

University of New Hampshire

University of New Hampshire Scholars' Repository

Doctoral Dissertations

Student Scholarship

Winter 1985

A RATE COMPARISON MODEL OF CONCURRENT SCHEDULE PERFORMANCE

DOUGLAS STUART LEA

University of New Hampshire, Durham

Follow this and additional works at: <https://scholars.unh.edu/dissertation>

Recommended Citation

LEA, DOUGLAS STUART, "A RATE COMPARISON MODEL OF CONCURRENT SCHEDULE PERFORMANCE" (1985). *Doctoral Dissertations*. 1468.

<https://scholars.unh.edu/dissertation/1468>

This Dissertation is brought to you for free and open access by the Student Scholarship at University of New Hampshire Scholars' Repository. It has been accepted for inclusion in Doctoral Dissertations by an authorized administrator of University of New Hampshire Scholars' Repository. For more information, please contact Scholarly.Communication@unh.edu.

INFORMATION TO USERS

This reproduction was made from a copy of a manuscript sent to us for publication and microfilming. While the most advanced technology has been used to photograph and reproduce this manuscript, the quality of the reproduction is heavily dependent upon the quality of the material submitted. Pages in any manuscript may have indistinct print. In all cases the best available copy has been filmed.

The following explanation of techniques is provided to help clarify notations which may appear on this reproduction.

1. Manuscripts may not always be complete. When it is not possible to obtain missing pages, a note appears to indicate this.
2. When copyrighted materials are removed from the manuscript, a note appears to indicate this.
3. Oversize materials (maps, drawings, and charts) are photographed by sectioning the original, beginning at the upper left hand corner and continuing from left to right in equal sections with small overlaps. Each oversize page is also filmed as one exposure and is available, for an additional charge, as a standard 35mm slide or in black and white paper format.*
4. Most photographs reproduce acceptably on positive microfilm or microfiche but lack clarity on xerographic copies made from the microfilm. For an additional charge, all photographs are available in black and white standard 35mm slide format.*

*For more information about black and white slides or enlarged paper reproductions, please contact the Dissertations Customer Services Department.

UMI University
Microfilms
International



8607459

Lea, Douglas Stuart

**A RATE COMPARISON MODEL OF CONCURRENT SCHEDULE
PERFORMANCE**

University of New Hampshire

Ph.D. 1985

**University
Microfilms
International** 300 N. Zeeb Road, Ann Arbor, MI 48106



PLEASE NOTE:

In all cases this material has been filmed in the best possible way from the available copy. Problems encountered with this document have been identified here with a check mark .

1. Glossy photographs or pages _____
2. Colored illustrations, paper or print _____
3. Photographs with dark background _____
4. Illustrations are poor copy _____
5. Pages with black marks, not original copy
6. Print shows through as there is text on both sides of page _____
7. Indistinct, broken or small print on several pages _____
8. Print exceeds margin requirements _____
9. Tightly bound copy with print lost in spine _____
10. Computer printout pages with indistinct print _____
11. Page(s) _____ lacking when material received, and not available from school or author.
12. Page(s) _____ seem to be missing in numbering only as text follows.
13. Two pages numbered _____. Text follows.
14. Curling and wrinkled pages
15. Dissertation contains pages with print at a slant, filmed as received
16. Other _____

University
Microfilms
International



A RATE COMPARISON MODEL OF
CONCURRENT SCHEDULE PERFORMANCE

BY

Douglas S. Lea
B.A., University of New Hampshire, 1976
M.A., University of New Hampshire, 1979

DISSERTATION

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Doctor of Philosophy
in
Psychology

December, 1985

This dissertation has been examined and approved.

William W. Baum

Dissertation director, William Baum
Associate Professor of Psychology

John A. Nevin

John A. Nevin, Professor of Psychology

Marie Gaudard

Marie Gaudard, Associate Professor of Mathematics

John Limber

John Limber, Associate Professor of Psychology

James Taylor

James Taylor, Associate Professor of Zoology

Oct. 15, 1985

Date

ACKNOWLEDGEMENTS

The work reported here was supported in part by National Science Foundation Grant BNS 79-24082 to J. A. Nevin. I thank the members of my committee for their assistance.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS.....iii

ABSTRACT..... v

CHAPTER PAGE

I. INTRODUCTION..... 1

 Equalizing..... 5

 Optimal Foraging Theory..... 7

 A Rate Comparison Model..... 10

 Models of Rate Estimation..... 13

 Patches and Concurrent Schedules..... 18

 Overview of the Experiment..... 24

II. THE EXPERIMENT..... 26

 Method..... 26

 Molar Results..... 29

 Stay Times..... 31

 Giving-up Times..... 35

 Evidence for Rate Comparison..... 39

 Schedule versus Patch Performance..... 42

III. CONCLUSIONS..... 50

REFERENCES..... 55

TABLES..... 60

FIGURE CAPTIONS..... 66

FIGURES..... 68

ABSTRACT

A RATE COMPARISON MODEL OF CONCURRENT SCHEDULE PERFORMANCE

By

DOUGLAS S. LEA

University of New Hampshire, December, 1985

A rate comparison model of concurrent schedule performance and foraging is proposed. The model is a molecular equalizing theory of matching, based on results from optimal foraging theory and corresponding data from behavioral ecology. It states that animals leave one concurrent alternative for another whenever their estimates of current local food rates fall below a criterion based on habitat-wide average rates. Linear operator rules are offered as among the most plausible rate estimation strategies. The model may be applicable to both schedule performance and foraging in patchy natural environments, even though differences between these situations may result in variations in how rate comparison processes are employed.

The model predicts that stay times in alternatives within concurrent schedules should reveal several consistent patterns when analyzed as giving-up

times, i.e., those times between the last food encounter (or entry) in an alternative and a switch. These predictions were applied to an experiment with pigeons using concurrent variable interval schedules and other schedules based on continuous responses with explicit travel requirements for switching.

In agreement with predictions, giving-up times increased with decreasing overall food density, and provided evidence for strategies such as linear operator rules which incorporate rate estimation and comparison rather than simpler time-based switching rules. Giving-up times were much shorter than average interfood intervals in variable interval schedules, but closer to interfood intervals in a similar condition in which local food rates were constant, demonstrating that locally high food probabilities affect switching criteria. The chief differences between concurrent schedule results and foraging data were seen as due to the differing extents to which animals can use cues signalling the quality of alternatives in the two situations.

CHAPTER I

INTRODUCTION

The time-based form (Baum & Rachlin, 1969) of Herrnstein's (1970) matching law,

$$\frac{T_1}{T_2} = \frac{R_1}{R_2},$$

states that the ratio of the total times, T_j ($j=1,2$), spent on the two alternatives of concurrent variable-interval variable-interval (conc VI VI) equals, or "matches", the ratios of reinforcements, R_j , obtained from those alternatives. Many results from conc VI VI experiments conform to this finding (deVilliers, 1977). However, most data deviate from simple matching in ways that are well approximated by

$$\frac{T_1}{T_2} = b \left(\frac{R_1}{R_2} \right)^s,$$

(Baum, 1974; 1979). The multiplicative parameter is interpreted as a "bias" coefficient, reflecting subjects' tendencies to spend more time on one alternative than the other when both provide equal rates of reinforcement. The role of the exponential parameter is less well understood. Empirically, values of this "sensitivity" parameter are most often less than 1.0 (Baum, 1979; Wearden & Burgess, 1982), a

result termed "undermatching". Despite these sorts of deviations, simple matching is widely considered a good approximation to conc VI VI performance.

Even though the overall molar aspects of behavior in conc VI VI display an especially simple relationship to average reinforcement rates, the mechanisms underlying matching have not been well specified. Matching does not appear to result from the strengthening effects of any simple differential reinforcement process (Herrnstein, 1970), nor does matching correspond well to optimal reinforcement rate maximization strategies (Houston & McNamara, 1981), nor even to any of several degraded or myopic maximizing strategies that track local reinforcement probabilities (although there is still some debate on this issue; see, e.g., Shimp, 1969; Nevin, 1969; Silberberg, Hamilton, Zirrax, & Casey, 1978; Hinson & Staddon, 1983). Nevertheless, some kinds of underlying processes must, of course, exist. Two recent, and rather different lines of research together suggest a new approach to studying these processes.

Before proceeding, it is important to define several aspects of time allocation and reinforcement rate on concurrent schedules. For reasons to become clear shortly, "reinforcement" rates on concurrent schedules are henceforth identified simply as "food" rates. In addition, the following notation is used.

t_j is the time since entering the concurrent alternative j on any given occasion. (Different visits to the same alternative are not explicitly distinguished in this notation.) The subscript is dropped when the identity of current alternative is irrelevant.

u_j is the time, t_j , at which an animal leaves (switches from) alternative j .

