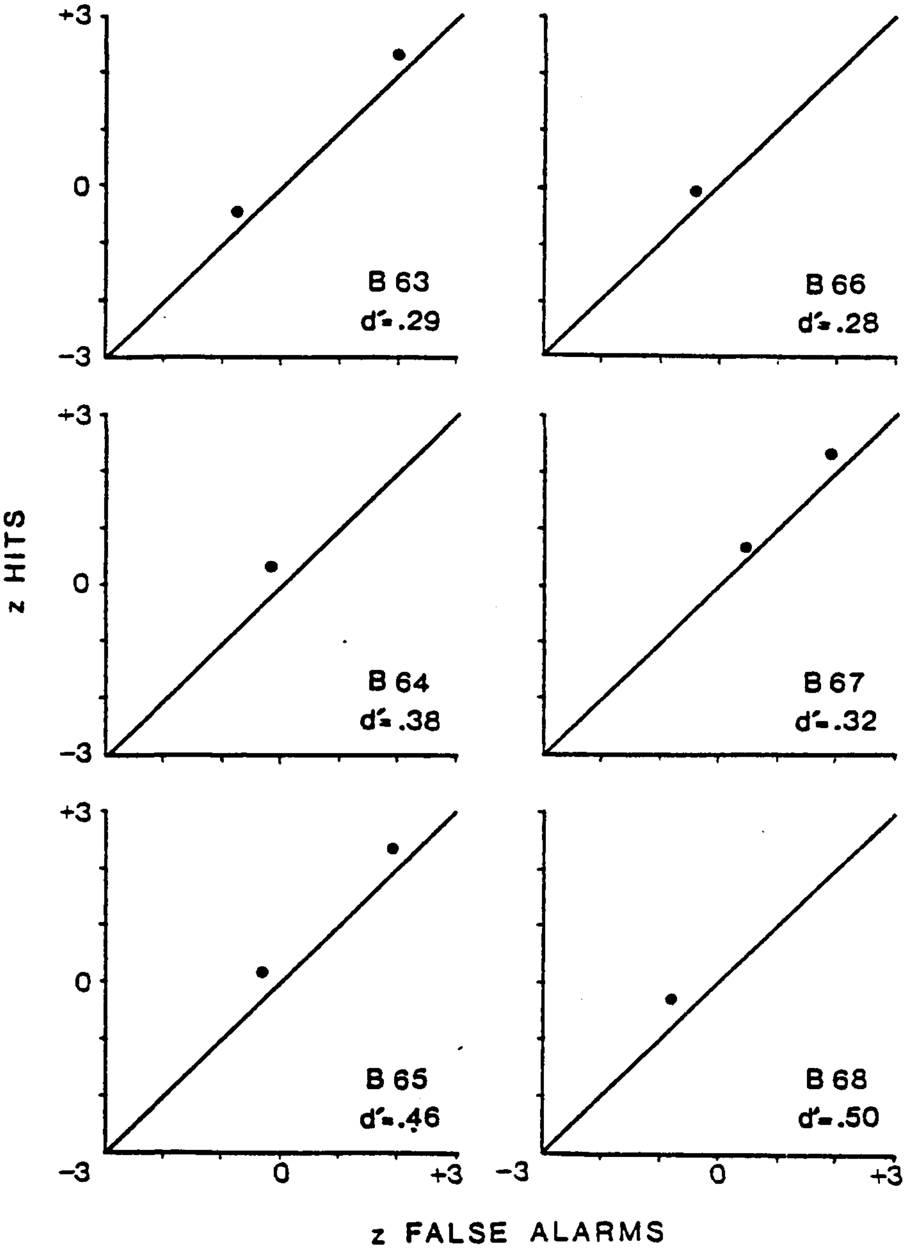

+3
0
-3
z HITS
B 63
d'=.29
B 66
d'=.28
B 64
d'=.38
B 67
d'=.32
B 65
d'=.46
B 68
d'=.50
-3
0
+3
-3
0
+3
z FALSE ALARMS

Table 2. Mean d's (both ROC and Thurstonian methods), C and RBI for each bird for the last 25 days of training in Experiment 2.

		d'			
Condition	Bird	ROC Method	Thurstonian Method	C*	RBI
Narrow Range	43	.52	.66	.065	.23
	44	.99	1.22	.105	.15
	45	.95	.94	.106	.20
	69	.98	1.08	.119	.22
	70	1.12	1.05	.090	.06
	71	1.00	1.10	.065	.16
	$\bar{x}$	.93	1.01	.092	.19
Wide Range	63	.29	.30	.513	.62
	64	.38	.38	.079	.06
	65	.48	.48	.138	.10
	66	.28	.28	.257	.28
	67	.32	.20	-.440	.61
	68	.50	.50	.324	.58
	$\bar{x}$	.38	.36	.145	.38

*in log ft.L.

1, C would be midway between S2 and S3. This criterion placement (.1 log ft.L.), which would result in the fewest misses and false alarms, will hereafter be referred to as C'. The mean C obtained for the birds in the narrow-range group was .092 log ft.L. Note that the C values for the narrow-range birds were all between S2 and S3 while the C values for only two of the six wide-range birds were between S2 and S3.

The R2 and R3 choice curves at the end of training (last 25-day block) under the narrow- (Figure 14) and wide-range (Figure 16) conditions are quite different. While for all birds the choice curves peak over the appropriate stimulus value, the R2 and R3 curves for five out of the six birds trained on the narrow range (B43 is the exception) intersect between S2 and S3, the curves for only one of the birds trained under the wide-range condition (B65) intersect between S2 and S3. The wide-range birds show strong key preferences in choosing between R2 and R3.

The degree of key preference or response bias may be measured by comparing all R2 first choices given S2 or S3 to all R3 first choices given S2 or S3. If the smaller of these numbers is divided by the larger and the result subtracted from 1, an index of response bias will result ranging from 0 to 1. An index of 0 indicating no key preference, (i.e., that $P(R2|S2 \text{ or } S3) = P(R3|S2 \text{ or } S3)$); this will be the case when C = C'. Indices approaching 1 indicating progressively greater response bias.

This index, the RBI, is sensitive to the position of all three criteria rather than to only the central criterion. In the wide-range condition the sensory effect distributions of the extreme stimuli do not substantially overlap those of the central stimuli and thus the criteria established between the extreme and central stimuli are not likely to include many sensory effects due to S1 and to S4 in the R2 or R3 regions. This is supported by the birds' near-perfect recrods of identifying S1 and S4. In the wide range condition, therefore, the RBI will be closely related to the distance of $\underline{C}$ from $\underline{C}'$; indeed, the two measures (RBI and $|\underline{C} - \underline{C}'|$) are significantly correlated ($\underline{r}$ (4) = .8927, $\underline{p} < .05$). In the narrow range condition, the sensory effects of the stimuli are likely to have overlapped to a greater extent, and since the RBI is influenced by such overlap, it is not surprising that the correlation between RBI and $|\underline{C} - \underline{C}'|$ shows no significant relationship ($\underline{r}$ (4) = .0858, $\underline{p} > .05$).

In order to determine whether sequential factors could be responsible for the observed range effect, each bird's performance over the last 25 days of training was analyzed for the possible dependence of any given response on the stimulus-response pairing reinforced on the immediately preceding trial. Unfortunately, due to an apparatus failure, this sequential data represents only 15 days of training for birds 63-71 (5-day blocks 28, 29 and 32). Since the data include the beginning and the end of the 25-day blocks and no clear difference is visible within subjects, it is unlikely that this loss of data significantly distorted the findings. Table 3 presents C for the discrimination between S2 and S3 for each bird after S1, after S2, after S3 and after S4.

As discussed earlier, it was expected that if the previous stimulus affected performance, then this effect would be most clear on trials immediately following one of the extreme stimuli (S1 and S4). The mean C position for the wide-range birds on trials following S1 and S4 did not differ significantly (t (5) = .426, $p > .05$). C for the narrow-range birds tended to be closer to S3 than to S2 after S1 was presented and closer to S2 than to S3 after S4 was presented; however, this difference was not significant (t (5) = 1.384, $p > .05$).

To obtain a measure of the degree to which criterion position was influenced by the preceding stimulus, the standard deviation of the four C positions presented in Table 4 was obtained for each bird; these values are included in the table. The mean of the standard deviations of the birds in the wide-range group was significantly larger than the mean of those in the narrow-range group (t (10) = 4.023, $p < .01$) indicating that C for the wide-range birds was significantly more variable than for the narrow-range birds.

To assess the extent to which reinforcement of R2 or R3 on trial N-1 influenced responses on trial N to S2 and S3,

Table 3. Mean criterion position as a function of the stimulus correctly identified on the preceding trial and the standard deviations (S.D.) of the obtained C values for each bird in Experiment 2. Data are based on the last 25 days of training.

		C*				
Condition	Bird	After S1	After S2	After S3	After S4	Subject S.D.
Narrow Range	43	.0088	.0537	.0777	.0681	.0305
	44	.1051	.1023	.1103	.0271	.0395
	45	.0529	.1090	.1164	.1203	.0315
	69	.0460	.0907	.1664	.1678	.0599
	70	.0769	.0675	.0837	.1452	.0352
	71	.0690	.0671	.1098	.0667	.0212
	$\bar{x}$	.0598	.0817	.1107	.0992	.0363
Wide Range	63	.2541	.2081	.3436	.6100	.1797
	64	.1122	.0827	.1872	.10402	.0455
	65	.4000	.1303	.1306	.1125	.1380
	66	.2146	.2364	.3538	.1474	.0860
	67	-.0958	-.4167	-.0481	-.2947	.1723
	68	.2528	.4765	.2337	.2278	..1197
	$\bar{x}$	.1897	.1196	.2001	.1512	.1235

* in log ft.L.

the RBI's were calculated for trials following S2 and S3. It was assumed that if a <u>win-stay</u> strategy was in operation, the RBI's would show a lowered bias toward the preferred key if a response on the non-preferred key had been reinforced on the previous trial. Five of the six birds in the narrow-range group and five of the six birds in the wide-range group maintained their key preferences regardless of which of the two responses had been reinforced on trial N-1. The other two birds (B71 and B64) were more likely to make the same response (R2 or R3) reinforced on trial N-1 to either S2 or S3 on trial N. To be certain that a win-stay strategy was not significantly influencing the birds' responses, the difference between the mean RBI's on the preferred and non-preferred keys following reinforced identifications of S2 and S3 were tested for both range conditions. These data are included in Appendix B. This difference, and thus the effect of such a strategy, was not significant for either the narrow-range group ($\underline{t}$ (5) = 1.393, $\underline{p} > .05$) or the wide-range group ($\underline{t}$ (5) = .215, $\underline{p} > .05$).

The mean response latencies to display key pecks preceding R2 or R3 choices were examined for all birds in Experiment 2 over the last 25 days of training. Latencies were longer for the birds trained with the wide range (1398 msec. on R2 and 1257 msec. on R3) than for those trained on the narrow range (1092 msec. on R2 and 1170 msec. on R3). These differences were not significant at the .05 level when t-tests were done on the reciprocal latencies (see Table 4).

Table 4. Mean latency of display key pecks preceding R2 and R3 for each bird for the last 25 days of training in Experiment 2.

Condition	Bird	Mean latency in msec.	
		R2	R3
Narrow Range	43	885	1004
	44	1070	1242
	45	957	1040
	69	1539	1398
	70	1124	1246
	71	978	1089
	$\overline{x}$	1092	1170
Wide Range	63	628	599
	64	1194	1084
	65	939	814
	66	1592	1360
	67	1133	1392
	68	2903	2291
	$\overline{x}$	1398	1257

* t-test on difference between reciprocals of the meanslatencies indicate no significant differences between the two range conditions (*p* .05). For R2 *t*(10) = .2891; for R3 *t*(10) = .4621.

Experiment 3

As Experiments 1 and 2 clearly demonstrated, the range effect exists in the pigeon. The mechanisms underlying the range effect, however, remain to be explained. It could be argued that the narrow-range birds learned more about S2 and S3 than the wide-range birds did, despite an equal number of reinforced correct identifications of these stimuli, and that the superior discrimination between S2 and S3 would endure regardless of range. It seemed, therefore, that the next logical step was to determine whether the discriminability of the two central stimuli is affected by a change in the stimulus range, i.e., the birds originally trained on the narrow range were switched to the wide range and the birds originally trained on the wide range were changed to the narrow range. If *d*' between the two central stimuli declined for the birds switched from the narrow to the wide range and increased for the birds switched from the wide to the narrow range, it could be concluded that the overall range is necessary to maintain as well as to establish the performance reported in Experiments 1 and 2.

Method

Subjects. The same 12 White Carneaux pigeons who served as subjects in Experiment 2 were used in Experiment 3.

Apparatus. The apparatus was identical to that used and described in Experiment 2.

Procedure. The procedure was the same as that used in Experiment 2 with one major exception. The birds previously trained on the narrow range were trained for 25 days on the wide range used in Experiment 2, and the birds previously trained on the wide range were trained for 25 days on the narrow range used in Experiment 2. This switch was made on the day immediately following the last day of training in Experiment 2.

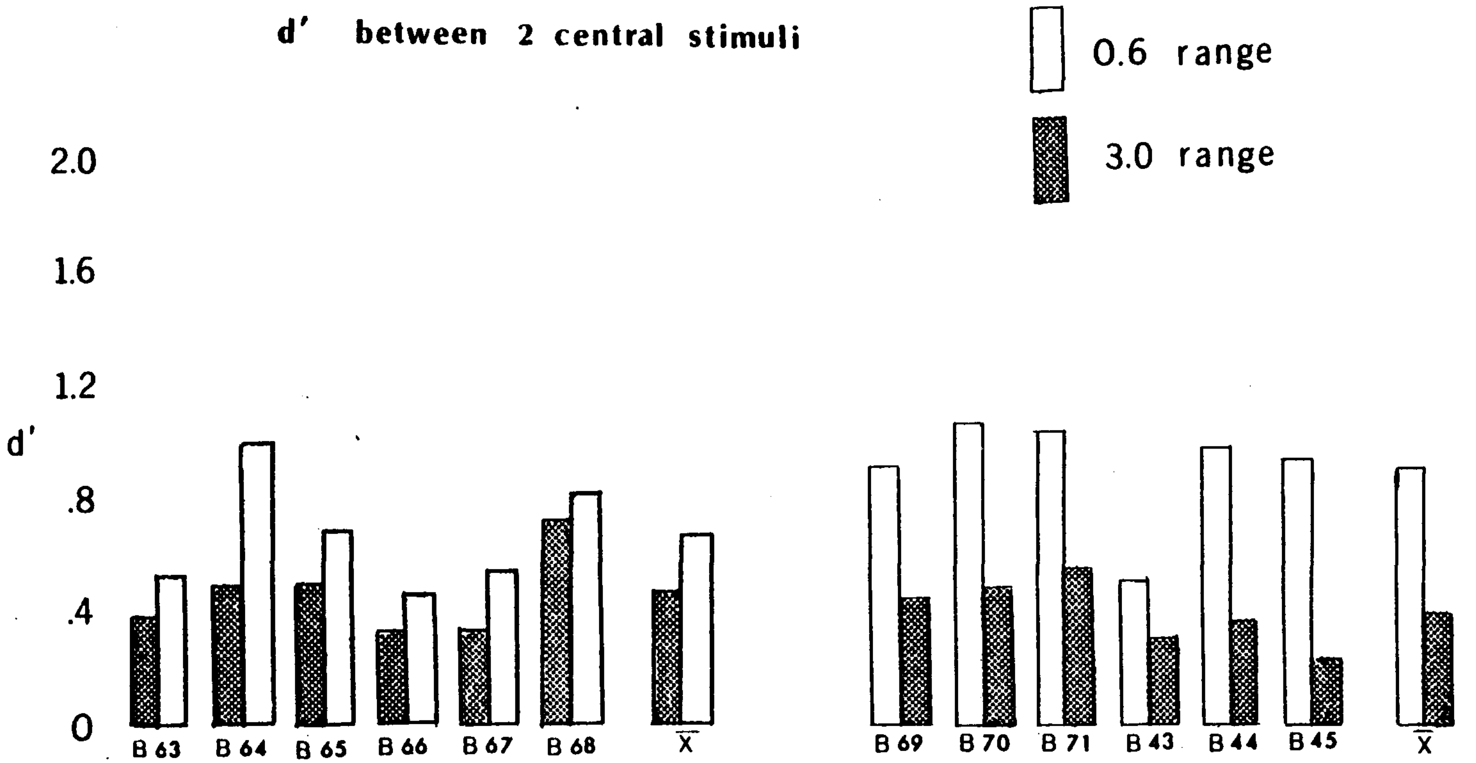
Results.

The results of this experiment very clearly show that range effects the establishment as well as the maintenance of the accuracy of discrimination between S2 and S3.

Table 6 shows d' based on the 25 days of training with conditions reversed. It is clear from Table 6 that the birds changed to the narrow range condition showed higher d's than those changed to the wide range condition (ROC method). This difference was significant (t (10) = 2.722, $p < .05$). The Thurstonian method of calculating d' also showed higher d's for the birds changed to the narrow range than for those changed to the wide range although the difference was not significant (t (10) = 1.404, $p > .05$).

The results of Experiment 3 are more striking when d' for each bird is compared before and after the switch in range conditions (see Figure 22). The difference between

Figure 22. Bar graph comparing _d'_ in Experiment 2 to _d'_ in Experiment 3 for each bird. Data represent the last 25 days of Experiment 2 and all of Experiment 3.


d' between 2 central stimuli
0.6 range
3.0 range
2.0
1.6
1.2
d'
.8
.4
0
B 63
B 64
B 65
B 66
B 67
B 68
X̄
B 69
B 70
B 71
B 43
B 44
B 45
X̄

the mean *d*'s for the last 25 days of training in Experiment 2 and the mean *d*'s for the 25 days of Experiment 3 is significant for both groups. The dependent t-tests indicate significance at the .001 level for the birds changed from the narrow to the wide range (*t* (5) = 7.021) and at the .02 level for the birds changed from the wide to the narrow range (*t* (5) = 4.375). The comparable t-tests for *d*' as calculated by the Thurstonian method also indicate a significant effect of the change in range. For the birds sw switched from the narrow to the wide range the difference was significant at the .001 level (*t* (5) = 9.140), and for the birds switched from the wide to the narrow range the difference was significant at the .01 level (*t* (5) = 6.401).

The ROC curves for each bird's discrimination between the two central stimuli are presented in Figures 23 and 24. In all cases the ROC points for the new narrow-range birds are further from the diagonal than those for the birds changed to the wide range. These plots may be compared to those generated by the same birds over the last 25 days of training in Experiment 2 (Figures 20 and 21); in all cases a clear change in the ROC points is visible in the expected direction.