T_j is the total time spent on alternative j , across possibly many different visits (e.g., across an experimental session).

τ is the time taken to switch from one alternative to another.

R_j is the total number of food deliveries obtained on alternative j during the time T_j .

$g_j(t)$ is the function describing the momentary (local) food rate at time t on alternative j .

$p_j(t)$ is the local probability of food delivery per unit time at time t on alternative j . $p_j(t)$ and $g_j(t)$ can be expressed in terms of one another when food is probabilistically delivered (Staddon, 1980).

$V_j(t)$ is an animal's estimate of $g_j(t)$.

$G_j(t)$ is the time integral of $g_j(t)$, describing the cumulative yield at time t .

E_j is the average local food rate on alternative j .
 R_j/T_j is an estimate of E_j .

Also, "*" is sometimes used as a suffix for these terms, indicating measures taken across all available alternatives.

Equalizing

It has often been noted (e.g., Revusky, 1963) that the matching law can be rearranged to give

$$\frac{R_1}{T_1} = \frac{R_2}{T_2},$$

a result labelled "equalizing" (Killeen, 1972). This states that the average local rates of reinforcement (i.e., the numbers of reinforcements obtained per unit time present) on the two alternatives are equal when matching holds (cf., Gibbon, Berryman, & Thompson, 1974).

Herrnstein and Vaughan (1980; Vaughan, 1981) have extended this observation into the outline of a theory of concurrent performance called "melioration": Subjects are said to compare the local rates of reinforcement on the two alternatives and to distribute their behavior on the basis of the differences in these local rates, in ways that preserve their average equality.

Herrnstein and Vaughan have focused attention on only the molar aspects of this account and have provided some empirical support for its predictions about average time ratios on several schedules. However, it is easy to see the general form of a more clearly molecular counterpart to melioration. Such a

theory would view the act of switching from one alternative to another as the result of a comparison process. For two-alternative concurrent schedules, animals may be said to form estimates of local food rates, $V_j(t)$, and switch from alternative 1 to alternative 2 whenever $V_1(t) < V_2(t)$, and vice versa.

There are many possible specific models of rate estimation and comparison processes compatible both with this framework and with molar matching. Plausible models include those which preserve a correspondance between local estimates, $V_j(t)$ and long term average rates, E_j , such that the proportion of time that $V_1(t)$ is greater than $V_2(t)$ equals $E_1/(E_1+E_2)$, (or $R_1/(R_1+R_2)$), at least over the long run (Vaughan, 1981).

Optimal Foraging Theory

This form of molecular equalizing bears a strong resemblance to theories proposed by behavioral ecologists to explain how animals forage for food in natural habitats (cf., Staddon, 1980). These models apply to behavior in situations similar to those studied in concurrent schedules, but contain very different assumptions and justifications.

Natural environments usually contain food items (e.g., seeds) that are distributed neither perfectly regularly nor just randomly throughout the habitat. Instead, food tends to clump together in "patches", i.e., occasional areas of high food concentration (e.g., individual pine cones, or small grassy spaces within wooded areas). Animals (e.g., birds) forage by travelling from one patch of usually initially unknown quality to another, searching for and consuming food. This situation is taken as a common basis for many theoretical and empirical studies of foraging (Pyke, Pulliam, & Charnov, 1977).

Although they may vary in size and food density, patches are, by definition, finite resources. Thus the rate of food encounters within patches is always some function, $g_j(t)$ that eventually decreases to zero with time spent consuming food in the patch (except in

unusual cases where food rapidly replenishes itself). The exact nature of any $g_j(t)$ depends on the type of patch, local search strategies, defensive behavior on the part of the prey, and the like.

Within this scenario, it is useful to ask how, in principle, animals can forage across different patches in an efficient manner. One answer may be approached most easily via some major simplifying assumptions. Assume that, instead of discrete items, food comes in a monotonically decreasing continuous flow from variable-rate spigots, one per patch. This idealization gives $g_j(t)$, the food rate, and related functions particularly simple meanings. The overall habitat wide food rate, g^* , across N patches may then be modelled as

$$g^* = \frac{\sum G_j(u_j)}{\sum u_j + N\tau} .$$

Note that g^* includes the zero rate obtained during interpatch travel.

Charnov has shown (Krebs, Ryan, & Charnov, 1974; Charnov, 1976) via calculus that this overall rate is maximal if animals leave patch j at time u_j such that $g_j(u_j) < g^*$, i.e., when the local food rate is less than the optimal average habitat-wide rate. This result has been labelled the "marginal value theorem" due to its analog in classical economic theory.

Further research on the patch exploitation

problem (Oaten, 1977; Green, 1980; McNair, 1982; McNamara, 1982) has employed somewhat more realistic characterizations wherein food items are acknowledged to be discrete, and encountered across time according to some stochastic process. These situations are a good deal more complex to model and solve than the above simplification. Optimal solutions require specification of the functional forms of intercapture times, and similar details of patches, and make extensive use of sequential statistical decision theory.

The formal properties of such solutions will not be detailed here. It is, however, important to note a few general features of this work. McNamara (1982) has shown that all stochastic solutions to patch exploitation specify that animals should leave alternatives at times such that the discrete stochastic version of $g_j(t)$ is no greater than (and often close to) the habitat-wide optimal average rate. Thus, depending on how rate is characterized (Oaten, 1977), the marginal value theorem and related simplifications may be useful approximations to these more thorough analyses in many circumstances. A well-known exception, perhaps typical of some real environments, holds when there are exactly zero or one food items per patch (Oaten, 1977; McNamara, 1982).

A Rate Comparison Model

As models of foraging animals, optimal foraging theories suffer from two deficiencies. Even the discrete stochastic solutions to patch exploitation involve simplifying assumptions (e.g., random within-patch food encounters; cf., Oaten, 1977) that make their application to real habitats tenuous. Indeed, the diversity and complexity of real habitats make even the formulation of realistic models to serve as bases for optimization seem all but impossible (Zach & Smith, 1981).

Moreover, optimal results in themselves rarely provide much insight into the ways in which animals might go about exploiting patches. It is indeed useful to know that animals should optimally leave patches when $g_j(t) < g^*$. However, this result does not explain how animals could actually do this (Houston, 1983).

On the other hand, optimal results do perform a valuable function in pointing out or clarifying the general nature of the problems animals face, the information available to animals, and the basic classes of rules involved in foraging at all efficiently. These are important features of any account of behavior in such situations.

Stripped of optimality requirements, foraging

analyses specify that patch exploitation relies on three interdependent processes that appear to be important components of efficient foraging. A general "rate comparison" model encompassing these features may be characterized as follows (Figure 1).

(1) Immediately upon entering an alternative j , animals assign an a priori value, $A_j = V_j(0)$, as an estimate of the initial actual food rate, $g_j(0)$.

(2) Animals have some means of updating current food rate estimates, $V_j(t_j)$, based on time spent in the alternative and the time course of the food (if any) encountered there.

(3) Animals compare $V_j(t_j)$ to some criterion value, V_c , leaving the alternative when $V_j(t) < V_c$. V_c is based, at least in part, on the habitat-wide average food rate.

Again, optimization results provide exact forms for each of these components. However, the goal here is to provide a framework for accounting for the ways in which real animals come to be (perhaps not optimally) efficient foragers. The resulting model is evidently a variation of classic decision models (e.g., Green & Swets, 1966; McNamara & Houston, 1980) common in the analysis of a wide variety of behavioral phenomena, including schedule performance (e.g., Gibbon, 1977). It is somewhat unusual as a decision model in its explicit temporal nature, and its use of

a criterion, V_C , that partially relies on the results of the behavior it controls.

The model can also be seen as a version of momentary equalizing. The first two features claim that rate estimation includes initial estimates, A_j , followed by a time-based means of integrating food deliveries into $V_j(t)$ estimates. The use of a single criterion, V_C , rather than pairwise comparisons is one natural means of extending equalizing to situations possibly involving more than two alternatives.

Models of Rate Estimation

Time-Based Methods

One of the simplest methods of estimating local food rates incorporates the notion that the longer it has been since a food encounter, the lower the apparent food rate. It is possible that animals use estimates, $V_j(t)$, based entirely on the time since the last food delivery (or time since entry into the alternative if no food is encountered). If corresponding switching criteria, V_c , are based on average rates, then $V_j(t)$ falls below V_c when the time since the last food encounter exceeds the habitat-wide average interfood time.

In this way, rate comparison could be performed solely through decisions based on time estimates (cf., Gibbon, 1977). This time-based strategy is a temporal analog of "lose-shift" (or "win-stay") rules (Olton, Handelmann, & Walker, 1981). Viewed differently, it is a type of "positive recency effect" (Menlove, 1975; Staddon, 1980) of food on behavior.

Foragers consistently using some manifestation of this rule would enter alternatives and stay until the time since food encounter (or entry) exceeded the average interfood interval. Thus, on average, they should stay longer in denser alternatives, where

interfood intervals are often short, but also display constant giving-up times (GUTs), i.e., times between food (or entry) and switching, across all alternatives (Krebs, et al, 1974).

Two kinds of predictions from such models have been tested empirically in semi-naturalistic experiments. Since V_c varies with habitat-wide food density, average giving-up times should be close to average interfood times, and thus shorter in generally dense, and longer in generally sparse habitats. Several experimental results support this prediction (e.g., Krebs, et al, 1974; see Pyke, et al, 1977; Krebs, 1978; Cowie & Krebs, 1980; and Krebs, Houston, & Charnov, 1981 for reviews). Second, since average food rates also fall when travel time is longer, this should be reflected in V_c , resulting in longer average GUTs with longer travel requirements. This too has found some support in experiments with real foragers (Cowie, 1977).

However, these studies have not really addressed just how animals estimate food rates. Observed trends in average giving-up times are compatible with a large number of rate comparison strategies, not just this simple time-based method. Individual giving-up times have not been subject to the detailed analysis required in order to differentiate various strategies.

Averaging Methods

More complex rate estimation rules have been proposed that are consistent with current empirical findings. Killeen (1981), Staddon (1980), and Harley (1981) have suggested that animals use exponentially weighted moving averages of food deliveries across time, i.e., a linear operator estimation rule. This idea has several attractive properties, both as a rate estimator and as a plausible psychological mechanism.

Linear operator rules take the form

$$V_j(t) = \beta X(t) + (1-\beta)V_j(t-1),$$

where time, t , is now taken as a discrete variable of arbitrary unit length, for convenience. $X(t)$ is a function taking high values in the presence of food and low values otherwise. β ($0 < \beta < 1$) is a "memory" parameter, controlling the relative importance of new versus old information. Under this rule, every food encounter increments the current rate estimate, and every unit of time passed without a food encounter decrements the estimate.

This model is actually just a relabelling of classic linear learning theory (Bush & Mosteller, 1955, Rescorla & Wagner, 1972). This may be seen by the algebraic manipulation,

$$\Delta V_j(t) = \beta (X(t) - V_j(t)).$$

Note that $V_j(t)$ does not refer, however, to

"conditioning", but to an animal's estimate of food rates, which, when compared to a criterion, controls switching from one alternative to another.

As a rate estimation technique, this rule appears to fare well. Explicitly including the a priori estimate, and solving (Killeen, 1981), the rule becomes

$$V_j(t) = \beta(1-\beta)^t A_j + \sum_{s=0}^t \beta(1-\beta)^s X(t-s),$$

which produces estimation functions like that in Figure 1. Animals using this estimator would display giving-up times with about the same average characteristics as found with the simple time-based scheme. The main behavioral difference between the two is that, since closely spaced food encounters are integrated into higher local rate estimates, giving-up times after several consecutive food encounters should be longer than those after just a single food encounter.

Pulliam (1983) has investigated some properties of this estimator as part of a decision strategy in simulated environments. He found this strategy to be robustly efficient, in that it results in nearly optimal yields across a variety of situations.

Several decision strategies involving some form of linear operator rule may also be compatible with molar matching in concurrent schedules, as shown by Staddon (1980) and Pulliam (1983; see also Vaughan,

1982 and below). Because of this, the rule also potentially satisfies the molar requirements of equalizing theories.

Thus, while the linear operator rule is only one of the many possible heuristics that animals could employ to solve time allocation problems, it possesses features not found in many other candidate models: psychological simplicity, similarity to other well-studied psychological theories, adequacy as part of an estimation and decision strategy, and potential compatibility with molar schedule performance data.

As noted above, there are currently no data concerning the relative empirical adequacy of any particular estimation and decision strategy. While specific models are difficult to test, differences among classes of models have more straightforward empirical consequences. It is possible to distinguish models claiming that giving-up times are based solely on time estimates from those based on rate averaging methods by analyzing how giving-up times vary with local patterns of food encounters during stays. Rate estimates under linear operator and similar rules lead to longer giving-up times after food encounters than after entry. This distinction forms part of the focus of the present experiment.

Patches and Concurrent Schedules

Even though the rate comparison model is phrased in a form applicable to both foraging and schedule performance, the two situations appear different enough to warrant closer inspection. There are three classes of differences that may cause problems for any general theory of how animals switch among alternatives.

Travel

Travel time between patches is superficially similar to the change-over delay (COD) in concurrent schedules. However, CODs are nearly always unsignalled and of experimenter-enforced duration, unlike travel. Methodologically, CODs are usually treated as integral parts of measured total times spent on alternatives, whereas analyses of foraging usually treat them as separate. Baum (1982) has discussed the significance of these and other differences. He has further shown in an experiment introducing true physical travel between alternatives in concurrent schedules that average stay times increased with increasing travel times, in agreement with results from behavioral ecology.

Schedule Functions

Most work in foraging assumes that food rate functions, $g_j(t)$, reflect depletion, i.e., decrease eventually to zero. Indeed, this is why rate comparison processes produce good results in most situations. Concurrent VI VI schedules do not share this depletion property. This may be seen by considering the momentary reinforcement probability functions (Houston & McNamara, 1981) on constant probability conc VI VI,

$$P_1(t_1) = \begin{cases} 1 - e^{-\lambda_1(u_2 + \tau)} & , t_1 = 0 \\ \lambda_1 & , t_1 > 0, \end{cases}$$

(Similarly for $p_2(t_2)$), where λ_j are the instantaneous probabilities of food delivery (i.e., the reciprocals of the mean programmed interfood intervals) on the two schedules, and t_j are times since the end of the COD. This function displays a "spike" of high food probability on entry to the alternative (i.e., after the COD), followed by a lower constant probability throughout the remainder of the stay (Dreyfus, Dorman, Fetterman, & Stubbs, 1982). Thus, while the kinds of rate comparison processes involved in foraging may be fairly efficient in conc VI VI, they cannot be seen as approximations to optimal strategies (Houston & McNamara), as they could be above, and cannot be relied on to consistently produce near-optimal yields.

Interestingly, a common variation of conc VI VI, "interdependent" conc VI VI (Shimp, 1966; Stubbs & Pliskoff, 1969) does possess the depletion property. This procedure results in behavior essentially identical (at the molar level) to that from conventional conc VI VI (Baum, 1979). Ignoring COD times (which obscure this property), the corresponding probability functions are

$$P_1(t_1) = \begin{cases} 1 - e^{-\lambda_2 t_1} & , t_1 = 0, \\ \lambda_1 e^{-\lambda_2 t_1} & , t_1 > 0. \end{cases}$$

Here, after the initial spike, food probability drops exponentially with time spent on the alternative. This fact does not imply that rate comparison strategies are optimal here either (Staddon, Hinson, & Kram, 1981), but does show one way in which schedule functions can display some patch-like properties.

External Cues

Concurrent schedules provide much more potential information to subjects about prevailing food densities than is probably available to most foraging animals. This is done in several ways. Since there are usually only two schedules associated with the concurrent alternatives, subjects must strictly alternate between two schedule types of increasing

familiarity. These two alternatives are always signalled via visual and/or positional cues, so subjects have continuous information on the nature of the current and alternative schedule types. Thus subjects in concurrent schedules have access to information relevant to rate estimation that may not be available to animals foraging across many unfamiliar patches of unsignalled quality.

There has been, however, one study of concurrent performance that minimized the presence of external cues, thereby limiting the extent to which subjects could rely on such information. Since this experiment more closely follows this aspect of foraging theory, it merits closer inspection in terms of the rate comparison model.

Bourland and Miller (1981) employed a change-over key conc VI VI procedure in which no key lights or other stimuli ever indicated which of two concurrent schedules were in effect. This sort of experiment can be modelled fairly easily. Assume a simplified time-based giving-up model in which all stays use the same giving-up time criterion, t_c , from either entry or the last food presentation. While overly simplistic, this model can be explicitly stated with only one free parameter, t_c , in order to demonstrate the present point. McNair (1982) shows (in a different situation having the same formal characteristics) that the

expected average stay time on alternative j under this model for the Bourland and Miller paradigm is

$$\frac{1}{\lambda_j} (e^{\lambda_j t_c} - 1),$$

where λ_j is the VI schedule parameter.

Under this and other pure rate comparison models, stay times in intervals with no food are of identical lengths on the two alternatives. The model leads to greater average stays in denser alternatives simply by virtue of their inclusion of more frequent food deliveries. Average stay durations under the model are thus heavily dependent on absolute food rates.