Figure 25 shows the choice curves for each of the four responses by five-day block over the course of Experiment 3 for a representative bird from each group. Data for all birds are included in Appendix C. The most apparent effect

Figure 23. Proportion of "hits" and "false alarms" for stimuli 2 and 3 for all birds switched to the narrow-range condition in Experiment 3. All data points are based on the 25 days of training and are plotted on normal deviate axes. The diagonal represents chance performance. Points further from the diagonal indicate higher *d'* values.

Narrow Range

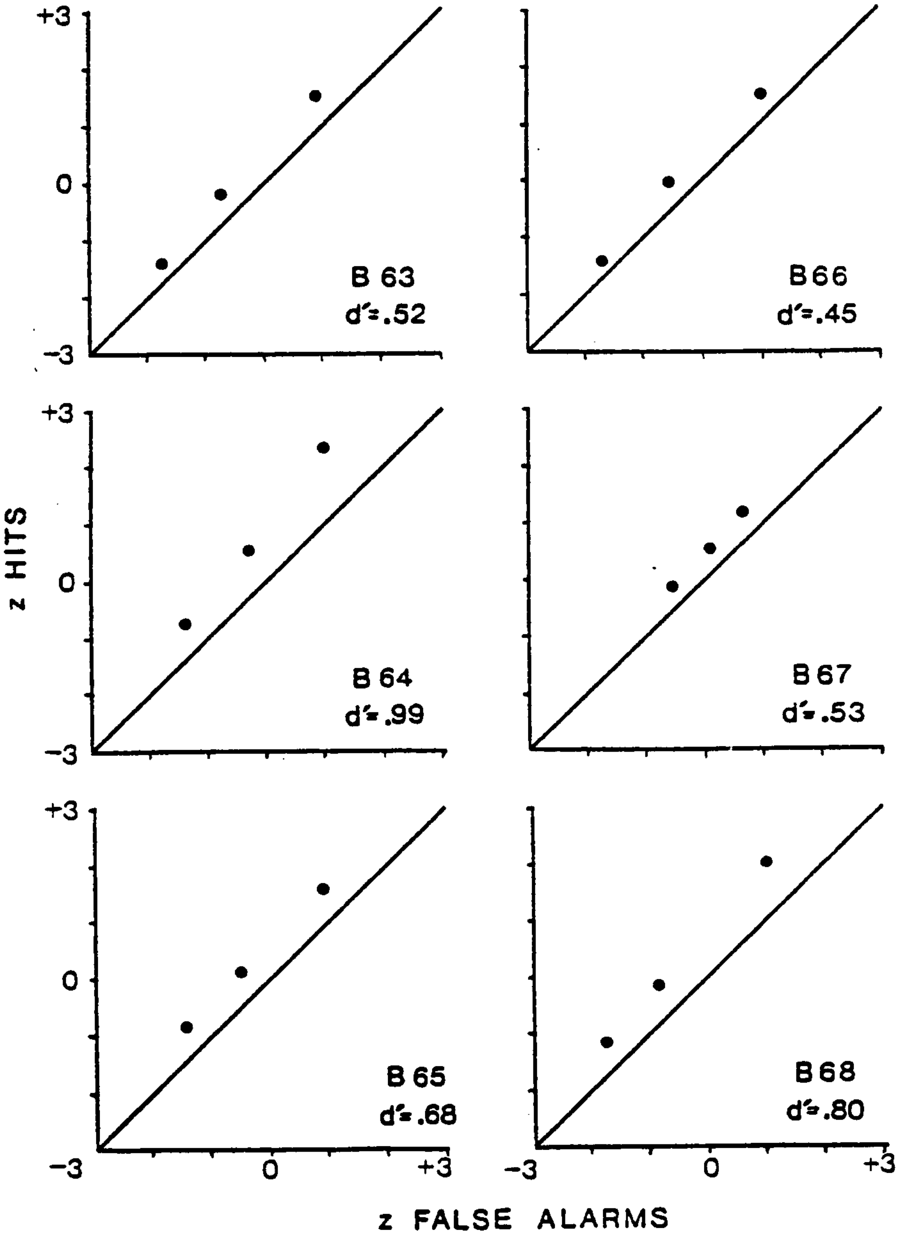


Figure 24. Proportion of "hits" and "false alarms" for stimuli 2 and 3 for all birds switched to the wide-range condition in Experiment 3. All data points are based on the 25 days of training and are plotted on normal deviate axes. The diagonal represents chance performance. Points further from the diagonal indicate higher *d'* values.

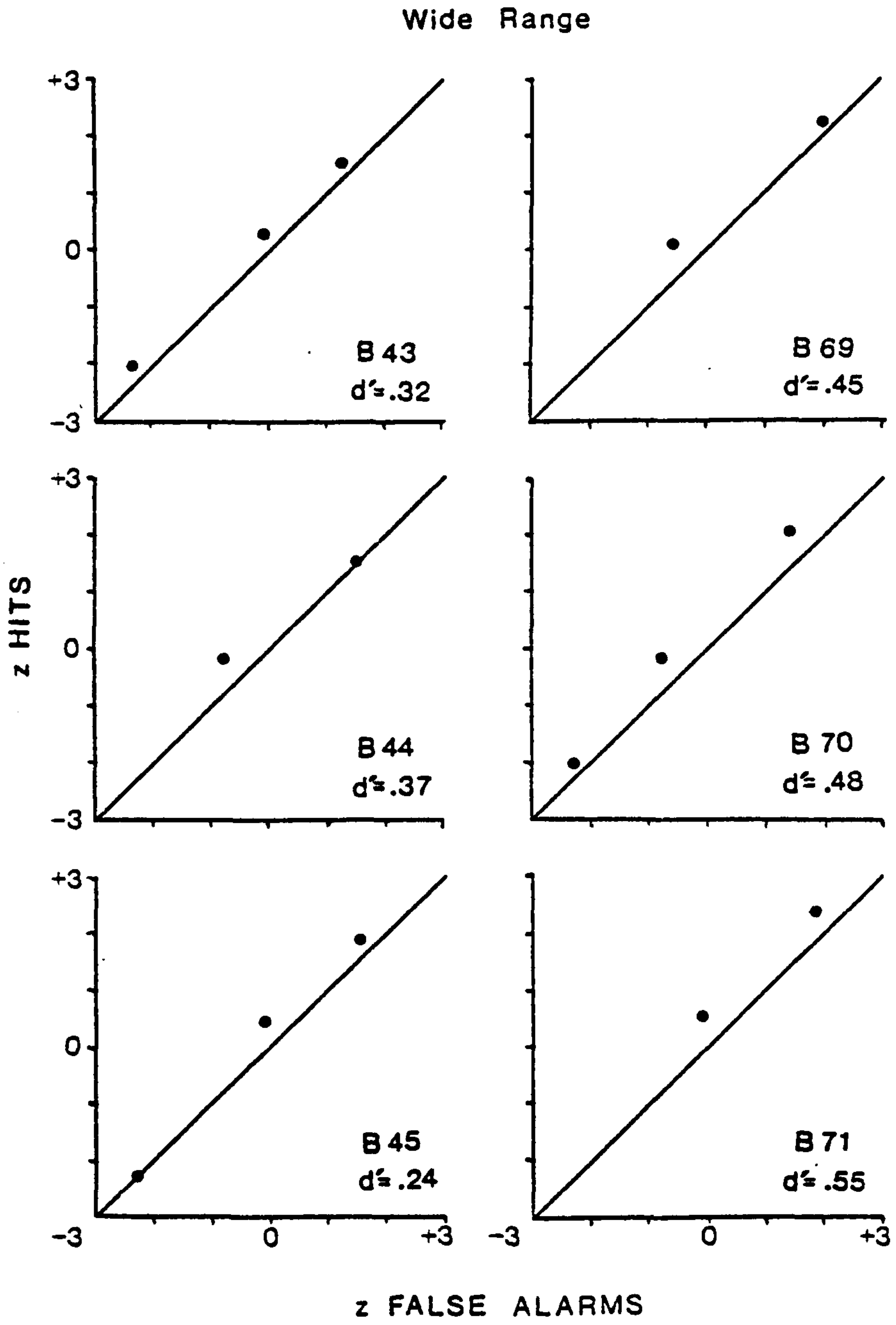
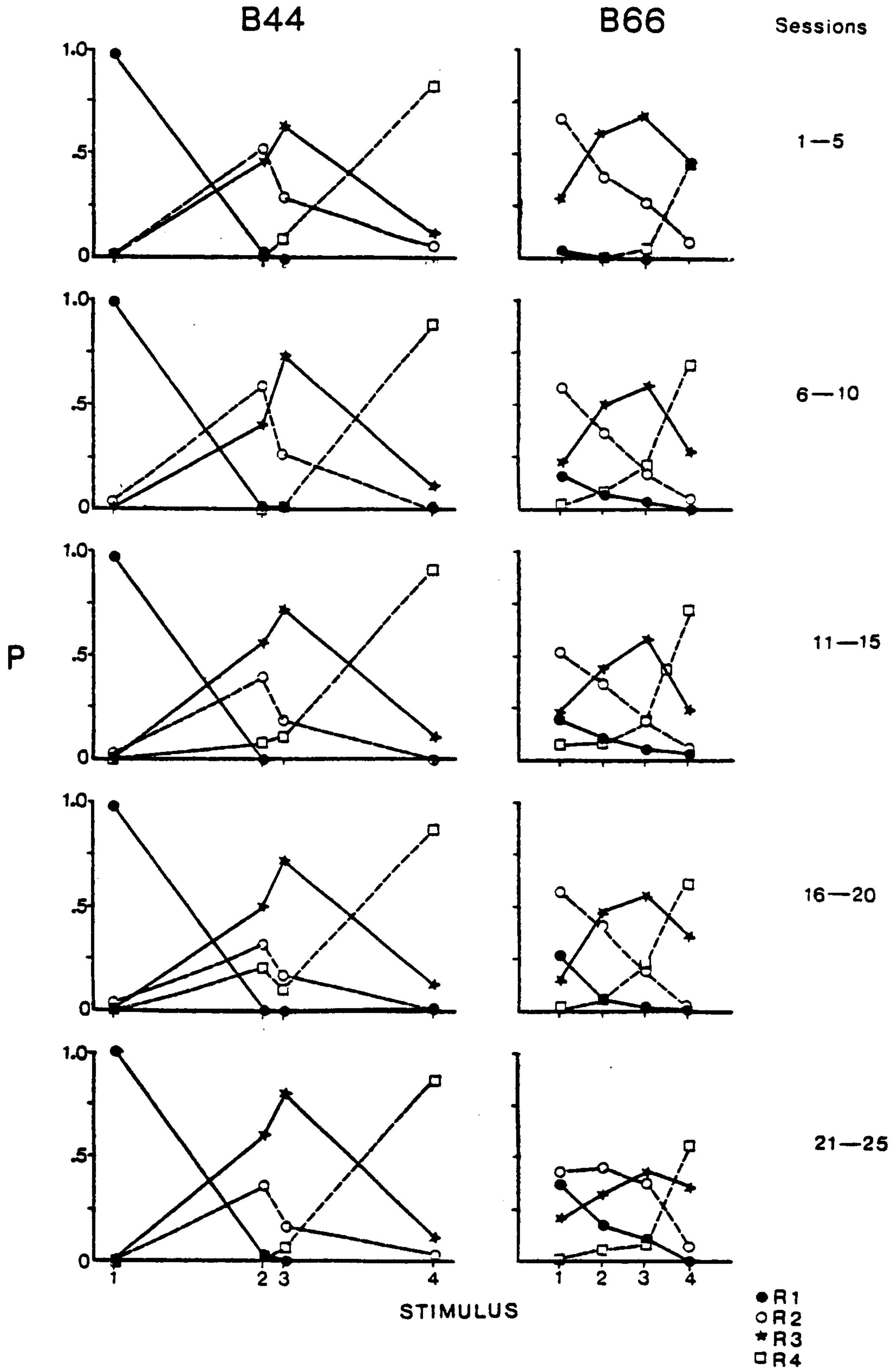

Wide Range
z HITS
+3
0
-3
B 43
d'=.32
B 69
d'=.45
B 44
d'=.37
B 70
d'=.48
B 45
d'=.24
B 71
d'=.55
-3
0
+3
z FALSE ALARMS

Figure 25. Four-response choice curves for two representative birds in Experiment 3. Data are shows by 5-day block for the 25 days of training. The data for B44 (wide range) appear in the left column. In this wide-range condition S1, S2, S3 and S4 were 1.6, .2, 0 and -1.4 log ft.L. respectively. The data for B66 (narrow range) appear in the right column. In this narrow range S1, S2, S3 and S4 were .4, .2, 0 and -.2 log ft.L. respectively.


B44
B66
Sessions
1.0
.5
0
1—5
6—10
11—15
16—20
21—25
P
1
2 3
4
1
2
3
4
STIMULUS
● R1
○ R2
★ R3
□ R4

of increasing range on the choice curves for R2 and R3 was an increase in response bias. In Figure 25 the four-response choice curves are shown for two representative birds, one from each group, over the course of Experiment 3. (Data for all birds are included in Appendix C.) For the birds originally trained on the narrow range and changed to the wide range (B43, 44, 45, 69, 70 and 71), the decrease in accuracy on the discrimination between S2 and S3 was clear by the last 5-day block although some deterioration was visible earlier. The R2 and R3 curves for the final five days reached their highest points over S2 and S3 respectively for all but one of the birds (B45), but these curves no longer intersected in the center of the range, between S2 and S3, for any of the birds switched from the narrow to the wide-range condition. It is clear from the data that response biases developed for these birds. Birds 43, 45 and 71 showed a tendency to respond on key 2 more often than on key 3 when either S2 or S3 was presented and birds 44, 69 and 70 showed a similar bias for key 3.

Increasing response bias was not evident in the comparable data for the birds originally trained on the wide range and changed to the narrow range. Although response biases are clear for all birds changed to the narrow range, these biases are probably merely a continuation of those seen in training on the wide range condition in Experiment 2.

A comparison of each bird's response bias index (RBI) over the last 25 days of training in Experiment 2 to the RBI for the 25 days of Experiment 3 indicates that the RBI increased for all of the birds changed from the narrow to the wide range although this increase was not statistically significant ($\underline{t}$ (5) = 1.775, $\underline{p} > .05$). No such clear change in RBI was found for the birds trained on the wide range in Experiment 2 and switched to the narrow range in this experiment (see Table 5).

When the birds previously trained on the wide range in Experiment 2 were switched to the narrow range in Experiment 3 (B63-68) they exhibited response biases significantly greater than those of the birds trained on the narrow range in Experiment 2 ($\underline{t}$ (10) = 2.558, $\underline{p} < .05$). These differences may be due either to the fact that birds 63-68 were trained for only 25 days on the narrow range in Experiment 3 rather than for 160 days as were the narrow range birds in Experiment 2 or, as mentioned above, the difference may be due to a continuation of the response biases developed during the birds' wide-range training.

An analysis of sequential effects over the entire 25 days of the experiment (see Table 6) indicated no specific effect common to all birds, i.e., consistent directional shifts in $\underline{C}$ after extreme stimuli were not evident. The difference in the mean position of $\underline{C}$ after S1 and after S4 was not significant ($\underline{t}$ (5) = .029, $\underline{p} > .05$) for the birds changed to the wide range, nor was it significant for the

Table 5. Mean *d*'s (both ROC and Thurstonian methods), *C* and RBI for each bird. Data are based on the 25 days of Experiment 3.

Condition	Bird	*d*' ROC Method	*d*' Thurstonian Method	*C**	RBI
Wide Range	43	.32	.42	.055	.29
	44	.37	.66	.245	.48
	45	.24	.39	-.041	.41
	69	.45	.63	.175	.30
	70	.48	.53	.306	.56
	71	.55	.63	.031	.32
	$\bar{x}$	.40	.54	.129	.39
Narrow Range	63	.52	.55	.268	.51
	64	.99	.78	.062	.12
	65	.68	.57	.234	.33
	66	.45	.63	.188	.36
	67	.53	.50	-.027	.37
	68	.80	.86	.207	.59
	$\bar{x}$	.66	.65	.155	.38

* in log ft.L.

Table 6. Mean criterion position as a function of the stimulus correctly identified on the preceding trial and the standard deviation (S.D.) of the obtained C values for each bird in Experiment 3. Data are based on the 25 days of training.

		C*				
Condition	Bird	After S1	After S2	After S3	After S4	Subject S.D.
Wide Range	43	.0588	-.1992	-.1046	-.1075	.1074
	44	.3940	.2351	.3122	.2000	.0863
	45	-.0128	-.1300	.1154	-.2000	.1384
	69	.3938	.1320	.2127	.2760	.1105
	70	.5936	.3314	.2211	.3756	.1563
	71	.0885	-.0094	.0571	-.0643	.0684
	$\bar{x}$	.2578	.0915	.1576	.1011	.1112
Narrow Range	63	.2827	.2366	.2667	.2902	.0237
	64	.0706	.0625	.0977	.0686	.0156
	65	.1449	.1208	.1665	.1502	.0189
	66	.1710	.1929	.1838	.2265	.0237
	67	.0775	.1830	.0208	.0072	.0939
	68	.2028	.2091	.2007	.2374	.0170
	$\bar{x}$	.1324	.1065	.1560	.1634	.0321

* in log ft.L.

birds changed to the narrow range ($\underline{t}$ (5) = 2.217, $\underline{p} > .05$). Examination of these data for signs of a significant win-stay response pattern also indicated no such sequential effect. For birds 43, 44 and 45 and 69, 70 and 71 the shift in RBI following reinforcement of a response on the non-preferred of the central keys was not significant ($\underline{t}$ (5) = 1.447, $\underline{p} > .05$) nor was this difference significant for birds 63-68 ($\underline{t}$ (5) = 1.447, $\underline{p} > .05$).

As in Experiment 2, the difference between the average standard deviation of $\underline{C}$ following each of the four choices was significantly greater for the birds in the wide range group than for those in the narrow range group ($\underline{t}$ (10) = 3.165, $\underline{p} < .02$). Comparison of the criterion position observed in Experiment 2 to that observed in Experiment 3 showed that the variability of $\underline{C}$ increased in all cases for the birds changed from the narrow to the wide range. The mean standard deviation of $\underline{C}$ for these birds (B43-45 and 69-71) increased from .036 to .100 log ft.L.; this change was significant ($\underline{t}$ (5) = 4.142, $\underline{p} < .01$). Similarly, the variability of $\underline{C}$ decreased for each of the birds trained on the wide range in Experiment 2 and then trained on the narrow range in Experiment 3. For these birds the average standard deviation of $\underline{C}$ decreased from .124 log ft.L. in Experiment 2 to .032 log ft.L. in Experiment 3; this change was also clearly significant ($\underline{t}$ (5) = 5.521, $\underline{p} < .01$).

The mean latencies between stimulus presentation and display key peck prior to responses 2 and 3 are presented in Table 7. The reciprocals of these mean latencies were analyzed for Experiment 3 as they were for Experiment 2 and again it was found that range had no significant effect. A t-test comparing the means of the transformed latencies for R2 across ranges indicated no significant difference ($\underline{t}$ (5) = .2831, $\underline{p} > .05$) nor did the same analysis of R3 latencies ($\underline{t}$ (5) = .1112, $\underline{p} > .05$).

The R3 latencies for birds 43-45 and 69-71 were significantly shorter under the wide range (Experiment 3) than under the narrow range ($\underline{t}$ (5) = 4.0250, $\underline{p} < .02$). There was no significant difference in R2 for these birds ($\underline{t}$ (5) = 2.1724, $\underline{p} > .05$). For birds 63-68 latencies were significantly shorter on the narrow range (Experiment 3) than on the wide range (Experiment 2) for R2 ($\underline{t}$ (5) = 6.5892, $\underline{p} < .01$), but the differences in latencies for R3 were not significant ($\underline{t}$ (5) = 2.3084, $\underline{p} > .05$).

Experiment 4

It is also of interest to know whether a range effect occurs when only two choices are required. The purpose of Experiment 4 was to investigate the effects of the number of criteria required upon performance in an absolute judgment task. Several authors (e.g., Nachmias, 1968, Shipley, 1971, Wickelgren, 1968) have suggested that when a subject is required to hold more than one criterion, each criterion held will be less stable than when a single criterion is

Table 7. Mean latency of display key pecks preceding R2 and R3 for each bird for the 25 days of training in Experiment 3.

Condition	Bird	Mean latency in msec.	
		R2	R3
Narrow Range	43	762	773
	44	1062	939
	45	667	823
	69	1497	1351
	70	1093	1051
	71	678	725
	$\bar{x}$	960	944
Wide Range	63	552	538
	64	926	835
	65	863	862
	66	1383	1306
	67	912	840
	68	1793	1650
	$\bar{x}$	1072	1005

required. If this is correct, then d' between R2 and R3 should be higher if one rather than three criteria are required. That is, if R2 is required for the brighter two stimuli (S1 and S2) and R3 is required for the dimmer two stimuli (S3 and S4) in the array of four stimuli, the discriminations between the two central stimuli should be better than when four choices are required.

Method

Subjects. Eight naive White Carneaux pigeons were assigned to two groups, four in each.

Apparatus. The apparatus was identical to that used in Experiments 2 and 3.

Stimuli. One group of birds was trained using the same stimuli as the narrow-range group in Experiment 2 and the other group was trained on the same stimuli as the wide-range group in Experiment 2. The same slides were used in Experiments 2, 3 and 4.

Procedure. The birds were pretrained in exactly the same manner as those in Experiments 1 and 2. During pretraining each bird was reinforced for a peck at whichever of the four choice keys was lit. All four keys were used in pretraining to make Experiment 4 comparable to Experiment 2 and to avoid any possible effects a difference in pretraining might have caused.

Results

The acquisition process for the narrow-range birds (B99-102) can be seen in Figure 26 which shows their percent correct first choices by five-day block. These birds appear to have reached a fairly stable level by block 28 (140 sessions) with less than a 10% increase in correct first choices over the next 25 days. The percentage of correct first choices per five-day block for the wide-range birds (B103-106) are also presented in Figure 26. It is clear that these wide-range birds reached a level very close to their asymptote by the seventh five-day block (35 sessions) of training. By the end of training both groups were correct on about 75% of their first choices. This is in contrast to the comparable four-response situation (Figure 13) which shows that the wide-range birds reached a higher level of percent correct first choices than did those trained on the narrow range.

Figures 27 and 28 make possible a closer examination of how the birds solved the four-stimulus, two-response problem. These figures take the place of the four-response choice curves presented in the previous experiments. The proportion of times R3 was made as a first choice in the presence of each of the four stimuli is shown as a function of training (in five-day blocks). R3 was correct in the presence of stimuli 3 and 4; R2 was correct in the presence of stimuli 1 and 2, therefore, if the discrimination was perfect, the curves for S1 and S2 would fall at zero and the

Figure 26. Percent correct first choices for each bird. Data are shown in five-day blocks for the 160 sessions of Experiment 4. Data for the birds trained on the narrow range are shown in panel a. Data for the birds trained on the wide range are shown in panel b.

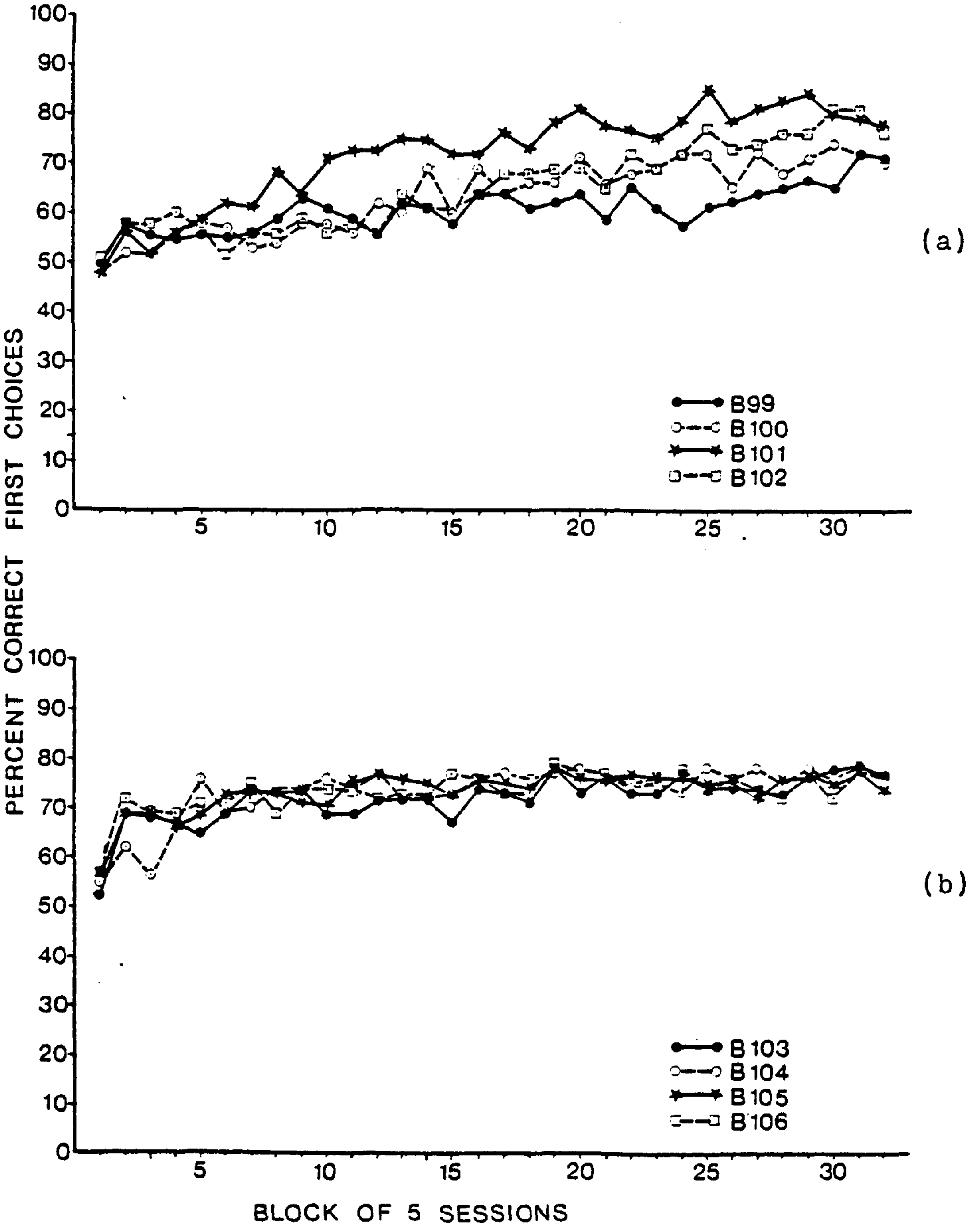

PERCENT CORRECT FIRST CHOICES
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
B99
B100
B101
B102
(a)
B103
B104
B105
B106
(b)
BLOCK OF 5 SESSIONS

Figure 27. Proportion of R3 first choices in the presence of each stimulus in Experiment 4. Data are shown for the narrow-range birds by 5-day block for the 160 days of training. In this narrow-range condition S1, S2, S3 and S4 were .4, .2, 0 and -.2 log ft.L. respectively.

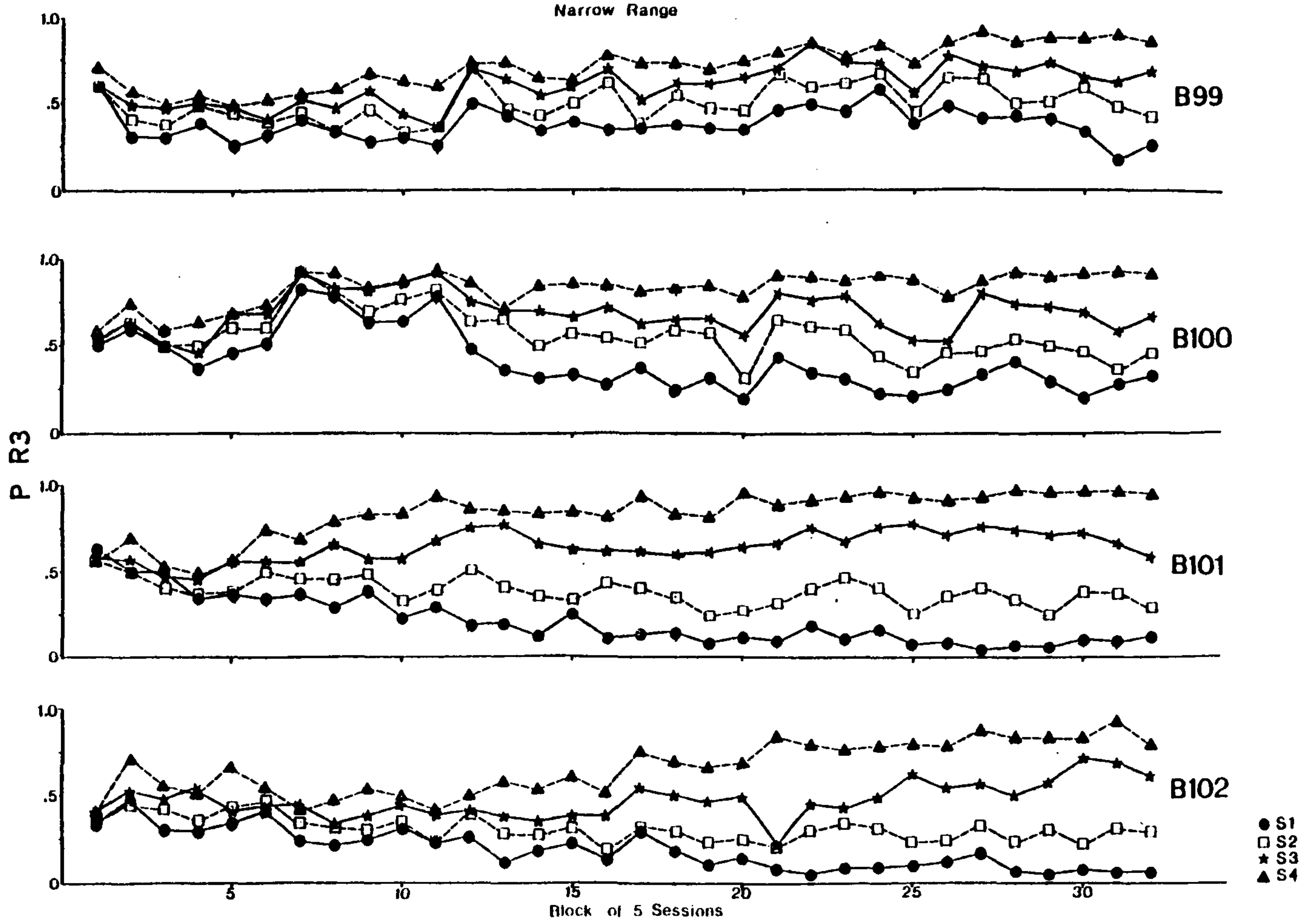
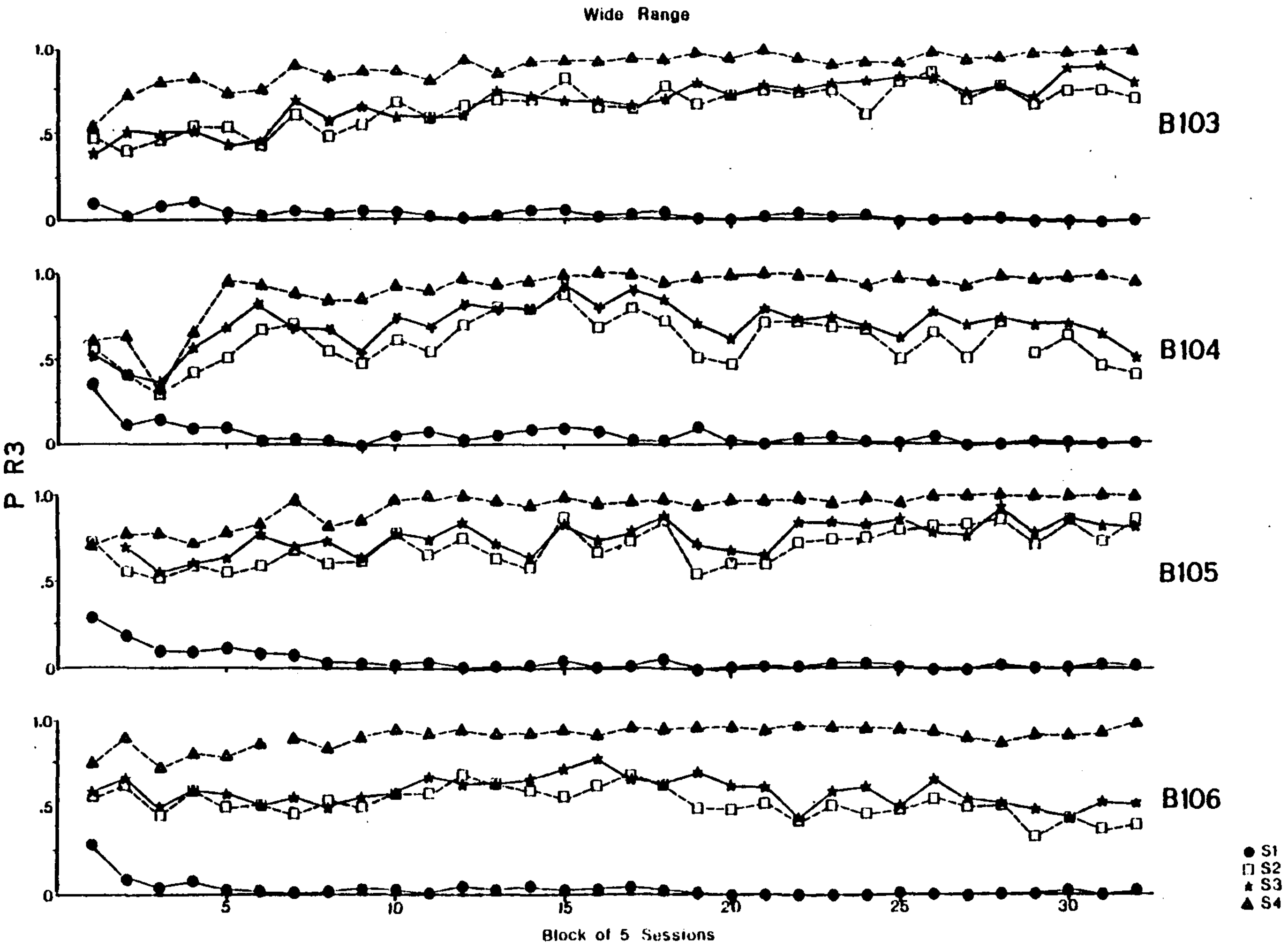

Narrow Range
1.0
.5
0
B99
B100
B101
B102
P R3
5
10
15
20
25
30
Block of 5 Sessions
● S1
□ S2
★ S3
▲ S4

Figure 28. Proportion of R3 first choices in the presence of each stimulus in Experiment 4. Data are shown for the wide-range birds by 5-day block for the 160 days of training. In this wide-range condition S1, S2, S3 and S4 were 1.6, .2, 0 and -1.4 log ft.L. respectively.


Wide Range
P R3
1.0
.5
0
B103
B104
B105
B106
5
10
15
20
25
30
Block of 5 Sessions
● S1
□ S2
★ S3
▲ S4

curves for S3 and S4 at 1.0. All of the narrow range birds showed evidence of the discrimination by the second five-day block. All four birds were somewhat more likely to make R3 in the presence of S3 and S4 than in the presence of S1 and S2. As training continued the curves for the four stimuli diverged further with R3 most likely in the presence of S4 and least likely in the presence of S1.

Figure 28 shows this data for the wide range birds. During the first five-day block the birds were clearly distinguishing S1 from S4 and they continued to do so throughout the experiment. The discrimination between S2 and S3, however, was not quite so clear since the curves never diverged as clearly as the comparable curves for the narrow-range birds. For the wide-range birds the S2 and S3 curves cross more frequently indicating that S2 and S3 were often confused. Response bias can be seen for Birds 103 and 105; at asymptote both birds were more likely to make R3 than R2 in the presence of all but S1. Bird 105 also showed a R3 bias prior to block 18 (session 90).

Figures 29 and 30 show d' for the discrimination between the two central stimuli throughout training for both groups. Of the narrow-range birds (Figure 29), B99 and B100 showed the smallest increases in d' over training and the lowest asymptotic levels as indicated in Figure 26 which shows the percent correct first choices for each bird to be low. Note also that Figure 27 shows less of a separation between the S2 and S3 curves for B99 and B100 at the

Figure 29. d' for S2 and S3 as a function of training for all narrow-range birds in Experiment 4. The solid lines are for data shown in 5-day blocks; the dashed lines are for data shown in 25-day blocks.