Computer simulations show that for plausible values of t_c and typical schedule ratios, undermatching essentially always results, but to different degrees depending on the absolute schedule values. Sensitivity exponents of about 0.25 result from sets of fairly dense schedules (e.g., VI 60 VI 30), while exponents of about 0.05 result from sparse ones (e.g., VI 480 VI 240). Bourland and Miller investigated performance on schedules in these two ranges and found exponents of about 0.40 for dense, and 0.10 for sparse sets of conditions. A better rate comparison model would probably mirror their results more accurately. For example, linear operator rules result in longer GUTs (and therefore stays) in intervals containing food, leading to more extreme

stay ratios.

This demonstration shows that behavior in some concurrent schedules may be highly consistent with predictions from simple foraging models. More important, it shows that models ignoring the signalling properties of conventional concurrent schedules tend to predict greater undermatching than is commonly found. This issue is further explored in the present experiment.

Overview of the Experiment

This experiment investigates performance on concurrent schedules in terms of features relevant to the proposed rate comparison model. The experiment involves many conditions, grouped in ways allowing answers to specific questions surrounding the general issue of whether pigeons use rate comparison processes in concurrent schedules.

The experiment employs two slightly unusual features.

Continuous responses. The chief dependent measure is the amount of time pigeons stand on panels associated with schedules programmed in a two-alternative concurrent paradigm, as in Baum and Rachlin (1969). A simple check was also performed comparing these results to those where discrete keypecks are required.

Explicit travel. Panels were physically separated by a small partition, requiring the pigeons to walk from one alternative to the other, without any extra imposed change-over delay, as in Baum (1982).

The experimental conditions may be classified into three groups. Four conditions employed conc VI VI schedules in which each alternative presents the same schedule type (i.e., equal schedules, like VI 60 VI

60). Using equal schedules helps minimize the effects of external cues, since stimuli associated with both alternatives signal the same schedule type. A standard series of conditions were also run using pairs of VI schedules with different food (reinforcement) rate ratios. Additionally, two conditions involving synthetic VI-like schedules, one with a constant food rate function, and the other offering occasional clusters of food presentations, were used for comparison with the results from the equal VI conditions.

The data from these conditions were analyzed in ways that provide at least partial evidence for several points concerning rate comparison processes: (1) whether individual stay times and giving-up times on alternatives display the regularity demanded by rate comparison models; (2) whether giving-up times in concurrent schedules vary with average food density; (3) whether there is any evidence for time-based versus rate averaging models of rate estimation and comparison rules; (4) whether the differences between patches and concurrent schedules affect rate comparison processes; (5) whether these molecular phenomena shed light on molar aspects of concurrent performance.

CHAPTER II

THE EXPERIMENT

Method

Subjects

Four pigeons, P487, P489, P490, and P355 served. All had previously served in experiments employing schedules of reinforcement. Subjects were run six or seven sessions per week at 80-100% of their free-feeding weight.

Apparatus

The experimental chamber, measuring 44 cm wide along the front wall by 38 cm deep by 36 cm high, was separated in half by a 36 cm high translucent plastic partition extending from the front wall 21 cm into the chamber. On each side of the partition was a pressure sensitive panel which activated when pigeons came within about 12 cm of the front wall.

To prevent improper recording, "debouncing" circuitry was employed such that a panel did not activate until a pigeon stood continuously on the panel for at least 0.3 sec, and remained activated until the pigeon was continuously off the panel for at

least 0.3 sec. Activation of a panel caused the corresponding standard response key light, mounted on the front wall on that side of the chamber, to illuminate. One food magazine could provide 2.5-sec mixed grain presentations. It was accessible from either side of the chamber through a small hole in the partition. Constant probability VI and other schedules were arranged by a computer.

Stay times were defined as starting from the moment of recorded panel activation on one side, and lasting until the moment of recorded activation on the other side. Measured stay times thus included travel times, the times it took for the pigeons to move from one side of the chamber to the other. Travel times were occasionally recorded by hand, and were found to range from about 0.8 to 1.8 sec. Stay times did not include food delivery times. All times, truncated to the nearest 0.125 sec, were recorded and analyzed on a computer.

Procedure

Most conditions in this experiment employed constant probability independent concurrent VI VI schedules. (All conditions, and their orders are listed in Table I.) These were preceded by exposure to 12 sessions of conc VI 30 VI 30 schedules. (All schedule values are indicated in seconds.) Each conc

VI VI condition was run for six or seven sessions, without reference to any stability criteria. Three other conditions were run:

Discrete conc VI VI. Immediately following the conc VI VI conditions, twelve sessions of conc VI 30 VI 30 were run in which keypecks to standard response keys were required for food delivery.

Clustered. Six months prior to the above conditions, a synthetic concurrent schedule was run for sixteen sessions with P487, P489, and P490. This condition involved two "clustered" schedules. Identical schedules were in force on each side of the chamber. In each, a baseline extinction schedule was irregularly interrupted (on a VI 100 sec schedule) by an unsignalled dense component of irregular duration (on a VI 20 sec schedule). This dense component delivered food on a VI 10 sec schedule. The effect of this schedule was to provide a situation in which clusters of food deliveries occasionally appeared.

conc VT VT. Following the clustered schedule, P487, P489, and P490 were exposed to eighteen sessions of a concurrent VT 30 VT 30 schedule. This schedule differed from conc VI VI only in that food deliveries were never "held" while subjects were away from an alternative. Thus each schedule presented food on average every 30 sec when the subject was present.

Molar Results

Figure 2 displays the ratios of average times versus the ratios of obtained food rates for all conc VI VI conditions. The group least-squares double-logarithmic slope (i.e., sensitivity exponent) was 0.45. Individual fits are listed in Table II and individual average stay times comprising time ratios are in Table III. (Due to an apparatus problem, data are not available for P489 in the VI 30 VI 240 condition.)

While these exponents appear lower than usual, they are actually quite consistent with those reported by Baum and Rachlin (1969) in a very similar experiment. They found exponents averaging 1.02 only when COD times were subtracted from total times spent on alternatives in forming time ratios. When these COD times are included, the exponents fall, averaging 0.47 (Myers & Myers, 1977). Since the analogous travel times in the present experiment were not directly recorded (see below), no such adjustment was made here. (However, it may be noted that assuming travel times of one and two seconds result in average exponents of 0.62 and 0.77, respectively.)

Baum and Rachlin's (1969) and the present experiment share another feature that may help to

explain the resulting undermatching. Both used relatively short condition lengths (six or seven sessions), and did not employ stability criteria. Results discussed below (Figure 17) show that at least some measures comprising times stayed on alternatives failed to show stability within conditions (cf., McSweeney, Melville, Buck, & Whipple, 1983).

Stay Times

The vast amount of individual stay time data obtained in this experiment necessitates presentation of only a fraction of these raw results. Most individual data are presented only for one subject, P490, for consistency.

Figure 3 displays sample records of stay-by-stay behavior for P490 for each of the four equal VI conditions. Vertical lines are proportional to stay times. Downward lines represent stays on the left side of the chamber and upward lines represent stays on the right. Thus sequences of stays are depicted as lines alternating up and down. Dark circles represent 2.5-sec food deliveries. All sample records are from one of the last three sessions of conditions, and include between 15% and 40% of total session lengths. Records showing relatively numerous food deliveries were selected for presentation. Otherwise, they are typical. Figure 4 displays sample records for P487, P489, and P355 for the equal VI 30, VI 60, and VI 120 conditions, respectively. Figure 5 displays sample stay time records for P490 in all unequal VI conditions.

Figure 6 displays sample daily stay time histograms for P490 in the equal VI conditions. The

conventional (right-side-up) histograms show stays on the right and the upside-down histograms show stays on the left.

Subjects showed a few individual differences (Figures 3-4). They displayed different amounts of "bias", i.e., greater stay durations on one side of the chamber than the other, even when both provided equal food rates (cf., Table II). Stays also differed across subjects in degrees of overall variability within sessions. Additionally, subjects differed in the "dynamic ranges" of stays, i.e., variability across conditions. Nevertheless, all demonstrated the same general trends.

One notable feature of the raw data is that stay times are less variable than one might expect on the basis of previous studies of switching in concurrent schedules. Heyman (1979), using discrete response interdependent conc VI VI schedules, measured the number of keypecks pigeons made on alternatives between entry and a switch. He found that the resulting distributions of pecks-before-switches provided acceptable evidence that switching obeys a simple constant probability random process, and did not find the regularity apparent in the present data. However, Heyman measured responses, not times. His findings may not be in contradiction to the present results, for several reasons.

Pigeons tend to respond in "bursts" of closely spaced keypecks (Nevin & Baum, 1980), especially early within stays (Pliskoff & Fetterman, 1981). If these bursts vary significantly in numbers of responses, but not necessarily in total time, Heyman's conclusions may be compatible with a wide range of stay time distributions, including these. For example, even if pigeons always stayed exactly five seconds on alternatives, but emitted bursts randomly varying from 1 to 20 responses, the response distribution could easily support a random switch model, masking the regularity of times.