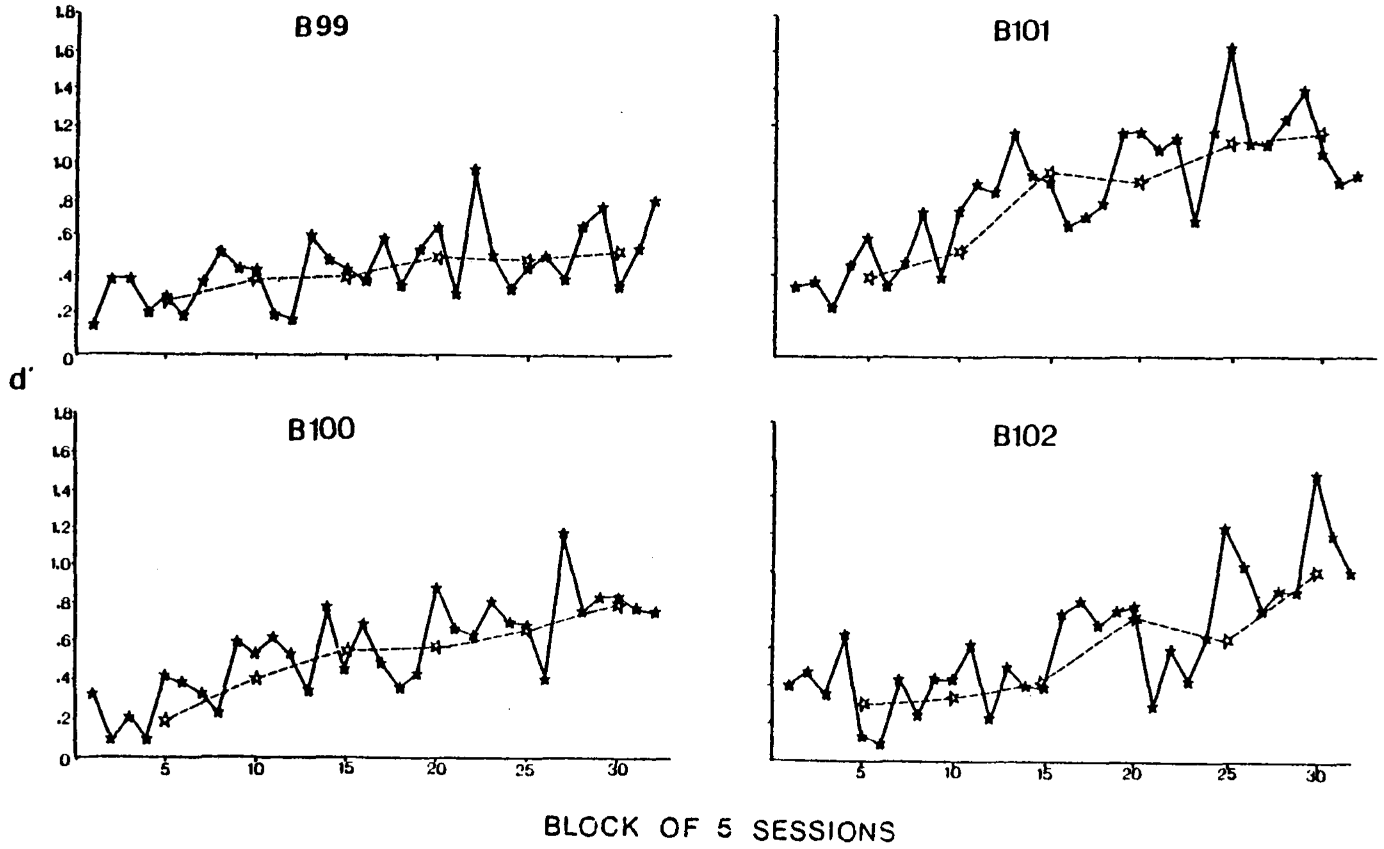
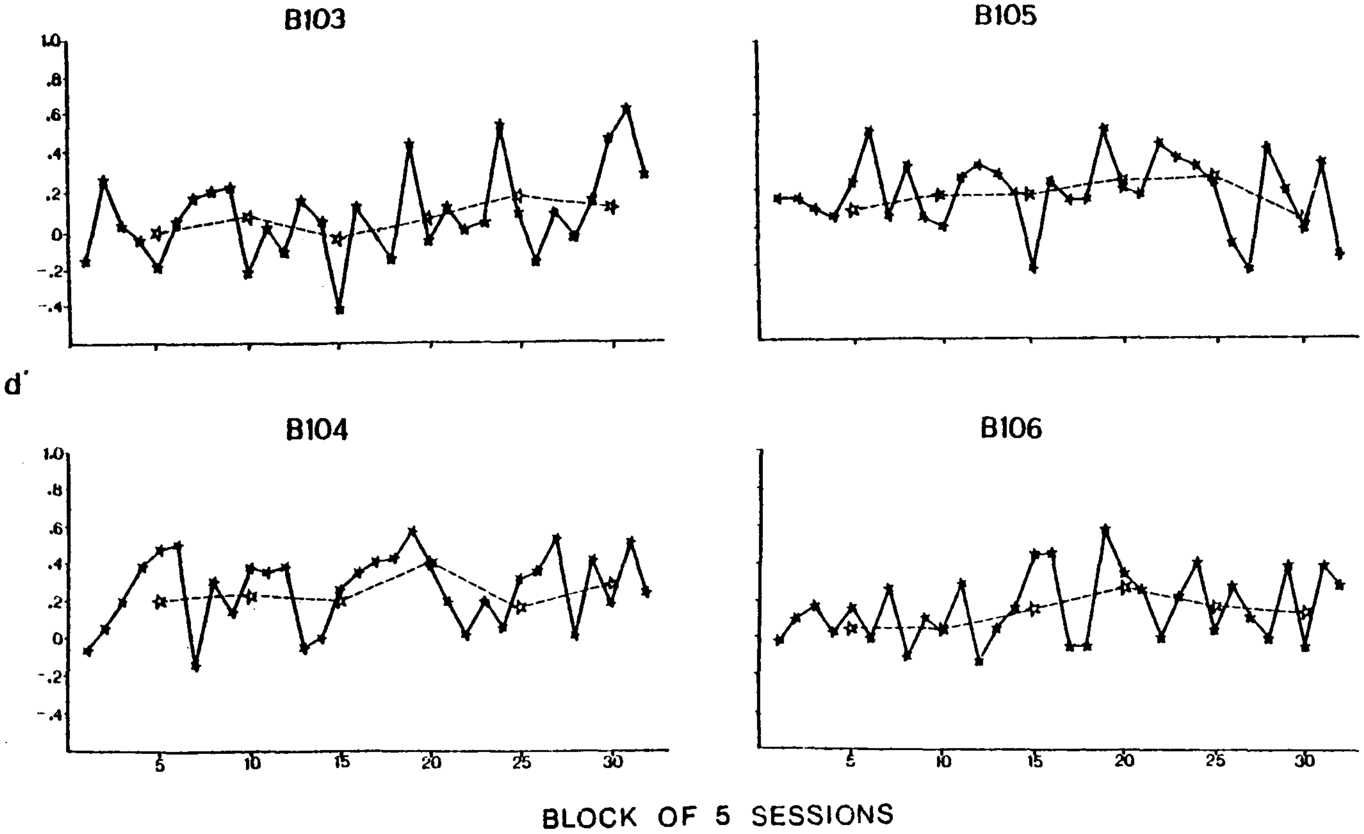

B99
B101
B100
B102
d'
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
5
10
15
20
25
30
BLOCK OF 5 SESSIONS

Figure 30. _d_' for S2 and S3 as a function of training for all wide-range birds in Experiment 4. The solid lines are for data shown in 5-day blocks; the dashed lines are for data shown in 25-day blocks.


B103
B105
B104
B106
d'
1.0
.8
.6
.4
.2
0
-.2
-.4
5
10
15
20
25
30
BLOCK OF 5 SESSIONS

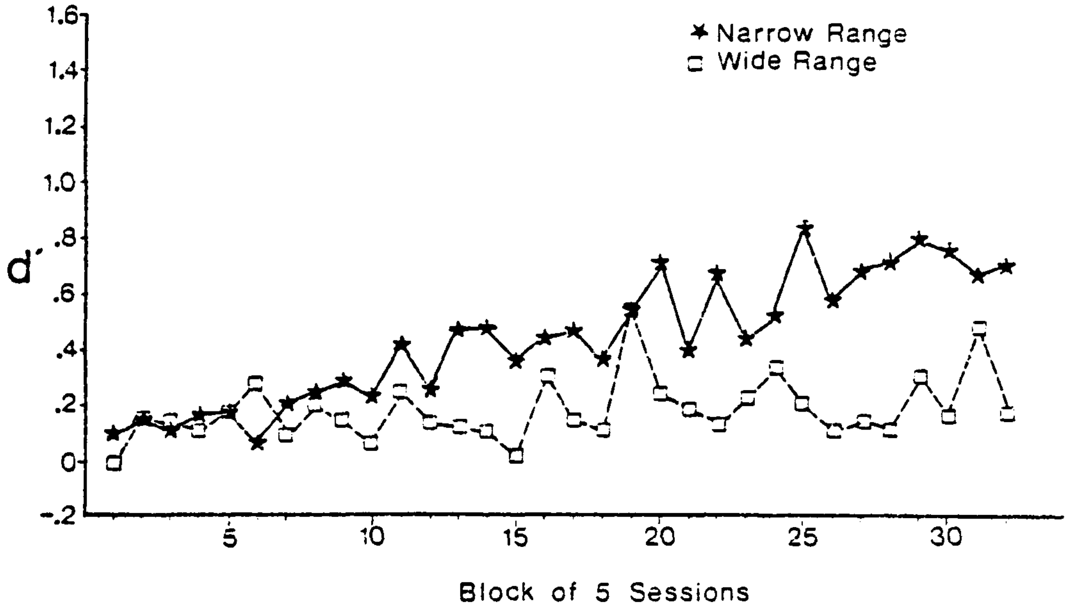
end of the experiment. Birds 101 and 102, however, showed increases in d' throughout training. The higher final d's of birds 101 and 102 are also suggested by their higher levels of percent correct first choices (Figure 26) and the greater separation of their S2 and S3 curves (Figure 27).

The d' data for the wide-range birds presented in Figure 30 show no clear trend. Occassional five-day blocks show levels substantially higher than zero while others show levels substantially lower than zero for all birds. Overall, the d's for the discrimination between S2 and S3 were slightly above chance (zero).

To compare performance under the two conditions, the d' data for the birds in each group were combined and are shown in Figure 31. Except for the first four blocks of training, d' is higher for the narrow-range birds than for the wide range. The difference in d' between the two groups for the last 25 days of training is significant (t (6) = 3.773, $p < .02$).

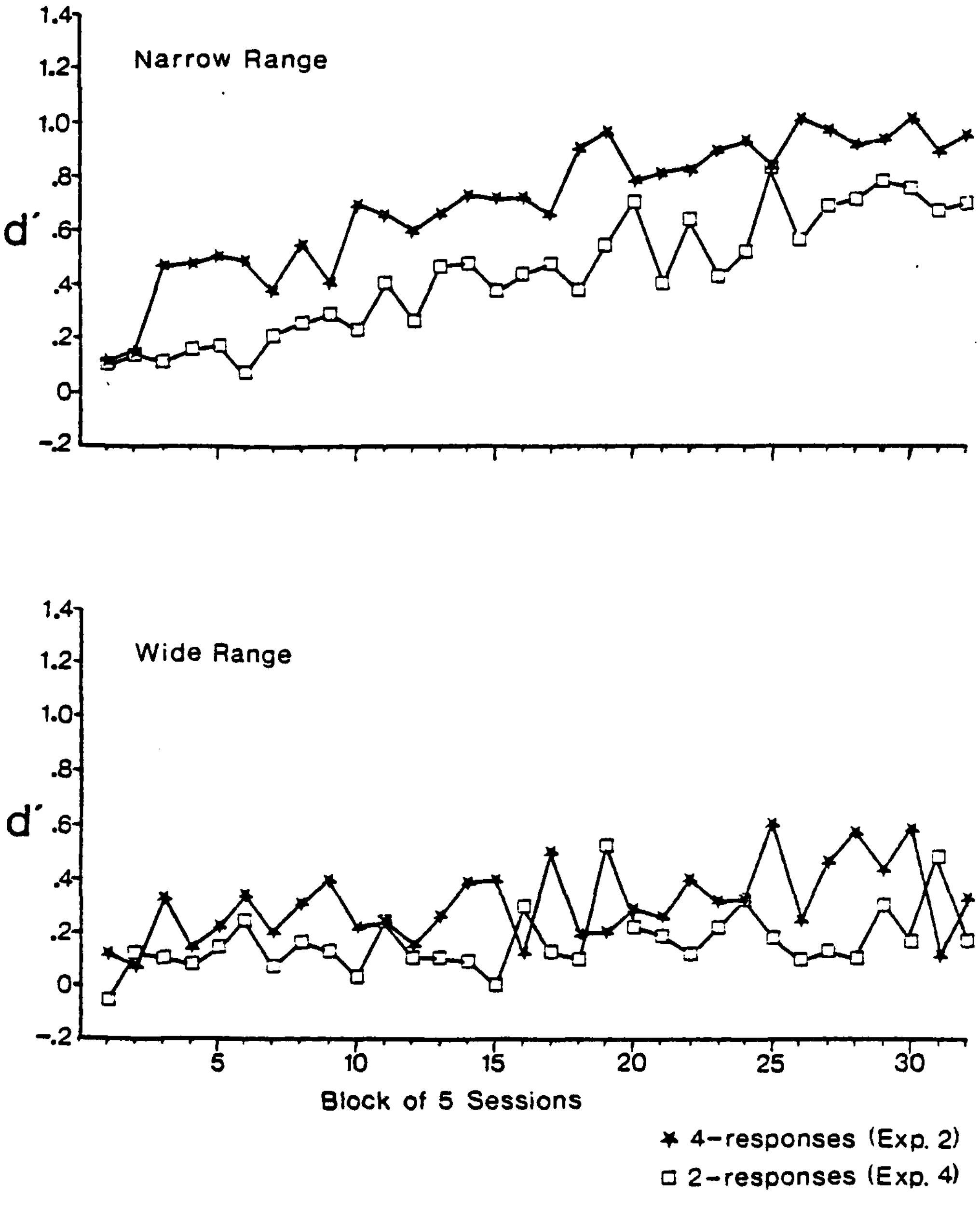
Figure 32a makes possible a comparison of d' for the narrow-range birds in the four-response experiment (Experiment 2) and the d' scores for the narrow-range, two-response experiment (Experiment 4). These data indicate that the four-response birds were actually better at the discrimination between S2 and S3 than were the two-response birds. This difference, however, was not significant over the last 25 days of training (t (8) = 1.3697, $p > .05$). Figure 32b

Figure 31. Comparison of d' between S2 and S3 throughout training for both range conditions in Experiment 4 (group data).



1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
-.2
d'
5
10
15
20
25
30
Block of 5 Sessions
✶ Narrow Range
□ Wide Range

Figure 32. Comparison of d' between S2 and S3 throughout training in Experiments 2 and 4. Panel a compares the 2- and 4-response conditions for the narrow range birds and panel b compares the 2- and 4-response conditions for the wide-range birds (group data).


Narrow Range
Wide Range
d′
1.4
1.2
1.0
.8
.6
.4
.2
0
-.2
5
10
15
20
25
30
Block of 5 Sessions
✶ 4-responses (Exp. 2)
□ 2-responses (Exp. 4)

presents the _d'_ analysis for the wide-range birds in both experiments. Again the four-response birds showed higher _d'_s than the two-response birds indicating that they were better at the discrimination between S2 and S3. This difference was significant (t (8) = 2.342, $p < .05$). Therefore, the hypothesis that requiring subjects to hold a single criterion rather than three criteria would result in higher _d'_s was not only not supported, but a result opposite to that predicted was obtained.

Table 8 summarizes the last 25 days of training in terms of _d'_ as calculated by both ROC and Thurstonian methods and RBI for all subjects in Experiment 4. It is clear that _d'_ is higher in all cases for the narrow-range birds. The difference in _d'_ between the two range conditions is significant at the .01 level as calculated by the both ROC method (t (6) = 3.785) and the Thurstonian method (t (6) = 4.027).

Table 8 also includes _C_ for each bird over the last 25 days of training. For three of the narrow-range birds _C_ was between S2 and S3 (between .2 and 0 log ft.L.). Only for B99 was _C_ not between the two central stimuli; note that B99 also showed the lowest _d'_. All of the birds in the wide-range group, except B106, established _C_ at luminance levels between S1 and S2 indicating a tendency to make R3 more often than R2 in the presence of either S2 or S3. As in the earlier experiments, RBI and the deviation

Table 8. Mean *d*'s (both ROC and Thurstonian methods), *C* (in log ft.L.) and RBI for each bird. Data are based on the last 25 days of training in Experiment 4.

		d'			
Condition	Bird	ROC Method	Thurstonian Method	*C*	RBI
Narrow Range	99	.44	.52	.210	.29
	100	.57	.50	.180	.25
	101	.94	.94	.106	.01
	102	.88	.81	.063	.18
	$\bar{x}$	.71	.69	.140	.18
Wide Range	103	.30	.30	.387	.69
	104	.28	.28	.293	.35
	105	.15	.15	1.320	.78
	106	.20	.20	.000	.15
	$\bar{x}$	.23	.23	.500	.49

of C from C' were positively correlated for the wide-range birds, however, this correlation was not significant (r (2) = .752, $p > .05$). The correlation between $|C-C'|$ and RBI for the narrow range was also not significant (r (2) = .943, $p < .05$).

As in the earlier experiments, the data were analyzed for any sequential effects. Again the extreme stimuli did not significantly affect C. For the narrow-range birds, the mean of the C values following S1 and S4 were .272 and .104 log ft.L. respectively (t (3) = 1.582, $p > .05$). The mean of the C values following S1 and S4 for the wide-range birds were .372 and -.383 log ft.L. respectively (t (2) = 1.141, $p > .05$). These data are presented in Table 9. As in Experiments 2 and 3 analysis for evidence of a win-stay response pattern affecting the extent of response bias indicated no significant effect at the .05 level for either the narrow-range birds (t (3) = .170) or for the wide-range birds (t (3) = .268).

In Experiment 4, which differed from Experiment 2 only in the number of different reinforced responses and, therefore, in the number of criteria to be held (one in Experiment 1 vs. three in Experiment 2), the effect of range upon the position of C following trials on which each of the four stimuli appeared and were correctly identified was not as clear as in Experiments 2 and 3. Again the mean of the standard deviations of C (see Table 9) for the wide-range group was larger than the comparable mean for the narrow-

Table 9. Mean criterion position as a function of the stimulus correctly identified on the preceding trial and the standard deviations of the obtained *C* values for each bird in Experiment 4. Data are based on the last 25 days of training.

		C				
Condition	Bird	After S1	After S2	After S3	After S4	Subject S.D.
Narrow Range	99	.1947	.1599	.3110	.0184	.1205
	100	.1467	.1280	.1840	.2355	.0474
	101	.6301	.0857	.1088	.1345	.2610
	102	.1160	.0382	.0600	.0282	.0392
	$\bar{x}$	.2719	.1030	.1660	.1042	.1170
Wide Range	103	.5412	.3833	.5657	.5917	.0937
	104	-.0385	.1344	.2837	.3154	.1620
	105	.6129	2.3000	1.7067	.7063	.8136
	106	---	-.0941	.0217	-.0800	.0632
	$\bar{x}$	.3719	.6809	.6445	.3834	.2831

range group, but this difference was not statistically significant (t (6) = .897, $p > .05$).

The latencies between stimulus presentation and display key peck preceding R2 and R3 are presented in Table 10 for all birds in Experiment 4. On the whole, the birds showed longer latencies preceding R2 than R3 and longer latencies on the wide-range condition than on the narrow. A t-test on the difference between the means of the reciprocal latencies indicated that the latency difference between R2 and R3 was not significant (t (7) = 1.977, $p > .05$). Similarly the difference in the reciprocal latencies between the two ranges was not significant for R2 (t (6) = .182) or for R3 (t (6) = .445) at the .05 level. The mean reciprocal latencies recorded in the two-response experiment were not significantly different from those recorded in the four response experiments.

Table 10. Mean latency of display key pecks preceding R2 and R3 for each bird for the last 25 days of training in Experiment 4.

Condition	Bird	Mean latency in msec.	
		R2	R3
Narrow Range	99	1467	1198
	100	709	724
	101	1336	1239
	102	963	901
	$\bar{x}$	1119	1016
Wide Range	103	757	635
	104	2333	2161
	105	593	632
	106	1459	958
	$\bar{x}$	1286	1097

DISCUSSION

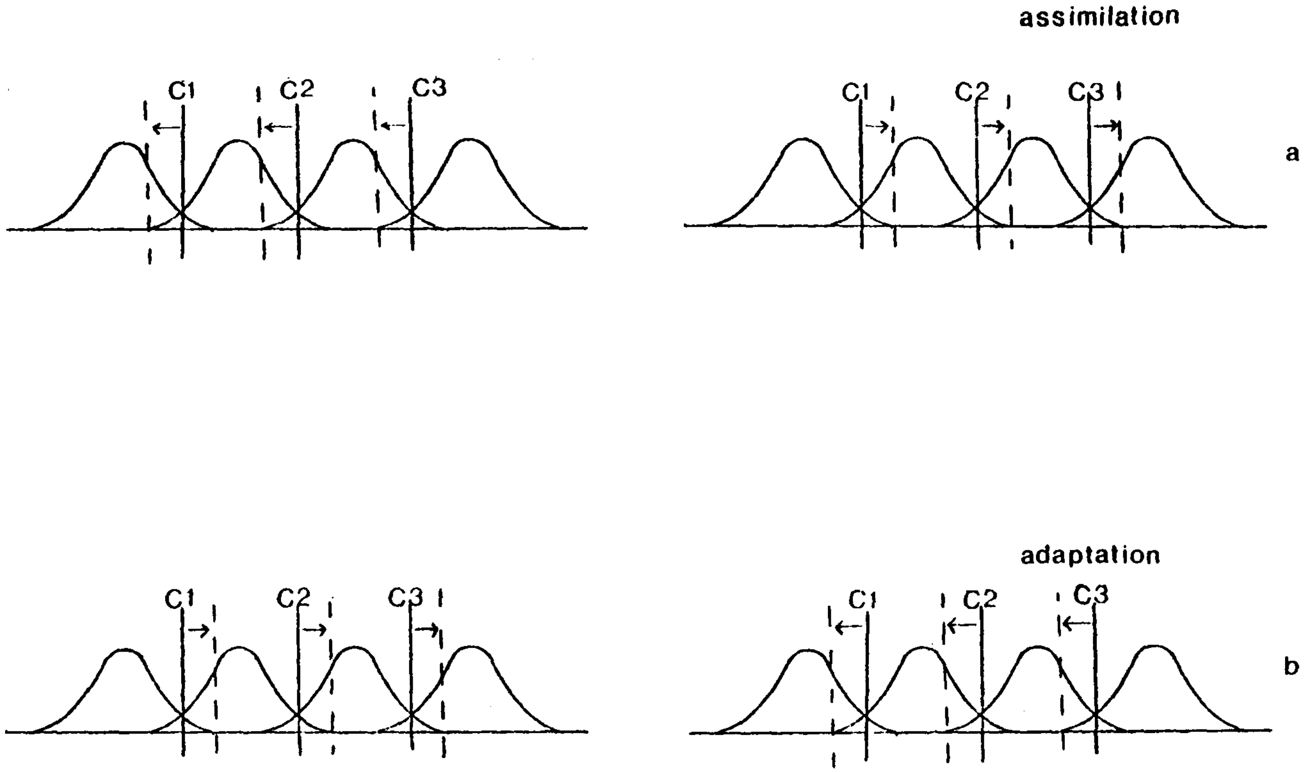
These experiments have clearly shown that the accuracy with which two stimuli are discriminated depends upon the range of stimuli to which the subject is exposed. This was found to be true in both the four-choice and the two-choice discrimination problems. This phenomenon, the range effect, until now, has been demonstrated only in humans. The fact that the pigeon too is susceptible to the range effect suggests that it is not simply due to the way humans use language in identifying their sensations. Rather, the range effect seems to reflect a basic mechanism in the processing of sensory information which is common to both humans and animals. These experiments were designed to examine two potential mechanisms which may account for the range effect: sequential effects and response latency. A second purpose of these experiments was to examine the effects of the number of choices, and thus of the number of criteria to be held, upon $\underline{d}'$.

There are several ways in which the range effect may be influenced by the sequence of stimuli presented. One sensory mechanism which could conceivably be responsible for the range effect is sensory adaptation. If adaptation occurs, the sensory effect will be higher (the stimulus will appear brighter) following adaptation to a low-intensity stimulus and lower (the stimulus will appear dimmer) following adaptation to a high intensity stimulus. If the parameters of the experimental situation are such that adaptation to the preceding stimulus occurs, it would be reflected in increased variance of the sensory effect distributions produced by the central stimuli. Such variance would be larger in the wide-range condition since the presence of more extreme stimuli would produce greater adaptation. If adaptation occurs the subject would be expected to treat the same stimulus as brighter following a low intensity stimulus and dimmer following a high intensity stimulus. This would be seen as a difference in the mean position of the criterion on the trial following a dim as compared to a bright stimulus. Figure 33a indicates how the mean criterion position ($\underline{C}_1$) would be affected following both extreme stimuli if sensory adaptation occurred.

In these experiments, analysis of $\underline{C}$ on trials following each of the four stimuli showed no evidence of sensory adaptation. These data were presented in Tables 4, 7 and 10. In no case was there a significant directional shift due to the stimulus presented on the preceding trial.

Some absolute judgment data obtained from human subjects show a sequential effect opposite to that expected if sensory adaptation occurs. It has been observed that there is an increase in the probability of a subject's making a high response to any stimulus on a given trial (N) if a high stimulus was presented on the preceding trial

Figure 33. Schematic representation of the shifts in C which would be expected on trials immediately following presentations of the extreme stimuli (S1 and S4). Panel a shows the expected shift if sensory adaptation occurred. Panel b shows the expected shift if assimilation occurred.



Sensory effect

(N-1) or, conversely, an increase in the probability of a low response if a low stimulus was presented on trial N - 1 (Ward & Lockhead, 1970, 1971; Holland & Lockhead, 1968; Lockhead, 1973). This phenomenon has been called assimilation and would be indicated by a shifting of the criterion away from the high end of the sensory effect continuum after a high stimulus, thus increasing the high response regions and, conversely, away from the low end after a low stimulus (see Figure 33a). Specifically,

> "...the response on Trial N is generated by the addition of the judged distance between the stimulus on Trial N and S's memory for the stimulus on Trial N - 1 to the remembered numerical value of the feedback on Trial N - 1." (Ward & Lockhead, 1970, p. 27)

As noted above, no clear sequential effects were observed in these experiments. This is not an unique finding for the wide-range condition since Lockhead (1973) reports that when stimulus range is increased by changing only the external stimuli, rather than by uniformly increasing the difference between all stimuli in the range, assimilation to the external stimuli is not observed. Lockhead's findings do not, however, explain the absence of assimilation in the narrow-range condition in which the stimuli were equally spaced.

As Figure 33 illustrates, the expected criterion shifts as a result of sensory adaptation and assimilation are in opposite directions. This leads to the question: Is it possible that both sensory adaptation <u>and</u> assimilation were operative in these experiments and resulted in essentially no shift in criterion since both were exerting opposing forces? The present experiments do not provide any way of directly answering this question. Lockhead's (1973) report that non-uniform increases in stimulus range result in the extreme stimuli exerting no assimilative effects would, however lead one to suspect that, if operative, the effects of sensory adaptation should have been evident in the wide-range condition since no assimilative effect should have been present to counteract it. No such effect was observed.

Another possible sequential effect is the win-stay/lose-shift phenomenon which has been reported in the animal literature (e.g., Williams, 1972). A subject exhibiting a win-stay response pattern would be more likely to make a specific response on trial N if that response was reinforced on trial N - 1. Although this response pattern would not explain the range effect, it might, if present, obscure such effects as sensory adaptation and, in general, decrease control by the discriminative stimuli. To ascertain whether this strategy affected the birds' responses, the sequential data were examined. As mentioned earlier, analysis of the frequency of R2 and R3 responses to S2 and S3 on trials immediately following reinforced pecks on key 2 or key 3 given S2 or S3 indicated that a win-stay strategy did not significantly effect the birds' choices of R2 or R3 given

S2 or S3. Since the sequential data included only first trials and since the correction procedure virtually eliminated repeats of an error made on the first trial, no analysis was possible for a lose-shift strategy.

In the hope of shedding some light upon the process by which the birds identified the stimuli, response latency (reaction time) was recorded. As discussed earlier, both human (e.g., Woodworth & Schlosberg, 1954, p. 262) and animal data (Heinemann et al, 1969) indicate that the more difficult a discrimination, the longer the subject will take to respond. Examination of the latency data was limited to responses on keys 2 and 3 since the major concern of these experiments was the accuracy of identifying S2 and S3 as a function of range. While the differences in latency were not significant, in Experiments 2 and 4 the narrow-range birds had shorter latencies than the wide-range birds suggesting that the identification of S2 and S3 was actually more difficult for the wide-range birds. The models proposed by both Gravetter and Lockhead (1973) and Durlach and Braida (1969) may be viewed as predicting these results since both hold that increasing the physical range over which the stimuli are spaced decreases the resolution power of the observer making the discrimination between stimuli 2 and 3 more difficult. Although in Experiment 3 the birds switched from the narrow to the wide range showed a shorter mean latency than those switched from the wide to the narrow range, these birds may merely have continued the latency patterns they had developed during the course of Experiment 2. Heinemann (1974) found that pigeons trained on a particular discrimination task developed individually characteristic latencies which persisted. Birds trained on more difficult discriminations typically had longer latencies than those trained on easy discriminations, but even when the discrimination task was complicated by adding test stimuli the birds maintained their characteristic pattern of responding (Heinemann et al., 1969).

As mentioned earlier, another purpose of these experiments was to examine the effects of the number of choices, and thus the number of criteria to be held, upon d'. Unlike the predictions of a number of authors (Nachmias, 1968, Wickelgren, 1968, Shipley, 1970) and the findings of Shipley, d' between S2 and S3 was found to be lower in the two-choice than in the four-choice situation for both ranges. These authors suggested that increasing the number of criteria to be held within a range of stimuli would reduce the accuracy with which a subject could correctly identify (discriminate between) any two adjacent stimuli within that range by increasing the variability of the criteria. In the present experiments, decreasing the number of categories (criteria) resulted in <u>less</u> accurate identification of the two central stimuli. Since these findings are directly opposite those reported by Shipley (1970), the relationship between the number of categories to be used and criterion variability and *d'* is not clear. It should be noted that Nachmias (1968) failed to find decreases in *d'* with increases in the number of categories. Since Experiments 2 and 4 of the present series were run at different times, caution must be exercised in comparing these data. It is clear, however, that these findings are worthy of further study.

It neither the sequence of stimuli preceding any given trial nor the duration of stimulus exposure prior to display key peck are responsible for the range effect, perhaps a more complex process is involved. Both Durlach and Braida (1969) and Gravetter and Lockhead (1973) contend that the range effect is due to increased criterion variability. They suggest that criterion variability increases as range increases. Their models do not explain the range effect but provide mathmatical descriptions of how sensitivity is affected by range. The essential difference between the two models lies in what is considered to be the effective range. For Durlach and Braida, the effective range is the entire range over which the stimuli extend; for Gravetter and Lockhead the effective range is the criterial range ("the physical range over which the criteria (boundaries) are placed" p. 205).

Durlach and Braida's (1969) model of what occurs in the absolute judgment task is essentially that a subject compares the stimulus presented to the range of stimuli (the context) previously experienced. As disucssed earlier, the response system contains noise which results in the subject's performance being less than perfect. As the physical range over which the stimuli are spaced is increased, more noise is added to the response system; this noise which is due to the increased range or context is called context-coding noise. This increase in context-coding noise counters the increase in discriminability which would be expected when they physical difference between adjacent stimuli is increased. (It should be noted that Durlach and Braida dealt only with ranges in which all stimuli were equidistant from one another.) They present an equation (Eq. 10, p. 377) to express the effect such increases in range will have upon d' for two stimuli, I_i and I_j.

$$d'(I_i;\, I_j) = \frac{\alpha(I_i) - \alpha(I_j)}{(\beta^2 + H^2W^2)^{\frac{1}{2}}}$$

The element in this equation which is affected by increases in the stimulus range is W which refers to the width of the context, or the effective intensity range; H is a constant. The variance of the stimulus distribution which is independent of intensity and range is β^2; i.e., β^2 is sensation noise assumed not to be affected by range. The numerator of the equation is the difference between the means of the two conditional probability density functions produced by each of the two stimuli being discriminated. In the present series of experiments, the numerator is .2 since the two central stimuli differ by .2 log ft.L. in all ranges.

Braida and Durlach (1972), in a test of their theory report that subjects are more accurate in identifying stimuli closer to the edges of the range than those in the center. They refer to this as the resolution edge effect and have modified their theory to account for this effect. An edge effect would be indicated in the present series of experiments if higher d' values were obtained for the discriminations between S1 and S2 and between S3 and S4 than for the discrimination between the two central stimuli, S2 and S3, on the narrow range conditions in Experiments 1, 2 and 3 where the stimuli were equidistant from one another. As Table 11 indicates, there was no evidence of an edge effect for any of the narrow range conditions. Since the edge effect increases with range, it is possible that its absence in these experiments was due to the narrow (.6 log ft.L.) range.

A model which is closely related to the Durlach and Braida model in terms of its predictions is that of Luce, Green and Weber (1976). According to this model a subject selects some portion of a stimulus range, an attention band, for more intensive analysis. This intensive analysis consists of the subject taking a sample (via his observations) of fixed size of the stimuli within the band. When the range is expanded beyond the width of the attention band, the sample sizes for all stimuli within the range may not be equal since fully monitoring one area of the stimulus range will result in monitoring other areas outside of the

Table 11. Summary of d's obtained for all pairs of adjacent stimuli for the narrow-range birds in Experiments 1, 2 and 3.

Experiment	Bird	d' between S1 & S2	S2 & S3	S3 & S4
1	43	1.21	1.45	.55
	44	1.89	1.22	1.21
	45	1.40	1.27	1.18
	$\bar{x}$	1.50	1.31	.98
2	43	.65	.52	.59
	44	.97	.99	.94
	45	.81	.95	1.35
	69	.94	.98	.89
	70	.71	1.12	1.01
	71	1.05	1.00	1.21
	$\bar{x}$	.86	.93	1.00
3	63	.32	.52	.81
	64	.41	.99	1.16
	65	.48	.68	1.13
	66	.56	.45	1.16
	67	.48	.53	.50
	68	.69	.80	1.03
	$\bar{x}$	.49	.66	.97

band less completely. Increasing range thus indirectly affects the ability of the observer to discriminate by increasing the probability of any given stimulus being represented by a small stimulus sample, and small samples result in poorer performance. According to the Luce et al. model, the edge effect is the result of the attention band being located at either end of the stimulus array more often than in the center. If a range is large, the central stimuli will rarely fall within the attention band and will, therefore, be correctly identified less frequently. However, when the stimulus range is narrow, the probability of the central stimuli being included in the attention band will be greater and the liklihood of the central stimuli being correctly identified will increase. This theory predicts that an edge effect will not be present when the stimulus range is small as it was in the narrow-range conditions of the present series of experiments.

The Gravetter and Lockhead (1973) model is very similar to the Durlach and Braida (1969) model. In their paper Gravetter and Lockhead illustrate a method of estimating the standard deviation (SD') of the psychophysical function representing the discrimination between any two adjacent stimuli. They use the Thurstonian method (described in Appendix A) to calculate SD' which may be divided into the difference between the two stimuli to obtain d'. According to this model, SD' reflects variability due to both sensory and subject-dependent factors as well as the variance added by the criterial range. More specifically,

$$\underline{SD}' = \sqrt{\underline{k}^2 + \underline{a}^2 \underline{R}^2}$$

Gravetter and Lockhead treat the variance of the sensory effect distributions ($\underline{k}^2$) and the subject-dependent variance ($\underline{a}^2$) as constants, the values of which can be found if the $\underline{SD}'$ is obtained for two ranges. Once $\underline{a}$ and $\underline{k}$ and the $\underline{SD}'$ obtained under a new range are known, the effective range ($\underline{R}$) can be found using the above equation. Note the similarity to Durlach and Braida's (1969) equation.

The results of Experiment 4 when compared to those of Experiment 2, in which pigeons were exposed to the same stimuli and duration of training, indicate that the four-choice birds were better at identifying S2 and S3 than the two-choice birds were. This finding is also directly opposite that predicted by the logical extention of the Gravetter and Lockhead (1973) model to the two-response situation. According to that model, the accuracy of the subjects' identifications are dependent upon the criterial range. In the two-choice experiment only one criterion should have been established. Holding only one criterion would require that the criterial range equal zero and thus, according to Gravetter and Lockhead's equation, all variance would be due to the sensory noise ($\underline{k}$). Therefore, not only should the two-choice birds have been better at the discrimination than the four-choice birds, but there should have been no range effect in the two-choice situation since the criterial range would have been equal for both range conditions. In their paper, Gravetter and Lockhead (1973) deal only with experimental designs in which the number of stimuli and responses are equal, but they state that their model is not limited to such cases.

All three theories predict the range effect. They all predict a negatively accelerated decrease in d' as range is increased. The models differ somewhat in their exact quantitative predictions, however, the data required to differentiate between these two theories is not easily obtained as Luce et al. (1976) have pointed out. Gravetter and Lockhead (1973) speak of the range switch on a voltmeter, Durlach and Braida (1969) of the subject's comparing each present sensation to those previously experienced, and Luce et al. (1976) of a limited attention band. All of these mechanisms, however, are entirely speculative at this time.