While not intended to provide direct support for this sort of explanation, a simple check was made to determine whether the lack of discrete response requirements contributed to the low variability of stay times. Results from the discrete response (keypeck) conc VI 30 VI 30 condition do show some evidence of this. The three pigeons that did peck reliably in this condition (P489 did not) all showed somewhat longer and more variable stay times than in the corresponding continuous response condition. This can be seen in the sample record (Figure 7) and histogram (Figure 8) for P490. This subject, like the other two, developed a fairly strong bias toward one side of the chamber in this condition.

One may conclude from this comparison that

discrete response requirements in conc VI VI schedules do tend to add variability to stay times on alternatives, but that neither discrete nor continuous conc VI VI schedules produce stay times compatible with a random switch model.

Giving-Up Times

Analysis of giving-up times proceeded by dividing stay times and their components into four categories:

- NE. Total stay times (time from entry to switch) in intervals during which no food was obtained.
- IE. The times stayed from the end of a food delivery until a switch in intervals during which one food delivery was obtained immediately (within 1 sec) on entry to the alternative, i.e., the total stay times minus the times to the end of food presentations.
- DE. The times stayed from the end of food delivery until a switch in intervals during which one food delivery was obtained later than 1 sec after entry.
- ME. The times stayed from the end of the last food delivery in intervals including more than one food presentation.

Individual data from the main results of this analysis, the medians for each category for the last three days of each condition, are listed in Table III.

Two minor cautions are necessary when interpreting these giving-up times. First, all GUTs include travel time from one alternative to the other. As noted above, travel times were not continuously

measured, but were found by occasional hand measurement to average around 1 sec. However, informal observation suggested that travel times may have covaried with stay times (i.e., that shorter travel times may have occurred with shorter stays). Thus it does not appear appropriate to merely subtract a common average travel time estimate from each giving-up time, although such an adjustment would not substantially change any of the present conclusions.

Also, medians from the different categories of giving-up times represent vastly different numbers of observations. NF intervals occurred most frequently, followed by IF, DF, and MF intervals (cf., Figures 3-5 and Dreyfus, et al, 1982). Medians were not computed for categories which did not occur on at least two of the last three days of any condition. (This "at least two" rule was also used for all other data summaries presented for this experiment.) The omitted medians include MF GUTs for many schedules, and DF GUTs for a few (Table III).

The relationship of giving-up times to density may be seen in Figures 9-11. Figure 9 displays GUTs averaged across sides and subjects versus average programmed interfood times for all VI conditions. MF GUTs are included only for those conditions in which they could be estimated for both alternatives. Since obtained interfood intervals were always close to

programmed ones, the plotted relationship is nearly identical versus either independent variable.

GUTs may be seen to increase with interfood intervals. The relationships between each category of GUT and density are approximately linear, but the slopes differ. This indicates that GUTs in intervals with food were increasingly different from those on NF intervals as density decreased. Although impossible to discern from this figure, data from the conditions with the most extreme schedule ratios are least consistent with these trends. In fact, this plot is a poor means of demonstrating these relationships, since GUTs from both sides of sometimes unequal schedules are averaged together.

A better view of these trends is contained in Figure 10. This shows all GUTs (except MF in VI 240 VI 240, for which there is insufficient data), averaged across sides (to average out bias) in the equal schedule conditions only, including the two additional schedules discussed below.

The best comparison of trends in GUTs across density between unequal alternatives is shown in Figure 11. This displays GUTs for the three conditions with the same 2:1 schedule ratio, but different overall food densities. It shows that all categories of GUTS were longer on the denser of two unequal alternatives, but otherwise varied with density in

approximately the same fashion as did those from equal schedules.

The relationships between different categories of giving-up times can be seen in Figure 12, where medians for each category are plotted against one another (including points for each side and subject). These show that GUTs in intervals containing food were longer than those in intervals without food (Figure 12a); GUTs in intervals with one food delivery were about the same, regardless of when during the stay food was obtained (Figure 12b); and GUTs in intervals with multiple food presentations were longer than in those with only one (Figure 12c).

Evidence for Rate Comparison

The prediction that average giving-up times should increase with decreasing food density is supported by the data from this experiment. These data show that absolute rates of food delivery are important determiners of how long animals stay on alternatives.

The data argue against two possible accounts of stay times and GUTs that stress the role of time estimation over rate estimation.

A quick glance at Figures 3-5 might lead one to forego a rate comparison model in favor of a "residence time" theory of performance (McNair, 1982). According to such an account, animals stay a certain length of time on an alternative, regardless of whether any food is encountered there. The relationships between GUTs in Figure 12 show that this cannot be true. For example, this account cannot explain why giving-up times (not stay times) are about the same in intervals in which food is obtained immediately (IF) and when it is delayed (DF) during a stay. This equality (Figure 12b) demonstrates that it is the time since food encounters, and not the time since entry (unless no food is obtained) that is the more important determiner of when subjects leave

alternatives.

There are several grounds for rejecting models including giving-up rules based strictly on time estimates in favor of those based on averaging. The most important comparison in this regard is that between MF and IF/DF intervals. Figures 12b-12c show that giving-up times in intervals with multiple food encounters were longer than all others. This result is hard to explain in accounts stating that switching is based only on estimates of the time since the last food encounter (or entry). This pattern is, however, fully consistent with linear operator or other rate estimation methods, since multiple food deliveries within short periods should be integrated into relatively high rate estimates, leading to longer giving-up times.

Before accepting the superiority of averaging accounts, a possible objection to the present interpretation of the MF data must be considered. Because MF intervals were rare (occurring about seven times per session in the densest schedules, and less than once in the sparsest), one might propose a "napping" account of the MF data: Suppose subjects occasionally stand idly at an alternative in total disregard of the prevailing schedules (i.e., they take naps). After relatively long periods they sometimes "wake up" and leave the alternative. Since the

resulting stays are long, they most often contain multiple food deliveries, and because the switches are random, MF GUTs are relatively long, thus the effect. There is no evidence of this sort of phenomenon in the sample records (Figures 3-5) of raw data. However, unusually long stays did infrequently occur, primarily during the first few intervals of sessions with sparse schedules. (These few long stays did not, of course, contribute much to the medians in Table III.)

To provide better evidence against such interpretations of the MF data, a synthetic "clustered" schedule was devised and run with P487, P489, and P490. This schedule (see above) presented occasional clusters of closely spaced food deliveries on each alternative. As seen in the sample stay time record for P490 (Figure 13), MF intervals occurred often in this condition. The medians across subjects in Figure 10 show that MF giving-up times averaged longer than all others, providing enough evidence to make "napping" accounts tenuous. These data thus strengthen the conclusion that animals use rate estimation methods that integrate events across time, not time-based rules.

Schedule versus Patch Performance

Two important differences appear between the data from this experiment and those from foraging studies. Both differences provide further evidence not only about the ways in which behavior in concurrent schedules differs from that in patches, but also on the nature of rate estimation and comparison processes more generally.

Absolute Giving-Up Times

All giving-up times in this experiment were shorter than one would predict if giving-up criteria, V_c , were based strictly upon average food rates. Most foraging studies (e.g., Krebs, et al, 1974) have found GUTs averaging close to the average interfood intervals, thus supporting a simple dependence of criteria to food rates. However, GUTs in the present experiment, while otherwise sharing the same overall relationships to density, were consistently much shorter than the average interfood times (Figure 9).

Several differences between concurrent schedules and patches may have contributed to this result. Among the most plausible explanations is that subjects may somehow take into account the fact that local food rates are momentarily high immediately after a switch in conc VI VI (see above and Dreyfus, et al, 1982;

Hinson & Staddon, 1983). If this were the case, then one possibility is that subjects simply raise switching criteria, V_c , to reflect higher apparent food rates. Higher criteria should then correspond to shorter giving-up times. For example, if rate estimation were along the lines of that shown in Figure 1, the monotonically decreasing estimates after entry or food would meet higher criteria sooner than lower ones.

This line of reasoning was explored in the present experiment by exposing P487, P489, and P490 to the conc VT 30 VT 30 condition. This schedule, by not "holding" food deliveries while subjects are away from alternatives, removes the spike of high food probability on entry to alternatives, resulting in constant food rates across time spent on alternatives.

Note that, because food rates are constant on these schedules, subjects should not switch at all to obtain maximal food rates. Subjects did however switch reliably. This fact alone appears to rule out accounts claiming that subjects switch exclusively on the basis of differences in momentary food probabilities (i.e., "momentary maximizing"; Shimp, 1969; Hinson & Staddon, 1983).