To say that resolution decreases with increases in range is not enough. The question remains as to why increasing the overall range in which two stimuli are embedded decreases the ability of a subject to discriminate these stimuli from each other, especially when the same subjects have previously demonstrated that they can discriminate these stimuli from each other.

It is possible that the effect of range on d' for the two central stimuli may simply reflect differences in the "strategies" used by the subjects in solving the discrimination problem. Under the wide-range condition S1 and S4 are easily identified; this is not true under the narrow-range condition. Subjects may, on many trials, have been dealing with the four-choice, wide-range problem as if it was a three-choice problem while consistently dealing with the narrow-range, four-choice problem as a four-choice problem. In other words, they may have been regarding S2 and S3 as identical and, therefore, holding only two criteria. On trials on which S2 and S3 are presented, one response (R2 or R3) may be consistently made. This would show up in the data as a strong key preference (i.e., a RBI approaching 1). If R2 and R3 are made randomly in the presence of S2 or S3, the RBI would be close to zero as would d'. Subjects using such a "strategy" would be correct on about 75% of all first trials.

Indeed, examination of the final performance levels in Experiments 2, 3 and 4 indicates clear response biases for the wide-range birds as pointed out earlier; such response biases are not evident in the data for the narrow-range birds. In addition, the acquisition curves for the wide-range birds (Figures 13 and 26) indicate that performance was maintained at about the 75% first choice level. While these data certainly do not refute earlier accounts of the range effect, the explanation in terms of different strategies cannot be discounted at this time.

The fact that even the wide-range birds performed somewhat above chance level in identifying S2 and S3 shows that S2 and S3 were certainly not treated as identical on every trial. At least on some trials a third criterion must have been held.

The difference in $\underline{d}'$ obtained in the two- and the four-choice experiments may also reflect differences in the birds' overall approach to the problem. The better discrimination between S2 and S3 shown by the birds in the four response experiment may reflect the fact that the probability of being correct purely by chance on any given trial would be only .25 when four choices are required and .50 when two choices are required. Therefore, in the four-choice situation it is of greater "relative value" to attend to the discriminative stimuli. If attending to the stimulus dimension is actually more "valuable" under the four-response conditions, it should result in better discrimination between adjacent stimuli along that dimension.

These alternative accounts of how range and the number of response categories may exert their effects in absolute judgment tasks can neither be verified or refuted on the basis of the data gathered in this series of experiments. Further examination of the way in which such absolute judgment tasks are approached by both animals and humans may help us to better understand the range effect and with it the findings reported here.

I suggest that future studies attempt to manipulate the "relative value" of correctly identifying the central stimuli. This could be done by reinforcing correct idenfications of the central stimuli on all trials and reinforcing correct identifications of the external stimuli on intermittant schedules. Better resolution in this situation would suggest that criterion variability reflects the specific requirements of the problem. Such a finding would indicate that range exerts its effect not simply by dulling the resolution power of the organism but by altering the way in which the organism approaches the problem.

At present, the range effect remains a mystery, although this series of experiments has ruled out a number of possible explanations and has demonstrated that it is not an exclusively human phenomenon.

APPENDIX A

APPENDIX A

1. Obtaining *d'* and *C*

Figure 34 illustrates both methods of obtaining *d'* (data for B43, last 25 days of Experiment 1). To obtain *d'* by either the rating scale method (ROC) or the Thurstonian method, the 4 x 4 matrix, indicating the proportion of times each response was made as a first choice in the presence of each of the four stimuli, must first be transformed into a cumulative proportion matrix.

Using the rating scale method (ROC), three estimates of *d'* can be calculated for each of the discriminations between adjacent stimuli and the mean of these three estimates used as *d'* for that discrimination over the block represented by the matrix. To obtain the three estimates of *d'* for the discrimination between S1 and S2, treat the proportion (P) of R1 responses given as first choices in the presence of S1 $(R1|S1)$ as the hit rate and $P(R1|S2)$ as the false alarm rate (FA), next treat $P(R1+R2|S1)$ as the hit rate and $P(R1+R2|S2)$ as the FA rate, and finally treat $P(R1+R2+R3|S1)$ as the hit rate and $P(R1+R2+R2|S2)$ as the FA rate. This procedure is repeated for each pair of stimuli; for example, in looking at the discrimination between S2 and S3, calculate *d'* for the following hit and FA rates:

Figure 34. Illustration of how d' is obtained using the ROC method (left panel) and the Thurstonian method (right panel).

Proportion

	S1	S2	S3	S4
R1	.62	.14	0	0
R2	.35	.54	.16	.06
R3	.02	.25	.35	.25
R4	.01	.07	.49	.69

Cumulative Proportion

	S1	S2	S3	S4
R1	.62	.14	0	0
R1+2	.97	.68	.16	.06
R1+2+3	.99	.93	.51	.31
R1+2+3+4	1.00	1.00	1.00	1.00

ROC method

d' for discrimination between

	S1+S2	S2+S3	S3+S4
R1	1.38	----	----
R1+2	1.41	1.46	.56
R1+2+3	.85	1.44	.53
$\bar{x}$	1.21	1.45	.55

Thurstonian method

z-score transform

	S1	S2	S3	S4
R1	+ .31	-1.08	----	----
R1+2	+1.88	+ .47	- .99	-1.55
R1+2+3	+2.33	+1.48	+ .03	- .50
R1+2+3+4	----	----	----	----

slope = +7.3

standard deviation = .14 log ft.L.

d' = 1.42

equation of line
$y = 7.3 - 10.42$

C = 1.436 log ft.L.

Hits	FA's
$P(R1 \mid S2)$	$P(R1 \mid S3)$
$P(R1+R2 \mid S2)$	$P(R1+R2 \mid S3)$
$P(R1+R2+R3 \mid S2)$	$P(R1+R2+R3 \mid S3)$

For the discrimination between S3 and S4:

Hits	FA's
$P(R1 \mid S3)$	$P(R1 \mid S4)$
$P(R1+R2 \mid S3)$	$P(R1+R2 \mid S4)$
$P(R1+R2+R3 \mid S3)$	$P(R1+R2+R3 \mid S4)$

d' may be calculated directly (as per Green & Swets, 1966) or may be obtained from tables published in Swets (1964). Figure 35 indicates the d's for each hit and FA rate and the mean d' for each of the three discriminations.

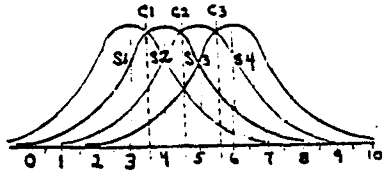
In the Thurstonian method, as used by Gravetter and Lockhead (1973), an estimate of criterion position may also be obtained. In this method, the cumulative proportion matrix is transformed to a normal deviate matrix (z-scores). Next a line is fitted to the points thus obtained for each of the discriminations by the method of least squares (only z-scores representing proportions between .1 and .9 are used as per Gravetter and Lockhead, 1973). The slope of the line is computed and from this the standard deviation of the psychophysical function (1/slope). From the equation of the line, the stimulus value for which $z = 0$ may be calculated and regarded as C, the position of the criterion separating the two response regions. d' for this discrimination may be obtained by dividing the difference between the two stimuli (.2 log ft.L. in this case) by the standard deviation.

The Thurstonian method differs from the rating scale (ROC) procedure described above in that in the Thurstonian method the presence of all stimuli are considered in obtaining d' for each discrimination. Consequently the estimates of d' obtained will be similar, but not identical, for real data (due to variability). The two procedures should not yield different conclusions as to the effect of range. Tables 1, 2, 5 and 8 present d' as obtained by both methods.

Figure 35 illustrates the logical equivalence of the ROC and Thurstonian methods. Four normal distributions of equal variance are assumed (a) with the mean of each distribution separated by 1 unit (which is equal to .5 z-score) from the mean of the next distribution. It is further assumed that there are three criteria (C1, C2 and C3) on the sensory effect or "decision axis" placed midway between adjacent distributions so as to divide this continuum into four sections corresponding to four different responses.

The first step in both methods is to obtain the areas under each of the curves for the portions to the left of C1 and then to the left of C2 and then to the left of C3. Next these are converted to z-scores resulting in what is essentially the z-score transform of a cumulative proportion matrix (b).

Figure 35. Illustration of the logical equivalence of the ROC and Thurstonian methods.



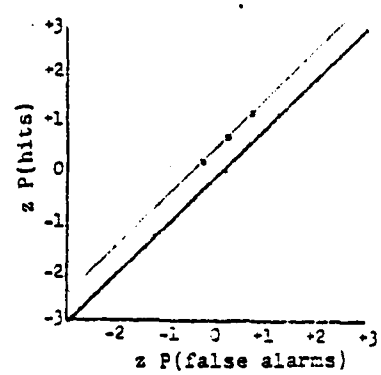
a

	S1	S2	S3	S4
C1	.5987	.4013	.2266	.1056
C2	.7734	.5987	.4013	.2266
C3	.8944	.7734	.5987	.4013

	Response		S1	S2	S3	S4
C1	R1	z=	.25	-.25	-.75	-1.25
C2	R1 or R2	z=	.75	.25	-.25	- .75
C3	R1,R2 or R3	z=	1.25	.75	.25	- .25

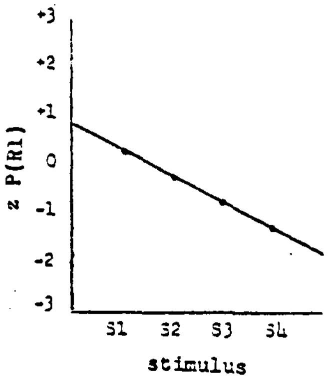
b

I



C1 $.25-(-.25) = .5$
C2 $.75 - .25 = .5$
C3 $1.25 - \underline{.75} = \underline{.5}$
$\bar{x}$ d' = .5

II



slope = .5/1 = .5
standard deviation = 1/.5 = 2
d' = 1/2 = .5

Using the ROC method (panel I) a z-ROC curve may be plotted as illustrated and d' obtained from the curve. It is also possible to obtain d' more directly by taking the mean of the three d' estimates obtained by finding the difference between the z-scores for each set of adjacent stimuli given first R1, then R1 or R2 and last R1 or R2 or R3. Both procedures are illustrated.

Using the Thurstonian method (panel II), z-scores are plotted against stimuli; the reciprocal of the slope of the line resulting from this plot is the standard deviation of the psychophysical function. When the stimulus difference (in the example, 1) is divided by the standard deviation, d' is obtained. The obtained value of d' is identical for both methods.

2.

Narrow Range birds -- Experiment 1 -- confusion matrices

	Bird 43				Bird 44				Bird 45				Sessions
	(P)R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	24	30	27	19	29	41	18	12	36	30	21	13	1-25
S2	12	25	33	30	14	32	35	19	25	28	27	20	
S3	4	25	35	36	6	23	48	23	10	19	34	37	
S4	3	19	38	40	1	17	55	27	5	9	24	62	
S1	41	51	7	1	62	32	5	1	49	39	11	1	26-50
S2	17	44	25	14	21	49	24	6	18	47	30	5	
S3	4	27	40	29	2	23	55	20	3	22	47	28	
S4	2	17	42	39	1	14	51	34	1	4	20	75	
S1	63	33	4	0	77	21	2	0	63	34	3	0	51-75
S2	13	43	34	10	13	62	23	2	22	48	28	2	
S3	0	19	44	37	0	24	57	19	2	31	49	18	
S4	1	11	34	54	0	5	25	70	0	8	17	75	
S1	62	35	2	1	74	25	1	0	67	30	3	0	76-100
S2	14	54	25	7	9	61	28	2	16	54	26	4	
S3	0	16	35	49	0	16	72	12	1	18	56	25	
S4	0	6	25	69	0	5	23	72	0	5	13	82	

Narrow Range birds -- Experiment 1 -- confusion matrices

	Bird 43				Bird 44				Bird 45				
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	Sessions
S1	20	28	30	24	21	29	21	30	15	26	29	31	1-5
S2	16	16	33	35	12	17	26	45	12	19	30	38	
S3	9	12	33	46	8	18	31	43	4	28	25	43	
S4	6	15	35	45	4	7	42	46	10	21	22	46	
S1	11	15	26	48	31	26	25	19	40	15	17	29	6-10
S2	4	9	30	58	16	16	46	21	25	17	23	36	
S3	1	11	30	58	11	9	54	26	17	15	20	49	
S4	0	8	23	70	1	8	61	30	5	10	24	61	
S1	17	31	33	20	27	44	17	4	50	29	19	3	11-15
S2	9	27	37	28	13	45	34	8	37	27	24	12	
S3	0	28	39	32	4	42	40	15	19	12	30	40	
S4	4	17	44	34	2	24	59	14	7	3	19	70	
S1	34	27	31	8	15	71	12	2	33	45	18	4	16-20
S2	17	22	41	20	17	54	23	6	29	39	26	6	
S3	7	17	41	38	5	34	49	12	7	18	42	34	
S4	5	16	51	29	0	33	48	19	1	6	23	70	
S1	36	52	12	0	41	35	14	10	40	39	19	2	21-25
S2	14	53	22	12	11	31	44	14	22	37	32	9	
S3	2	57	31	12	1	11	69	20	5	22	50	24	
S4	0	40	38	22	0	11	64	25	1	7	31	61	

Moderate Range birds -- Experiment 1 -- confusion matrices

	Bird 46				Bird 47				Bird 48				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	52	38	9	1	65	22	9	4	79	13	6	2	1-25
S2	4	38	46	12	7	35	45	13	9	36	43	12	
S3	1	23	59	17	2	17	60	21	4	16	55	25	
S4	1	5	25	69	1	4	28	67	2	3	24	71	
S1	79	20	1	0	94	6	0	0	93	6	1	0	26-50
S2	1	55	43	1	5	55	37	3	4	52	41	3	
S3	0	29	68	3	0	34	56	10	1	31	55	13	
S4	0	2	16	82	0	3	23	74	0	1	23	76	
S1	76	23	1	0	98	1	1	0	98	1	0	1	51-75
S2	2	55	42	1	1	62	36	1	5	57	35	3	
S3	0	28	66	6	0	22	74	4	1	27	60	12	
S4	0	2	11	87	0	0	24	76	0	1	9	90	
S1	70	29	1	0	98	2	0	0	98	2	0	0	76-100
S2	0	64	34	2	1	73	25	1	3	68	28	1	
S3	0	36	58	6	0	26	70	4	0	27	66	7	
S4	0	0	13	87	0	0	12	88	0	1	5	94	

Moderate Range birds -- Experiment 1-- confusion matrices

	Bird 46				Bird 47				Bird 48				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	16	53	38	4	28	29	30	15	44	25	23	9	1-5
S2	6	10	54	30	7	27	39	37	15	21	39	26	
S3	0	8	41	51	8	18	39	35	14	3	36	48	
S4	3	6	33	58	3	12	30	55	9	3	38	51	
S1	34	55	10	0	62	22	10	6	76	18	5	1	6-10
S2	5	38	46	11	7	40	41	12	10	28	39	13	
S3	3	29	49	21	1	24	53	23	2	26	49	23	
S4	0	10	34	58	0	1	28	71	1	2	24	73	
S1	56	40	4	0	82	15	3	0	82	17	1	0	11-15
S2	4	37	54	5	14	40	38	8	5	46	43	6	
S3	0	29	64	7	1	17	60	22	2	20	61	18	
S4	0	5	31	64	0	1	46	53	1	0	12	87	
S1	75	23	2	0	61	35	4	0	97	3	0	0	16-20
S2	5	46	47	2	3	29	63	5	7	33	56	4	
S3	0	28	70	2	1	15	66	18	1	12	68	19	
S4	0	1	16	83	0	4	20	76	1	1	13	84	
S1	80	17	3	0	93	7	0	0	95	5	0	0	21-25
S2	1	61	36	2	3	39	57	1	6	54	37	3	
S3	0	23	72	5	0	12	82	7	0	21	59	22	
S4	0	4	14	82	0	3	16	81	0	5	36	60	

APPENDIX B

Narrow Range birds -- Experiment 2 -- confusion matrices

	Bird 69				Bird 70				Bird 71				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	12	64	16	8	27	40	15	18	28	44	17	11	1-25
S2	15	63	14	8	20	25	23	32	20	39	24	17	
S3	15	55	18	12	15	19	23	43	12	26	29	33	
S4	11	49	25	15	8	10	19	63	6	17	32	45	
S1	27	46	25	2	35	43	19	3	37	51	10	2	26-50
S2	17	42	33	8	15	40	33	12	19	45	28	8	
S3	10	36	41	13	9	23	37	31	10	28	37	25	
S4	4	20	42	34	1	11	31	57	1	8	32	59	
S1	36	39	23	2	46	41	12	1	48	46	5	1	51-75
S2	24	36	33	7	24	44	26	6	25	48	24	3	
S3	11	32	40	17	10	31	37	22	10	30	42	18	
S4	3	14	48	35	1	12	32	55	1	6	40	53	
S1	31	43	24	2	38	53	8	1	51	44	5	0	76-100
S2	22	36	39	3	18	55	24	3	21	56	20	3	
S3	9	25	50	16	7	37	39	17	6	33	47	14	
S4	1	9	38	52	0	13	21	66	0	5	42	53	

Narrow Range birds -- Experiment 2 (cont.) -- confusion matrices

	Bird 69				Bird 70				Bird 71				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	45	36	18	1	39	52	9	0	48	48	4	0	101-125
S2	17	41	38	4	13	54	29	4	15	61	22	2	
S3	4	26	54	16	5	32	42	21	3	31	52	14	
S4	0	7	37	60	0	11	33	56	0	4	40	56	
S1	52	37	11	0	55	38	6	1	58	38	4	0	126-150
S2	18	44	34	4	25	47	25	3	23	57	18	2	
S3	4	21	54	21	4	29	44	23	4	31	53	12	
S4	1	3	37	59	1	5	26	68	1	2	37	60	
S1	61	30	9	0	64	27	9	0	59	35	6	0	151-160
S2	26	41	30	3	29	44	24	3	18	57	25	0	
S3	7	19	60	14	5	18	48	29	4	31	54	11	
S4	1	2	48	49	1	4	21	74	1	3	36	60	
S1	57	34	9	0	61	31	7	1	58	38	4	0	136-160
S2	21	46	30	3	28	44	25	3	19	58	22	1	
S3	4	22	57	17	5	27	42	26	4	32	54	10	
S4	1	3	45	51	1	5	20	74	1	2	37	60	

Narrow Range birds -- Experiment 2 (retrained after Exp. 1)
-- confusion matrices

	Bird 43				Bird 44				Bird 45				Sessions
	(P)R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	5	68	22	4	37	42	17	3	37	48	10	5	1-25
S2	2	48	42	8	9	41	45	6	17	44	28	11	
S3	0	32	49	19	2	18	66	13	5	25	40	29	
S4	0	13	46	42	0	2	66	31	1	4	20	75	
S1	11	78	11	1	58	36	6	0	63	27	7	3	26-50
S2	4	64	28	4	15	54	27	4	35	39	19	8	
S3	1	39	43	17	2	26	55	18	11	31	28	30	
S4	0	7	42	50	0	4	39	57	1	5	13	81	
S1	11	77	11	1	64	33	2	0	71	25	3	2	51-75
S2	4	57	36	3	21	53	24	1	34	41	20	5	
S3	2	35	52	11	4	24	53	19	5	31	39	25	
S4	0	10	41	50	1	2	36	61	0	3	11	86	
S1	23	64	12	1	65	32	2	1	68	24	7	1	76-100
S2	10	56	29	5	22	50	25	3	37	30	28	5	
S3	5	37	43	15	5	21	58	16	9	22	46	23	
S4	3	16	39	42	1	3	45	51	1	2	14	83	

Narrow Range birds -- Experiment 2 -- confusion matrices

	Bird 69				Bird 70				Bird 71				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	10	49	19	24	20	39	17	25	18	34	14	34	1-5
S2	18	39	17	28	23	18	20	39	25	36	19	20	
S3	18	39	22	23	20	19	20	41	19	29	17	35	
S4	13	33	22	32	16	16	20	48	13	25	26	36	
S1	18	43	23	18	33	22	8	38	26	47	22	5	6-10
S2	20	49	21	11	24	19	7	51	14	36	27	23	
S3	21	35	26	18	26	14	7	54	15	25	26	35	
S4	16	33	29	25	19	5	5	71	4	22	28	46	
S1	10	82	9	1	31	43	8	18	43	38	18	1	11-15
S2	10	75	14	2	19	25	20	37	21	41	28	13	
S3	13	69	10	8	14	16	19	51	7	24	36	33	
S4	14	70	11	5	2	3	24	70	4	20	35	38	
S1	9	76	13	4	28	45	18	9	36	46	12	6	16-20
S2	8	83	7	2	18	29	31	22	25	39	19	17	
S3	7	74	11	8	6	22	31	41	15	28	25	32	
S4	1	66	25	7	1	13	20	66	5	10	39	46	
S1	13	68	18	2	24	50	24	2	18	54	21	7	21-25
S2	21	66	10	3	15	37	35	13	13	47	29	11	
S3	16	59	18	7	10	24	35	31	5	21	44	30	
S4	10	46	34	13	3	11	25	61	2	8	33	57	

Narrow Range birds -- Experiment 2 (retrained after Exp. 1) -- confusion matrices

	Bird 43				Bird 44				Bird 45				
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	Sessions
S1	3	34	44	19	2	24	60	8	32	37	22	9	1-5
S2	4	19	59	17	4	12	67	17	19	30	26	25	
S3	0	21	48	31	2	8	73	17	7	17	40	36	
S4	1	7	46	46	0	0	83	17	3	5	24	68	
S1	2	69	28	0	41	48	9	2	21	65	13	2	6-10
S2	0	56	33	11	8	42	48	2	16	44	32	8	
S3	0	36	38	26	0	19	68	13	3	22	49	26	
S4	0	16	42	42	0	0	67	33	0	6	18	76	
S1	5	73	21	1	41	49	10	0	37	53	7	3	11-15
S2	1	56	37	6	11	44	41	4	10	56	27	7	
S3	0	34	56	10	3	20	66	11	5	22	41	32	
S4	0	11	52	37	0	2	51	47	0	5	17	78	
S1	11	78	70	1	49	49	0	2	36	57	3	4	16-20
S2	1	53	40	6	13	53	30	4	13	40	35	12	
S3	0	28	54	18	2	18	63	17	2	25	42	31	
S4	0	15	31	54	1	3	62	34	0	3	27	70	
S1	4	88	9	1	53	39	6	2	61	29	5	6	21-25
S2	2	54	42	2	9	52	37	2	28	49	20	3	
S3	2	41	49	8	5	27	61	7	9	40	30	21	
S4	0	14	57	30	0	5	69	26	0	3	16	81	

Wide Range birds -- Experiment 2 -- confusion matrices

	Bird 63				Bird 64				Bird 65				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	83	11	4	2	89	8	1	2	84	13	2	1	1-25
S2	2	30	54	14	3	36	50	11	3	38	46	13	
S3	1	26	59	14	7	22	55	16	2	37	47	14	
S4	0	3	23	74	3	9	27	61	2	7	46	45	
S1	96	3	1	0	97	3	0	0	96	4	0	0	26-50
S2	0	39	58	3	0	52	46	2	1	64	33	2	
S3	0	35	51	4	0	32	61	7	1	53	43	3	
S4	0	2	4	94	0	4	20	76	0	4	11	85	
S1	98	1	1	0	98	2	0	0	96	4	0	0	51-75
S2	0	38	59	3	1	50	47	2	1	50	47	2	
S3	0	24	71	5	0	37	57	6	0	43	52	5	
S4	0	0	6	94	0	2	9	89	0	1	6	93	
S1	97	3	0	0	99	1	0	0	98	2	0	0	76-100
S2	0	30	68	2	0	57	41	2	0	54	44	2	
S3	0	28	70	2	1	45	50	4	0	36	60	4	
S4	0	3	11	86	0	2	7	91	0	0	6	94	

Wide Range birds -- Experiment 2 (cont.) -- confusion matrices

	Bird 63				Bird 64				Bird 65				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	93	6	1	0	97	2	1	0	99	0	1	0	101-125
S2	0	29	70	1	0	59	40	1	0	47	52	1	
S3	0	24	71	5	0	44	54	2	0	28	68	4	
S4	0	1	7	92	0	1	4	95	0	1	9	90	
S1	91	8	1	0	99	1	0	0	99	1	0	0	126-150
S2	0	37	63	0	0	59	41	0	0	54	45	1	
S3	0	24	74	2	0	40	60	0	0	34	63	3	
S4	0	0	4	96	0	1	4	95	0	0	6	94	
S1	88	12	0	0	100	0	0	0	99	1	0	0	151-160
S2	0	22	77	1	0	61	39	0	1	57	41	1	
S3	0	18	78	4	0	56	44	0	0	41	57	2	
S4	0	0	4	96	0	0	5	95	0	0	5	95	
S1	87	13	0	0	100	0	0	0	99	1	0	0	136-160
S2	0	32	67	1	0	59	41	0	0	59	41	0	
S3	0	22	76	2	0	44	56	0	0	37	60	3	
S4	0	0	5	95	0	1	4	95	0	0	6	94	

Wide Range birds -- Experiment 2 -- confusion matrices

	Bird 66				Bird 67				Bird 68				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	85	14	1	0	93	6	1	0	90	9	0	1	1-25
S2	2	61	34	3	2	50	39	9	2	61	28	9	
S3	2	50	41	7	1	39	44	16	2	55	35	8	
S4	1	16	35	48	1	4	24	71	0	8	23	69	
S1	94	6	0	0	99	1	0	0	97	2	1	0	26-50
S2	1	58	41	0	1	51	45	3	0	78	20	2	
S3	0	44	53	3	0	40	54	6	1	66	29	4	
S4	0	0	7	93	0	2	22	76	0	1	3	96	
S1	98	1	1	0	99	1	0	0	99	1	0	0	51-75
S2	0	58	42	0	2	68	28	2	0	63	35	2	
S3	0	46	52	2	1	61	32	6	0	50	48	2	
S4	0	2	5	93	1	2	13	84	0	1	3	96	
S1	98	2	0	0	99	1	0	0	98	2	0	0	76-100
S2	0	51	48	1	0	70	27	3	1	62	37	0	
S3	0	37	61	2	0	58	37	5	0	46	53	1	
S4	0	0	4	96	0	0	8	92	0	1	1	98	

Wide Range birds -- Experiment 2 (cont.) -- confusion matrices

	Bird 66				Bird 67				Bird 68				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	99	1	0	0	99	0	1	0	98	2	0	0	101-125
S2	0	42	57	1	0	85	12	3	0	34	66	0	
S3	0	30	66	4	0	74	22	4	0	15	84	1	
S4	0	2	9	89	0	1	12	87	0	0	4	96	
S1	100	0	0	0	99	1	0	0	96	2	1	0	126-150
S2	0	44	55	1	0	76	23	1	0	48	52	0	
S3	0	30	68	2	0	68	29	3	0	22	77	1	
S4	0	1	7	92	0	1	11	88	0	1	4	95	
S1	100	0	0	0	99	1	0	0	99	1	0	0	151-160
S2	0	46	54	0	1	74	23	2	1	26	73	0	
S3	0	33	65	2	0	67	30	3	0	24	75	1	
S4	0	1	5	94	0	2	7	91	0	0	3	97	
S1	100	0	0	0	99	1	0	0	99	0	1	0	136-160
S2	0	47	53	0	1	73	25	1	0	38	62	0	
S3	0	36	62	2	0	67	30	3	0	21	78	1	
S4	0	1	7	92	0	2	8	90	0	0	3	97	

Wide Range birds -- Experiment 2 -- confusion matrices

	Bird 63				Bird 64				Bird 65				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	1-5
S1	47	28	13	12	61	25	6	8	54	35	4	8	
S2	5	17	47	30	15	36	26	23	8	28	36	29	
S3	4	26	46	24	15	16	46	23	5	30	39	26	
S4	2	9	36	53	14	15	38	34	9	16	58	18	
S1	86	12	2	0	97	3	0	0	81	16	3	0	6-10
S2	5	32	41	23	2	34	49	15	3	33	58	7	
S3	3	27	52	18	2	31	39	28	1	33	50	16	
S4	0	2	24	74	0	13	27	60	0	4	68	28	
S1	92	8	0	0	96	4	0	0	97	2	1	0	11-15
S2	0	42	52	7	0	39	52	9	1	33	59	7	
S3	0	24	71	6	1	28	58	13	1	32	54	13	
S4	0	1	21	78	0	10	27	63	0	4	56	40	
S1	95	5	0	0	96	3	0	0	95	3	2	0	16-20
S2	1	22	73	3	0	38	59	3	1	47	40	12	
S3	0	21	68	10	0	29	66	5	3	46	40	11	
S4	0	1	28	71	0	4	24	72	0	5	27	68	
S1	93	6	1	0	95	5	0	0	94	6	0	0	21-25
S2	0	34	60	6	0	32	62	6	0	53	45	2	
S3	0	31	55	14	0	24	64	12	0	45	53	2	
S4	0	0	6	94	0	3	21	76	0	7	21	72	

Wide Range birds -- Experiment 2 -- confusion matrices

	Bird 66				Bird 67				Bird 68				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	63	31	4	2	77	18	4	1	76	20	1	3	1-5
S2	4	38	52	6	8	45	27	20	5	46	25	24	
S3	6	30	52	12	5	32	27	36	3	49	30	19	
S4	2	23	61	14	5	20	24	51	1	13	33	54	
S1	87	13	0	0	96	4	0	0	84	14	1	1	6-10
S2	0	75	17	8	2	37	41	20	1	51	36	12	
S3	1	63	26	10	1	33	42	24	3	49	42	6	
S4	1	39	35	26	0	1	31	68	1	11	28	60	
S1	96	4	0	0	95	5	0	0	95	4	1	0	11-15
S2	1	71	28	0	0	59	40	1	1	60	32	7	
S3	0	50	42	8	0	42	46	12	0	52	41	7	
S4	0	10	37	53	0	1	31	68	0	7	25	68	
S1	93	7	0	0	96	4	0	0	98	2	0	0	16-20
S2	1	60	37	2	1	53	44	2	1	60	37	3	
S3	1	53	43	3	0	43	51	6	1	47	45	7	
S4	0	8	28	64	0	0	19	81	0	4	16	81	
S1	85	14	1	0	99	1	0	0	95	5	0	0	21-25
S2	2	62	35	1	0	57	41	2	0	90	10	0	
S3	3	54	42	2	0	42	54	4	1	79	16	3	
S4	0	3	11	86	0	0	15	85	0	1	14	85	

t-test for win-stay strategy -- Experiment 2

A. Narrow Range birds

Bird	Overall RBI	Preferred Key	RBI after R2	R3	D*	D^2
43	.23	2	.308	.172	.136	.018496
44	.15	3	.108	.193	.085	.007225
45	.30	3	.294	.395	.101	.010201
69	.22	3	.024	.433	.409	.167281
70	.06	2	.264	.160	.104	.010816
71	.16	2	.296	.215	.081	.006561
Sum					.918	.220580
$\bar{X}$	.187		.216	.261	.153	

(*t* (5) = 1.393, *p* > .05)

B. Wide Range birds

63	.62	3	.441	.526	.085	.007225
64	.06	2	.105	.276	-.171	.029241
65	.10	3	.082	.117	.036	.001296
66	.28	3	.364	.230	-.134	.017956
67	.61	2	.637	.485	.152	.023104
68	.58	3	.619	.584	-.035	.001225
Sum					-.067	.080005
$\bar{X}$	.375		.375	.370	-.011	

(*t* (5) = -.215, *p* > .05)

D* = difference in RBI (Preferred - Non-preferred)

APPENDIX C

Birds switched from narrow to wide range -- Experiment 3 -- confusion matrices

	Bird 43				Bird 44				Bird 45				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	78	21	1	0	97	2	1	0	97	3	0	0	1-5
S2	6	47	36	11	3	51	45	1	2	77	19	2	
S3	1	40	40	19	0	29	62	9	2	56	35	7	
S4	0	12	28	60	0	5	13	82	0	3	12	85	
S1	94	6	0	0	98	2	0	0	96	4	0	0	6-10
S2	0	62	32	6	1	59	40	0	3	78	17	2	
S3	0	39	54	7	1	26	72	1	2	49	42	7	
S4	0	15	47	38	0	0	12	88	0	2	1	97	
S1	94	6	0	0	97	2	1	0	99	1	0	0	11-15
S2	0	54	40	6	0	38	54	8	1	60	32	7	
S3	0	52	40	8	0	18	71	11	2	55	37	6	
S4	0	6	44	51	0	0	10	90	0	0	3	97	
S1	100	0	0	0	98	2	0	0	98	2	0	0	16-20
S2	2	66	28	4	0	30	51	19	0	62	33	5	
S3	1	43	42	14	0	17	73	10	0	39	52	9	
S4	0	13	48	39	1	0	14	85	0	0	10	90	
S1	97	3	0	0	100	0	0	0	96	4	0	0	21-25
S2	1	65	29	4	1	36	61	2	1	55	43	1	
S3	1	56	38	5	0	16	78	6	1	57	39	3	
S4	0	12	37	51	0	3	11	86	0	1	7	92	

Birds switched from narrow to wide range -- Experiment 3 -- confusion matrices

	Bird 69				Bird 70				Bird 71				Sessions
	(P)R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	85	13	2	0	93	7	0	0	97	3	0	0	1-5
S2	9	38	51	2	7	39	50	4	4	59	34	3	
S3	0	17	78	5	1	21	55	23	1	43	48	8	
S4	1	1	12	86	0	1	19	80	0	2	13	85	
S1	95	4	1	0	98	2	0	0	97	3	0	0	6-10
S2	1	55	43	1	1	33	63	3	1	74	25	0	
S3	1	28	71	0	1	23	71	5	0	40	57	3	
S4	0	1	6	93	0	0	16	84	0	0	8	92	
S1	100	0	0	0	94	6	0	0	99	1	0	0	11-15
S2	0	57	42	1	0	32	66	2	2	76	22	0	
S3	0	33	66	1	1	15	82	2	0	47	53	0	
S4	0	0	11	89	0	0	4	96	0	0	13	87	
S1	100	0	0	0	99	1	0	0	97	3	0	0	16-20
S2	1	65	34	0	3	32	65	0	0	68	32	0	
S3	0	38	61	1	1	12	84	3	0	40	58	2	
S4	0	0	11	89	0	0	14	86	0	1	3	96	
S1	99	1	0	0	99	1	0	0	99	1	0	0	21-25
S2	1	39	60	0	0	46	53	1	0	72	28	0	
S3	0	27	71	2	0	29	66	5	0	60	38	2	
S4	0	1	10	89	0	0	10	90	0	0	5	95	

Birds switched from wide to narrow range -- Experiment 3 -- confusion matrices

	Bird 66				Bird 67				Bird 68				Sessions
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	3	67	29	1	23	63	13	1	1	63	35	1	1-5
S2	1	39	59	1	23	61	8	8	0	38	62	0	
S3	0	27	68	5	14	56	18	12	0	14	80	6	
S4	0	8	46	46	11	45	25	19	0	5	74	21	
S1	17	58	22	3	61	30	8	1	27	51	19	3	6-10
S2	6	36	50	8	49	25	18	8	9	38	49	4	
S3	3	17	59	21	25	25	24	26	6	17	51	26	
S4	0	5	26	69	25	12	19	44	0	1	32	67	
S1	19	52	22	7	71	16	6	7	40	39	21	0	11-15
S2	11	37	44	8	55	21	17	7	13	32	52	3	
S3	5	19	57	19	42	21	14	23	2	16	63	19	
S4	0	5	23	72	21	16	23	40	0	4	46	50	
S1	26	58	14	2	64	19	11	6	43	42	15	0	16-20
S2	5	42	47	6	52	10	18	20	14	27	54	5	
S3	2	20	55	23	24	18	23	35	4	11	62	23	
S4	1	2	36	61	6	10	25	59	0	2	36	62	
S1	38	43	19	0	69	11	8	12	58	31	11	0	21-25
S2	18	45	31	6	49	22	13	16	28	28	44	0	
S3	11	39	41	9	32	13	15	40	7	21	65	7	
S4	1	8	35	56	11	5	17	67	2	2	42	54	