The results are shown in Figure 14 (sample stay times for P490) and Figure 10 (median GUTs). All giving-up times in this condition were longer than

those in the conc VI 60 VI 60 schedule, which provided nearly identical average food rates. In fact all categories of GUTs in the VT condition were longer than those in any VI condition, although still somewhat less than the average interfood interval.

The results are thus in general agreement with the idea that locally high food probabilities after switches affect giving-up criteria. Unfortunately, without further parametric manipulation of local food rates in concurrent schedules, no strong conclusions appear possible on just how criteria depend on schedule functions.

Asymmetrical Switching

As discussed above, foraging animals appear to have little a priori information on the quality of newly encountered patches, and foraging analyses (e.g., Oaten, 1977) usually assume that they use the same initial rate estimate, A^* , for each patch. Subjects in concurrent schedules, on the other hand, have many sources of specific information (i.e., external cues) which they may take advantage of in forming initial rate estimates for alternatives.

The data from this experiment demonstrate that subjects do take advantage of existing cues in forming rate estimates. This is evidenced by several features of concurrent performance, most obviously in the unequal giving-up times in the two alternatives of unequal schedules. Asymmetrical giving-up times are seen, for example, in Figure 11, comparing GUTs on the denser and sparser alternatives of 2:1 schedules. Figure 15 shows this phenomenon in more detail by plotting the ratios of GUTs across the two alternatives for intervals with food (IF, DF, and MF) and without food (NF), against obtained food ratios for all VI schedule conditions. While somewhat less orderly than the relationship between average stay ratios and food ratios (Figure 2), these show a similar trend.

According to the rate comparison model, unequal giving-up times should be due primarily to unequal A_j estimates upon entry to alternatives. Giving-up times in intervals without food (NF) are the most straightforward indicators of unequal A_j , since they reflect the application of A_j upon entry, followed by a rate updating process resulting in monotonically decreasing $V_j(t)$ estimates (because no food is encountered), until $V_j(t)$ falls below V_c , at which point subjects switch. Thus, if A_j estimates differ, even stays within intervals without food (equivalent to NF GUTs) should vary across unequal alternatives. The data in Figures 11 and 15 support this account; even NF GUTs were longer on the denser of two alternatives in unequal schedules.

An alternative explanation exists for this phenomenon. It is possible that switching criteria, rather than initial rate estimates, differ across unequal alternatives. However, the present data provide some (weak) evidence against this hypothesis: If A_j differ, then $V_j(t)$ should be maximally different on the two alternatives when no food is encountered, since food information is averaged into initially unequal $V_j(t)$, making them more similar. Thus NF GUTS should differ more extremely (i.e., display more extreme ratios across alternatives) than others. No such prediction appears to stem from the variable

criteria hypothesis.

The double-logarithmic slope in Figure 15 is 0.33 for NF GUTs, and 0.26 for the others. While these slopes do not differ statistically at the $p=0.05$ level of significance, they do show differences in the predicted direction. The results thus suggest that subjects do form unequal initial rate estimates on the two schedules. Again, since the presence of cues was not parametrically varied in this experiment, a complete account of how stimuli are used in estimating rate cannot be given here. However, a few characterizations of this process can be made.

The most notable feature of A_j is its apparent local stability. There is little evidence that A_j changes dynamically with recent patterns of food deliveries to an alternative. If A_j did change dynamically, then NF GUTs should be relatively long on alternatives where food had been obtained recently, since the rate on this alternative should appear momentarily higher.

Figure 16 shows that this phenomenon did not occur. It plots the percentages (to relativize across schedules) of overall median NF GUTs for NF GUTs on the left alternative within sequences of stays immediately following those in which food was obtained. (Those for the right alternative are not shown but similar.) The displayed GUTs are those in

stays not containing food that occurred between two that did contain food. Left NF GUTs are plotted for sequences after both left and right side food intervals. The data show only weak and inconsistent trends, and thus show the insensitivity of A_j to short-term fluctuations in local food rates.

A similar picture emerges from looking at schedule transition data. Figure 17 shows the daily median NF giving-up times during the transition from conc VI 240 VI 120 to conc VI 120 VI 480. Even though these conditions differed greatly, giving-up times display only slow daily changes. In fact, these data suggest that condition-wide stability in GUTs (and thus average stays) was not achieved even after seven sessions.

Comparing Bourland and Miller's (1981) data, from unsignalled alternatives, with the present results demonstrates that asymmetrical A_j must play a large role in determining the extent to which subjects display molar matching versus undermatching (or, at least the degree of undermatching found). Rate comparison processes that employ common A_j estimates across unequal alternatives do not appear compatible with matching. Moreover, if unequal A_j estimates are used, molar evidence alone argues that they are stable across time. Otherwise, it would be improbable for molar matching to reliably occur in typical VI

schedules that include large random fluctuations in food rates across time.

CHAPTER III

CONCLUSIONS

The results of this experiment provide reasons to believe that a rate comparison model of schedule and patch performance may well be successful in accounting for the ways in which animals switch between alternative food sources. To summarize the major results concerning the model:

(1) Giving-up times display regular, consistent trends that show them to be natural units of analysis in the study of concurrent performance, perhaps more so in continuous-response than discrete-response schedules.

(2) Giving-up times increase with decreasing overall food rates, indicating the dependence of switching criteria on overall density.

(3) Giving-up times are longer in intervals including food presentations than in those without food, and longer still in intervals with multiple food presentations. These results support models claiming that switching is controlled by estimates of food rates, not merely by times since food encounters.

(4) Giving-up times are shorter in schedules where food rates are momentarily high immediately after a switch (i.e., conc VI VI) than in those where

food rates are constant (conc VT VT). This shows that switching criteria are sensitive to at least some local features of food rate functions.

(5) Giving-up times in unequal conc VI VI schedules come to be longer in the denser than in the sparser of the two alternatives, implying that subjects form different initial rate estimates (A_j) for the two alternatives. These initial estimates appear to change relatively slowly through time.

The data from this experiment are not entirely unique in demonstrating several features of the model in concurrent schedules. Aspects of studies by Menlove (1975), Silberberg, Hamilton, Zirrax, and Casey (1978), Real (1979), and Baum (1982) all include data consistent with some of the results reported here. An apparent exception is Hinson and Staddon (1983), who report a failure to obtain a "positive recency effect" of reinforcement upon responding in a different conc VI VI procedure. However, their conclusions were based on trends in keypecks to the alternatives, not stay times. Because stay times are difficult even to define in their procedure, which provided no significant spatial or temporal separation of the alternatives, it is difficult to determine whether the two sets of results actually conflict. Moreover, it seems likely that analyses of the local effects of reinforcement on subsequent behavior based on discrete responses may

well produce different results than those based on stay times, due to such phenomena as the post-reinforcement pause in response patterns (Zeiler, 1977), as well as the differences in behavior in the continuous versus discrete response conditions shown in this experiment (Figures 3-8).

The present results show that some form of linear operator model remains highly plausible. While the model as stated cannot account for results (4) and (5), it is otherwise generally consistent with observed trends. Moreover, introducing asymmetrical A_j estimates may prove to be a straightforward extension. The data are compatible with the idea that the A_j themselves vary according to a separate, concurrent rule,

$$A_j(t) = \alpha X(t) + (1-\alpha)A_j(t-1),$$

with $\alpha \ll \beta$ (i.e., a linear operator rule with a very slow memory parameter). In fact, this sort of stimulus-related processes can be seen as a variation of Rescorla and Wagner's (1972) account of stimulus effects, and may turn out to be explicable within their theory (cf., Vaughan, 1982). Unfortunately, it is impossible to make a case for this hypothesis given the meager data currently available on this issue.

The observed sensitivity of switching criteria to momentary food rates after switches may be a greater

challenge to the model. Further empirical results seem necessary before a serious attempt can be made to account for these data. Experiments showing the nature of this phenomenon in situations offering more than two alternatives, and in those where the schedule type encountered after each switch is unknown to the subject (e.g., probabalistically arranged) would be especially useful. In the absence of such data, several possibilities appear equally likely. The most obvious of these is that the idea of a single criterion breaks down in situations involving a fixed number of signalled alternatives (cf., McNair, 1982), in favor of direct comparisons incorporating both global food rates and anticipated rates after switching. Support for such modifications await further study.

Despite such uncertainties, this work has provided some molecular support for more molar theories like Herrnstein and Vaughan's (1980; Killeen, 1972; Rachlin, 1973) involving equalization. Perhaps its most important contribution in this regard is to show more clearly (cf., Baum, 1974; Bourland & Miller, 1981) how the continuum from undermatching to overmatching is interpretable as arising from differences in the means by which subjects combine stimulus and reinforcement rate information into a common estimate.