Birds switched from wide to narrow range -- Experiment 3 -- confusion matrices

	Bird 63				Bird 64				Bird 65				
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	Sessions
S1	5	46	48	1	27	60	11	2	15	46	38	1	1-5
S2	3	31	64	2	16	59	21	4	7	42	49	2	
S3	2	15	75	8	6	44	34	16	6	24	61	9	
S4	0	7	64	29	0	16	20	64	0	5	55	40	
S1	23	34	34	9	46	43	10	1	43	33	20	4	6-10
S2	15	21	49	15	26	49	23	2	26	29	39	6	
S3	7	13	52	28	12	26	32	30	5	26	48	21	
S4	2	3	30	65	0	9	12	79	0	1	37	62	
S1	10	67	20	3	51	40	8	1	57	33	8	2	11-15
S2	13	53	26	8	32	46	22	0	18	34	41	7	
S3	9	31	33	27	10	26	47	17	10	18	52	20	
S4	1	4	19	76	0	4	25	71	2	2	25	71	
S1	2	69	24	5	54	41	4	1	44	41	14	1	16-20
S2	0	39	56	5	24	43	33	0	26	33	39	2	
S3	1	26	56	17	5	24	59	12	8	23	39	29	
S4	1	9	33	57	0	1	25	74	1	6	30	63	
S1	21	44	33	2	42	48	10	0	51	38	9	2	21-25
S2	9	31	59	1	22	47	21	0	25	42	26	7	
S3	3	9	76	12	7	33	52	8	4	30	53	13	
S4	1	1	47	51	3	3	52	42	0	0	31	69	

t-test for win-stay strategy ---Experiment 3

A. Birds switched from wide to narrow range

Bird	Overall RBI	Preferred Key	RBI after		D*	D^2
			R2	R3		
63	.51	3	.452	.505	.053	.002809
64	.12	2	.128	.159	-.031	.000961
65	.33	3	.286	.411	.125	.015625
66	.36	3	.327	.355	.028	.000784
67	.37	2	.646	.222	.424	.179776
68	.59	3	.576	.535	-.041	.001681
Sum					.558	.201636
$\bar{X}$	.38		.403	.365	.093	

(t (5) = 1.011, $p > .05$)

B. Birds switched from narrow to wide range

43	.29	2	.459	.333	.126	.015876
44	.48	3	.612	.504	.108	.011664
45	.41	2	.386	.286	.100	.010000
69	.30	3	.202	.485	.283	.080089
70	.56	3	.492	.504	.012	.000144
71	.32	2	.424	.229	.195	.038025
Sum					.822	.155798
$\bar{X}$	.39		.429	.390	.137	

(t (5) = 1.447, $p > .05$)

D* = difference in BRI (preferred - non-preferred)

APPENDIX D

Narrow Range birds -- Experiment 4 -- confusion matrices

	Sessions 1-25				Sessions 26-50				Sessions 51-75				Bird
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	0	62	37	1	0	67	33	0	0	61	39	0	99
S2	0	53	47	0	0	60	40	0	0	51	49	0	
S3	0	50	50	0	0	52	48	0	0	34	66	0	
S4	0	45	55	0	0	40	59	1	0	34	66	0	
S1	0	49	50	1	0	32	68	0	0	55	45	0	100
S2	0	44	55	1	0	24	76	0	0	37	63	0	
S3	0	44	55	1	0	18	82	0	0	25	75	0	
S4	0	36	63	1	0	15	85	0	0	16	84	0	
S1	1	53	46	0	0	68	32	0	0	78	22	0	101
S2	1	55	44	0	0	55	45	0	0	60	40	0	
S3	0	47	53	0	0	41	59	0	0	30	70	0	
S4	0	43	57	0	0	22	78	0	0	13	87	0	
S1	0	65	35	0	0	71	29	0	0	80	20	0	102
S2	0	60	40	0	0	65	35	0	0	70	30	0	
S3	0	53	47	0	0	60	40	0	0	62	38	0	
S4	0	44	56	0	0	52	48	0	0	48	52	0	

Narrow Range birds -- Experiment 4 (cont.) -- confusion matrices

	Sessions 76-100				Sessions 101-125				Sessions 126-150				Bird
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	0	64	36	0	0	52	48	0	0	58	42	0	99
S2	0	51	49	0	0	40	60	0	0	42	58	0	
S3	0	38	62	0	0	28	72	0	0	29	71	0	
S4	0	27	73	0	0	20	80	0	0	13	87	0	
S1	0	72	28	0	0	69	31	0	0	70	30	0	100
S2	0	50	50	0	0	47	53	0	0	52	48	0	
S3	0	36	64	0	0	30	70	0	0	30	70	0	
S4	0	18	82	0	0	10	90	0	0	13	87	0	
S1	0	88	12	0	0	87	13	0	0	92	8	0	101
S2	0	66	34	0	0	63	37	0	0	65	35	0	
S3	0	37	63	0	0	27	73	0	0	27	73	0	
S4	0	13	87	0	0	7	93	0	0	6	94	0	
S1	0	83	17	0	0	91	9	0	1	89	10	0	102
S2	0	74	26	0	0	72	28	0	0	73	27	0	
S3	0	53	47	0	0	55	45	0	0	42	58	0	
S4	0	34	66	0	0	20	80	0	0	17	83	0	

Narrow Range birds -- Experiment 4 (cont.) -- confusion matrices

	Sessions 151-160				Sessions 136-160				Bird
(P)	R1	R2	R3	R4	R1	R2	R3	R4	
S1	0	78	22	0	0	67	33	0	99
S2	0	55	45	0	0	50	50	0	
S3	0	35	65	0	0	33	67	0	
S4	0	13	87	0	0	13	87	0	
S1	0	70	30	0	0	70	30	0	100
S2	0	59	41	0	0	54	46	0	
S3	0	38	62	0	0	32	68	0	
S4	0	9	91	0	0	9	91	0	
S1	0	90	10	0	0	91	9	0	101
S2	0	67	33	0	0	67	33	0	
S3	0	37	63	0	0	31	69	0	
S4	0	5	95	0	0	4	96	0	
S1	0	94	6	0	0	93	7	0	102
S2	0	70	30	0	0	72	28	0	
S3	0	36	64	0	0	38	62	0	
S4	0	14	86	0	0	15	85	0	

Narrow Range birds -- Experiment 4 -- confusion matrices

	Sessions 1-5				Sessions 6-10				Sessions 11-15				Bird
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	1	35	60	4	0	68	31	1	0	69	30	1	99
S2	1	39	60	1	0	59	41	0	0	62	38	0	
S3	1	42	57	0	0	51	49	0	0	54	46	0	
S4	0	28	70	2	1	44	55	0	0	52	48	0	
S1	1	42	52	5	0	37	63	0	0	50	50	0	100
S2	1	43	51	5	0	36	64	0	0	50	50	0	
S3	0	42	51	7	0	40	60	0	0	50	50	0	
S4	1	39	57	3	0	26	73	1	0	43	57	0	
S1	2	36	62	0	0	50	49	1	2	49	49	0	101
S2	2	43	55	0	0	50	50	0	1	58	41	0	
S3	1	41	58	0	0	43	57	0	1	53	46	0	
S4	1	44	55	0	1	31	68	1	0	47	53	0	
S1	1	64	32	3	0	53	47	0	0	70	30	0	102
S2	0	62	35	3	0	57	43	0	0	59	41	0	
S3	0	56	39	5	0	47	52	1	0	53	47	0	
S4	2	58	38	2	0	30	70	0	0	46	54	0	

Narrow Range birds -- Experiment 4 (cont.) -- confusion matrices

	Sessions 16-20				Sessions 21-25				Bird
(P)	R1	R2	R3	R4	R1	R2	R3	R4	
S1	0	63	37	0	0	74	26	0	99
S2	0	51	49	0	0	55	45	0	
S3	0	50	50	0	0	51	49	0	
S4	0	46	54	0	0	53	47	0	
S1	0	63	37	0	0	54	46	0	100
S2	0	51	49	0	0	40	60	0	
S3	0	55	45	0	0	32	68	0	
S4	0	37	63	0	0	32	68	0	
S1	0	66	34	0	0	63	37	0	101
S2	0	63	37	0	0	61	39	0	
S3	0	53	45	2	0	44	56	0	
S4	0	51	48	1	0	42	55	3	
S1	0	71	29	0	0	66	33	1	102
S2	0	65	35	0	0	57	42	1	
S3	0	47	53	0	0	60	40	0	
S4	0	49	50	1	0	35	65	0	

Wide Range birds -- Experiment 4 -- confusion matrices

	Sessions 1-25				Sessions 26-50				Sessions 51-75				Bird
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	4	87	8	1	1	95	4	0	1	95	4	0	103
S2	0	52	48	0	0	46	54	0	0	33	67	0	
S3	1	51	47	1	0	42	58	0	0	34	66	0	
S4	0	27	72	1	0	16	84	0	0	12	88	0	
S1	0	84	15	1	0	98	2	0	0	95	5	0	104
S2	0	57	43	0	0	41	59	0	0	27	73	0	
S3	0	49	50	1	0	32	68	0	0	21	79	0	
S4	0	36	63	1	0	12	88	0	0	6	94	0	
S1	2	82	15	1	0	96	4	0	0	98	2	0	105
S2	0	41	58	1	0	35	65	0	0	31	69	0	
S3	0	34	65	1	0	29	71	0	0	25	75	0	
S4	0	24	75	1	0	11	89	0	0	3	97	0	
S1	1	88	9	2	0	99	1	0	1	97	2	0	106
S2	0	45	53	2	0	49	51	0	0	40	60	0	
S3	0	41	57	2	0	47	53	0	0	34	66	0	
S4	0	18	79	3	0	10	87	3	0	7	93	0	

Wide Range birds -- Experiment 4 (cont.) -- confusion matrices

	Sessions 76-100				Sessions 101-125				Sessions 126-150				Bird
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	0	97	3	0	0	98	2	0	0	99	1	0	103
S2	0	33	67	0	0	28	72	0	0	26	74	0	
S3	0	30	70	0	0	22	78	0	0	22	78	0	
S4	0	6	94	0	0	7	93	0	0	4	96	0	
S1	0	95	5	0	0	98	2	0	0	98	2	0	104
S2	0	37	63	0	0	35	65	0	0	39	61	0	
S3	0	23	77	0	0	29	71	0	0	28	72	0	
S4	0	2	98	0	0	3	97	0	0	4	96	0	
S1	0	99	1	0	0	98	2	0	0	99	1	0	105
S2	0	32	68	0	0	27	73	0	0	18	82	0	
S3	0	24	76	0	0	19	81	0	0	17	83	0	
S4	0	4	96	0	0	3	97	0	0	1	99	0	
S1	0	98	2	0	0	100	0	0	1	99	0	0	106
S2	0	42	58	0	0	51	49	0	0	52	48	0	
S3	0	32	68	0	0	44	56	0	0	46	54	0	
S4	0	4	96	0	0	4	96	0	0	8	92	0	

Wide Range birds -- Experiment 4 (cont.) -- confusion matrices

	Sessions 151-160				Sessions 136-160				Bird
(P)	R1	R2	R3	R4	R1	R2	R3	R4	
S1	0	100	0	0	0	100	0	0	103
S2	0	29	71	0	0	28	72	0	
S3	0	16	84	0	0	19	81	0	
S4	0	2	98	0	0	3	97	0	
S1	0	99	1	0	0	99	1	0	104
S2	0	58	42	0	0	45	55	0	
S3	0	43	57	0	0	34	66	0	
S4	0	4	96	0	0	3	97	0	
S1	0	99	1	0	0	98	2	0	105
S2	0	21	79	0	0	20	80	0	
S3	0	18	82	0	0	16	84	0	
S4	0	0	100	0	0	0	100	0	
S1	1	99	0	0	1	98	1	0	106
S2	0	61	39	0	0	58	42	0	
S3	0	47	53	0	0	50	50	0	
S4	0	5	95	0	0	7	93	0	

Wide Range birds -- Experiment 4 -- confusion matrices

	Sessions 1-5				Sessions 6-10				Sessions 11-15				Bird
(P)	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	
S1	13	70	11	6	5	93	2	0	1	91	8	0	103
S2	1	50	47	1	0	61	39	0	0	54	46	0	
S3	4	53	39	4	1	49	50	0	0	52	48	0	
S4	2	41	53	4	0	27	73	0	0	20	80	0	
S1	0	64	35	1	2	86	10	2	0	87	13	0	104
S2	0	43	56	1	0	60	40	0	0	72	28	0	
S3	0	46	54	0	0	58	40	2	0	65	35	0	
S4	1	35	60	4	1	36	63	0	0	68	32	0	
S1	8	59	28	5	0	81	19	0	1	89	10	0	105
S2	1	21	73	5	0	44	55	1	0	49	51	0	
S3	0	16	78	6	0	30	69	1	0	45	55	0	
S4	0	24	71	5	0	21	78	1	0	22	78	0	
S1	3	60	27	10	0	93	7	0	0	98	2	0	106
S2	2	34	54	10	0	39	61	0	0	57	43	0	
S3	0	34	57	9	0	35	65	0	0	51	49	0	
S4	1	14	75	10	0	7	90	3	0	29	71	0	

Wide Range birds -- Experiment 4 -- confusion matrices

	Sessions 16-20				Sessions 21-25				Bird
(P)	R1	R2	R3	R4	R1	R2	R3	R4	
S1	0	88	11	1	0	96	4	0	103
S2	0	46	54	0	0	47	53	0	
S3	0	48	52	0	0	54	44	2	
S4	0	17	81	2	0	28	72	0	
S1	0	90	10	0	0	91	9	0	104
S2	0	59	41	0	0	50	50	0	
S3	0	44	55	1	0	32	68	0	
S4	0	35	65	0	0	5	94	1	
S1	0	91	9	0	2	87	11	0	105
S2	0	42	58	0	0	46	54	0	
S3	0	40	60	0	0	37	63	0	
S4	0	29	71	0	0	22	78	0	
S1	0	94	6	0	0	99	1	0	106
S2	0	42	58	0	0	50	49	1	
S3	0	41	58	1	0	44	56	0	
S4	0	19	81	0	0	22	78	0	

t-test for win-stay strategy -- Experiment 4

A. Narrow-range birds

Bird	Overall RBI	Preferred Key	RBI after		D*	D^2
			R2	R3		
99	.29	3	.246	.387	.141	.019881
100	.25	3	.148	.020	-.128	.016384
101	.01	3	.095	.088	-.007	.000049
102	.18	2	.246	.214	.032	.001024
sum						
sum					.038	.037338
$\bar{x}$	.18		.184	.177	.010	

(t (3) = .1696, $p > .05$)

B. Wide-range birds

103	.69	3	.658	.709	.051	.002601
104	.35	3	.148	.462	.314	.098596
105	.78	3	.765	.870	.105	.011025
106	.15	2	.230	.246	-.016	.000256
sum					.456	.112478
$\bar{x}$	.49		.450	.572	.114	

(t (3) = .2682, $p > .05$)

References

Beebe-Center, J. G., Rogers, M. S., & O'Connell, D. N. Transmission of information about sucrose and saline solutions through the sense of taste. Journal of Psychology, 1955, 39, 157-160.

Blough, D. S. The study of animal sensory processes by operant methods. In W. K. Honig (Ed.), Operant Behavior: Areas of Research and Application. New York: Appleton-Century-Crofts, 1966.

Boakes, R. A. The bisection of a brightness interval by pigeons. Journal of the Experimental Analysis of Behavior, 1969, 12, 201-209.

Braida, L. D., & Durlach, N. I. Intensity perception. II. resolution in one-interval paradigms. Journal of the Acoustical Society of America, 1972, 51, 483-502.

Carterette, E. C., Friedman, M. P., & Wyman, M. J. Feedback and psychophysical variables in signal detection. Journal of the Acoustical Society of America, 1966, 39, 1051-1055.

Cuddy, L. L. Training the absolute identification of pitch. Perception and Psychophysics, 1970, 8, 265-269.

Durlach, N. I., & Braida, L. D. Intensity perception. I. preliminary theory of intensity resolution. Journal of the Acoustical Society of America, 1969, 46, 372-383.

Flagg, S. F., Medin, D. L., & Davis, R. T. Stimulus generalization in monkeys following discrimination training with gray stimuli. Animal Learning and Behavior, 1974, 2, 19-22.

Garner, W. R. An informational analysis of absolute judgments of loudness. Journal of Experimental Psychology, 1953, 46, 373-380.

Gravetter, F., & Lockhead, G. R. Criterial range as a frame of reference for stimulus judgment. Psychological Review, 1973, 80, 203-216.

Green, D. M., & Swets, J. A. Signal detection theory and psychophysics. New York: Wiley, 1966.

Heinemann, E. G. Multimodal distributions of pigeon's reaction time. Bulletin of the Psychonomic Society, 1974, 3, 75-77.

Heinemann, E. G., Avin, E., Sullivan, M. A., & Chase, S. Analysis of stimulus generalization with a psychophysical method. Journal of Experimental Psychology, 1969, 80, 215-224.

Holland, M. K., & Lockhead, G. R. Sequential effects in absolute judgments of loudness. Perception and Psychophysics, 1968, 3, 409-414.

Larkin, W. Response mechanisms in detection experiments. Journal of Experimental Psychology, 1971, 91, 140-151.

Lockhead, G. R. Choosing a response. In Korblum, S. (Ed.), Attention and performance IV. New York: Academic Press, 1973.

Luce, R. D., Green, D. M., & Weber, D. L. Attention bands in absolute identification. Perception and Psychophysics, 1976, 20, 49-54.

Lee, W. Relationship between Thurstone category scaling and signal detection theory. Psychological Bulletin, 1969, 71, 101-107.

McNicol, D. Feedback as a source of information and as a source of noise in absolute judgments of loudness. Journal of Experimental Psychology: Human Perception and Performance, 1975, 104, 175-182.

Miller, G. A. The magical number sever, plus or minus two: some limits on our capacity for processing information. Psychological Review, 1956, 63, 81-97.

Nachmias, J. Effects of presentation probability and number of response alternatives on simple visual detection. Perception and Psychophysics, 1968, 3, 151-155.

Parducci, A. Category judgment: a range-frequency model. Psychological Review, 1965, 72, 407-418.

Pollack, I. The information of elementary auditory displays. Journal of the Acoustical Society of America, 1952, 24, 745-749.

Pollack, I. The information of elementary auditory displays II. Journal of the Acoustical Society of America, 1953, 25, 765-769.

Shipley, E. F. A signal detection theory analysis of a category judgment experiment. Perception and Psychophysics, 1970, 7, 38-42.

Simpson, A. J., & Fitter, M. J. What is the best index of detectability? Psychological Bulletin, 1973, 80, 481-486.

Speeth, S. D., & Mathews, M. V. Sequential effects in the signal-detection situation. Journal of the Acoustical Society of America, 1961, 33, 1046-1053.

Swets, J. A. Signal detection and recognition by human observers. New York: Wiley, 1964.

Torgerson, W. S. Theory and methods of scaling. New York: Wiley, 1958.

Ward, L. M., & Lockhead, G. R. Sequential effects and memory in category judgments. Journal of Experimental Psychology, 1970, 84, 27-34.

Wever, E. G., & Zener, K. E. The method of absolute judgment in psychophysics. Psychological Review, 1928, 35, 466-493.

Wickelgren, W. A. Unidimensional strength theory and component analysis of noise in absolute and comparative judgments. Journal of Mathematical Psychology, 1968, 5, 102-122.

Williams, B. A. Probability learning as a function of momentary reinforcement probability. *Journal of the Experimental Analysis of Behavior*, 1972, *17*, 363-368.

Woodworth, R. S., & Schlosberg, H. *Experimental Psychology*. New York: Holt, Rinehart & Winston, 1954.