The model shares other features with molar views of performance. The role of $V_j(t)$, presented here in terms of rate estimation bears similarities with that of "value" in molar accounts (e.g., Rachlin, 1978). In fact, the model claims that value has short-term dynamic properties involved in deciding when to leave an alternative, as well as more stable, long-term components seen in the slowly changing character of A_j . Such correspondences may help close the current gap between molecular and molar views of schedule performance.

REFERENCES

- Baum, W. M. On two types of deviations from the matching law: bias and undermatching. *Journal of the Experimental Analysis of Behavior*, 1974, 22, 231-242.
- Baum, W. M. Matching, undermatching, and overmatching in studies of choice. *Journal of the Experimental Analysis of Behavior*, 1979, 32, 269-281.
- Baum, W. M. Choice, changeover, and travel. *Journal of the Experimental Analysis of Behavior*, 1982, 38, 35-49.
- Baum, W. M. & Rachlin, H. C. Choice as time allocation. *Journal of the Experimental Analysis of Behavior*, 1969, 12, 861-874.
- Bourland, G., & Miller, R. The role of discriminative stimuli in concurrent performances. *Journal of the Experimental Analysis of Behavior*, 1981, 36, 231-240.
- Bush, R. R., & Mosteller, F. *Stochastic models for learning*. N.Y.: Wiley, 1955.
- Charnov, E. L. Optimal foraging: the marginal value theorem. *Theoretical Population Biology*, 1976, 9, 129-136.
- Cowie, R. J. Optimal foraging in great tits. *Nature*, 1977, 268, 137-139.
- Cowie, R. J., & Krebs, J. R. Optimal foraging in patchy environments. In P. Marler & J. G. Vandenberg (Eds.) *Handbook of behavioral neurobiology, Vol. 3, Social behavior and communication*. N.Y.: Plenum, 1980.
- deVilliers, P. Choice in concurrent schedules and a quantitative formulation of the law of effect. In W. K. Honig & J. E. R. Staddon (Eds.) *Handbook of operant behavior*. Englewood Cliffs, N.J.: Prentice Hall, 1977.
- Dreyfus, L. R., Dorman, L. G., Fetterman, J. G., & Stubbs, D. A. An invariant relation between changing over and reinforcement. *Journal of the Experimental Analysis of Behavior*, 1982, 38, 327-338.
- Gibbon, J. Scalar expectancy theory and Weber's law in animal timing. *Psychological Review*, 1977, 84, 279-325.

Gibbon, J., Berryman, R., & Thompson, R. L. Contingency spaces and measures in classical and instrumental conditioning. Journal of the Experimental Analysis of Behavior, 1974, 21, 585-605.

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

Green, R. F. Bayesian birds: a simple example of Oaten's stochastic model of optimal foraging. Theoretical Population Biology, 1980, 18, 244-256.

Harley, C. B. Learning the evolutionary stable strategy. Journal of Theoretical Biology, 1981, 89, 611-633.

Herrnstein, R. J. On the law of effect. Journal of the Experimental Analysis of Behavior, 1970, 13, 243-266.

Herrnstein, R. J., & Vaughan, W. Melioration and behavioral allocation. In J. E. R. Staddon (Ed.) Limits to action. N.Y.: Academic Press, 1980.

Heyman, G. M. Markov description of changeover probabilities on concurrent variable-interval schedules. Journal of the Experimental Analysis of Behavior, 1979, 31, 41-51.

Heyman, G. M. & Luce, R. D. Operant matching is not a logical consequence of maximizing reinforcement rate. Animal Learning and Behavior, 1979, 7, 133-140.

Hinson, J. M., & Staddon, J. E. R. Hill-climbing by pigeons. Journal of the Experimental Analysis of Behavior, 1983, 39, 25-47.

Houston, A. I. The control of foraging decisions. Paper presented at Sixth Harvard symposium on quantitative analyses of behavior. June, 1983.

Houston, A. I., & McNamara, J. How to maximize reward rate on two variable-interval paradigms. Journal of the Experimental Analysis of Behavior, 1981, 35, 367-396.

Killeen, P. A yoked-chamber comparison of concurrent and multiple schedules. Journal of the Experimental Analysis of Behavior, 1972, 18, 13-22.

Killeen, P. Averaging theory. In C. M. Bradshaw, E. Szabadi, & C. F. Lowe (Eds.) Quantification of steady-state operant behavior. N.Y.: Elsevier North Holland, 1981.

Krebs, J. R. Optimal foraging: decision rules for predators. In J. R. Krebs & N. B. Davies (Eds.) Behavioral ecology: an evolutionary perspective. Sunderland, Mass.: Sinauer, 1978.

Krebs, J. R., Houston, A. I., & Charnov, E. L. Some recent developments in optimal foraging. In A. C. Kamil & T. D. Sargent (Eds.) Foraging behavior. N.Y.: Garland Press, 1981.

Krebs, J. R., Ryan, J. C., & Charnov, E. L. Hunting by expectation or optimal foraging? A study of patch use by chickadees. Animal Behavior, 1974, 22, 953-964.

McNair, J. N. Optimal giving-up times and the marginal value theorem. American Naturalist, 1982, 119, 511-529.

McNamara, J. Optimal patch use in a stochastic environment. Theoretical Population Biology, 1982, 21, 269-288.

McNamara, J., & Houston, A. I. The Application of statistical decision theory to animal behavior. Journal of Theoretical Biology, 1980, 85, 673-690.

McSweeney, F. K., Melville, C. L. Buck, M. A., & Whipple, J. E. Local rates of responding during concurrent schedules. Journal of the Experimental Analysis of Behavior, 1983, 40, 79-9.

Menlove, R. L. Local patterns of responding maintained by concurrent and multiple schedules. Journal of the Experimental Analysis of Behavior, 1975, 23, 309-337.

Myers, D. L. & Myers, L. E. Undermatching: a reappraisal of performance on concurrent variable-interval schedules of reinforcement. Journal of the Experimental Analysis of Behavior, 1977, 28, 203-214.

Nevin, J. A. Interval reinforcement of choice behavior in discrete trials. Journal of the Experimental Analysis of Behavior, 1969, 12, 875-885.

Nevin, J. A., & Baum, W. M. Feedback functions for variable-interval reinforcement. Journal of the Experimental Analysis of Behavior, 1980, 34, 207-217.

Oaten, A. Optimal foraging in patches: a case for stochasticity. Theoretical Population Biology, 1977, 12, 263-285.

Olton, D. S., Handelmann, G. E., & Walker, J. A. Spatial memory and food searching strategies. In A. C. Kamil & T. D. Sargent (Eds.) *Foraging behavior*. N.Y.: Garland, 1981.

Pliskoff, S., & Fetterman, J. G. Undermatching and overmatching: the fixed ratio changeover requirement. *Journal of the Experimental Analysis of Behavior*, 1981, 36, 21-28.

Pulliam, H. R. The acquisition of choice probabilities. Paper presented at *Sixth Harvard Symposium on quantitative analyses of behavior*, June, 1983.

Pyke, G. H., Pulliam, H. R., & Charnov, E. L. Optimal foraging: a selected review of theory and tests. *Quarterly Review of Biology*, 1977, 52, 137-154.

Rachlin, H. C. Contrast and Matching. *Psychological Review*, 1973, 80, 27-234.

Rachlin, H. C. A Molar theory of reinforcement schedules. *Journal of the Experimental Analysis of Behavior*, 1978, 30, 345-360.

Real, P. G. An analysis of the temporal pattern of changeover responses and reinforcement during concurrent performance. Paper presented to the *Eastern Psychological Association*, Philadelphia, Pennsylvania, 1979.

Rescorla, R. A., & Wagner, A. R. A Theory of Pavlovian conditioning: variations in the effectiveness of reinforcement and nonreinforcement. In A. H. Black & W. F. Prokasy (Eds.) *Classical conditioning II: Current research and theory*. N.Y: Appleton-Century-Crofts, 1972.

Revusky, S. H. A Relationship between responses per reinforcement and performance during concurrent VI VI. *Journal of the Experimental Analysis of Behavior*, 1963, 6, 518.

Shimp, C. P. Probabilistically reinforced choice behavior in pigeons. *Journal of the Experimental Analysis of Behavior*, 1966, 9, 443-455.

Shimp, C. P. Optimal behavior in free operant experiments. *Psychological Review*, 1969, 76, 97-112.

Silberberg, A., Hamilton, B. Ziriax, J. M., & Casey, J. The structure of choice. Journal of Experimental Psychology: Animal Behavior Processes, 1978, 4, 368-398.

Staddon, J. E. R. Optimality analyses of operant behavior and their relation to optimal foraging. In J. E. R. Staddon (Ed.) Limits to action. N.Y.: Academic Press, 1980.

Staddon, J. E. R., Hinson, J. M., & Kram, R. Optimal choice. Journal of the Experimental Analysis of Behavior, 1981, 35, 397-414.

Stubbs, D. A., & Pliskoff, S. Concurrent responding with fixed relative rate of reinforcement. Journal of the Experimental Analysis of Behavior, 1969, 12, 887-895.

Vaughan, W. Melioration, matching, and maximization. Journal of the Experimental Analysis of Behavior, 1981, 36, 141-150.

Vaughan, W. Choice and the Rescorla-Wagner model. In Commons, M. L. & Herrnstein, R. J. (Eds.) Quantitative analyses of behavior, Vol. II, Matching and maximizing accounts. Cambridge, MA: Balinger, 1982.

Wearden, J. H., & Burgess, I. S. Matching since Baum (1979). Journal of the Experimental Analysis of Behavior, 1982, 38, 339-348.

Zach, R. & Smith, J. N. M. Optimal foraging in wild birds? In A. C. Kamil & T. D. Sargent (Eds.) Foraging behavior. N.Y.: Garland, 1981.

Zeiler, M. D. Schedules of reinforcement: the controlling variables. In W. K. Honig & J. E. R. Staddon (Eds.) Handbook of operant behavior. Englewood Cliffs, N.J.: Prentice Hall, 1977.

TABLE I

Experimental Conditions

VI schedule (sec)		Order
Left	Right	
30	240	4
60	240	5
120	240	7
30	30	14
60	60	3
120	120	6
240	240	13
60	30	11
120	60	10
240	120	12
480	120	9
480	60	8
Discrete VI	VI	15
VT 30	VT 30	2
Clustered		1

TABLE II

Least squares fits to generalized matching

Subject	Slope	Intercept	VAC
P487	0.42	-0.08	0.92
P489	0.44	0.03	0.87
P490	0.41	0.05	0.94
P355	0.49	-0.12	0.91
Group	0.45	-0.03	0.96

TABLE III
Giving Up Times and Stays^a

P487											
LEFT						RIGHT					
NF	IF	DF	MF	Stay	Schedule	NF	IF	DF	MF	Stay	
76	96	84	115	98	30	240	40	75	53	--	45
58	79	94	123	73	60	240	46	78	93	--	49
85	98	98	111	99	120	240	69	61	68	90	74
24	28	25	34	27	30	30	31	33	40	31	35
28	34	31	50	29	60	60	36	39	36	61	38
48	63	68	98	55	120	120	50	43	41	66	54
63	95	102	--	81	240	240	81	104	100	--	100
24	26	25	28	25	60	30	41	33	31	40	43
26	31	25	40	28	120	60	44	40	43	62	46
39	54	56	74	44	240	120	66	56	59	59	70
45	85	68	--	52	480	120	66	70	65	154	90
36	39	71	--	39	480	60	78	141	144	188	107
60	45	80	126			Discrete	47	30	30	43	
98	142	114	158			VT	143	184	178	196	
64	160	110	209			Clustered	152	155	201	241	

TABLE III, continued

LEFT					P489		RIGHT				
NF	IF	DF	MF	Stay	Schedule		NF	IF	DF	MF	Stay
--	--	--	--	--	30	240	--	--	--	--	--
32	44	41	45	51	60	240	18	30	29	--	19
36	44	58	--	38	120	240	25	36	--	--	29
18	25	32	28	19	30	30	18	21	20	25	20
20	31	26	29	22	60	60	19	25	25	30	24
34	40	39	46	38	120	120	28	38	34	55	34
33	44	50	--	39	240	240	36	45	48	--	44
21	20	23	25	23	60	30	27	33	40	36	29
21	29	35	35	24	120	60	29	36	41	51	37
24	31	34	--	24	240	120	30	40	39	42	31
28	38	28	--	31	480	120	35	64	56	82	50
23	35	34	--	24	480	60	35	46	39	50	47
--	--	--	--			Discrete	--	--	--	--	
38	92	82	103			VT	39	89	75	94	
40	73	77	74			Clustered	52	109	137	114	

TABLE III, continued

LEFT					P490		RIGHT				
NF	IF	DF	MF	Stay	Schedule		NF	IF	DF	MF	Stay
60	85	79	90	78	30	240	29	36	40	--	30
54	90	93	103	65	60	240	33	48	38	--	35
60	91	70	104	70	120	240	41	79	69	97	48
33	28	23	29	31	30	30	25	23	22	25	27
40	46	44	47	45	60	60	33	29	23	24	33
56	81	74	85	62	120	120	44	49	49	87	46
60	91	81	--	66	240	240	66	91	78	--	80
35	32	30	36	39	60	30	45	50	46	58	50
38	46	33	38	40	120	60	46	66	56	87	49
49	50	52	--	53	240	120	59	85	79	89	70
45	78	77	--	53	480	120	69	116	128	162	80
39	50	61	--	40	480	60	60	90	87	113	69
48	39	38	39			Discrete	31	30	35	70	
55	100	93	99			VT	72	102	94	106	
68	130	83	184			Clustered	78	118	144	169	

TABLE III, continued

P355											
LEFT					RIGHT						
NF	IF	DF	MF	Stay	Schedule	NF	IF	DF	MF	Stay	
48	63	65	81	65	30	240	29	51	50	--	34
41	74	66	68	46	60	240	22	71	95	--	28
31	61	--	--	46	120	240	30	58	60	--	34
24	33	30	34	31	30	30	33	60	56	88	44
26	43	43	81	31	60	60	38	53	71	119	56
29	45	57	46	32	120	120	37	45	63	86	40
34	57	60	--	39	240	240	47	103	119	140	59
29	34	33	38	33	60	30	53	69	69	76	60
29	43	53	60	30	120	60	55	93	90	111	74
30	53	50	70	33	240	120	54	75	80	136	66
21	60	--	--	24	480	120	41	71	80	95	53
24	52	60	--	26	480	60	59	80	74	94	79
58	75	53	119			Discrete	40	63	59	101	

^aNote: Giving up times are medians, in tenths of seconds, over the last three sessions of conditions. Medians were not computed for categories occurring in less than two of the last three sessions. Stays are medians of means for the last three days. Mean stays were only computed for continuous VI schedules. See text for abbreviations.

FIGURE CAPTIONS

Figure 1. The rate comparison model. The form and height of the rate estimation function after entry and food encounters is drawn in accord with a linear operator rule.

Figure 2. Average stay time ratios versus food (reinforcement) rate ratios for VI schedules, averaged across subjects. The line is the least-squares fit.

Figure 3. Sample records of stay times (in seconds) for P490 in equal conc VI VI schedules: (a) VI 30 VI 30; (b) VI 60 VI 60; (c) VI 120 VI 120; (d) VI 240 VI 240. See text for explanation.

Figure 4. Sample records of stay times for P487, P489, and P355 in equal conc VI VI schedules: (a) P487 in VI 30 VI 30; (b) P489 in VI 60 VI 60; (c) P355 in VI 120 VI 120.

Figure 5. Sample records of stay times for P490 in the unequal conc VI VI conditions: (a) VI 30 VI 240; (b) VI 60 VI 240; (c) VI 120 VI 240; (d) VI 60 VI 30; (e) VI 120 VI 60; (f) VI 240 VI 120; (g) VI 480 VI 120; (h) VI 480 VI 60.

Figure 6. Sample daily stay time histograms for P490 in equal conc VI VI conditions: (a) VI 30 VI 30 (b) VI 60 VI 60; (c) VI 120 VI 120; (d) VI 240 VI 240. See text for explanation.

Figure 7. Sample record of stay times for P490 in discrete response conc VI 30 VI 30.

Figure 8. Sample daily stay time histogram for P490 in discrete response conc VI 30 VI 30.

Figure 9. Giving-up times, averaged across alternatives for the conc VI VI conditions.

Figure 10. Giving-up times in equal concurrent schedules: (a) Group average; (b) P487; (c) P489; (d) P490; (e) P355.

Figure 11. Giving-up times on schedules with 2:1 food ratios: (a) Group average; (b) P487; (c) P489; (d) P490; (e) P355.

Figure 12. Relationships between median giving-up times (in seconds) across all conc VI VI schedules: (a) Immediate food vs. no food; (b) Delayed food vs. immediate food; (c) Multiple food vs. delayed food. Diagonal lines indicate points of equality.

Figure 13. Sample record of stay times for P490 in a synthetic clustered schedule.

Figure 14. Sample record of stay times for P490 in conc VT 30 VT 30.

Figure 15. Giving-up time ratios versus food rate ratios, averaged across subjects.

Figure 16. Average percent of the median left NF stay for NF intervals immediately following a stay containing food on the left or right. One sample is shown for each subject.

Figure 17. Session-by-session transition from conc VI 240 VI 240 to conc VI 120 VI 480, averaged across subjects.

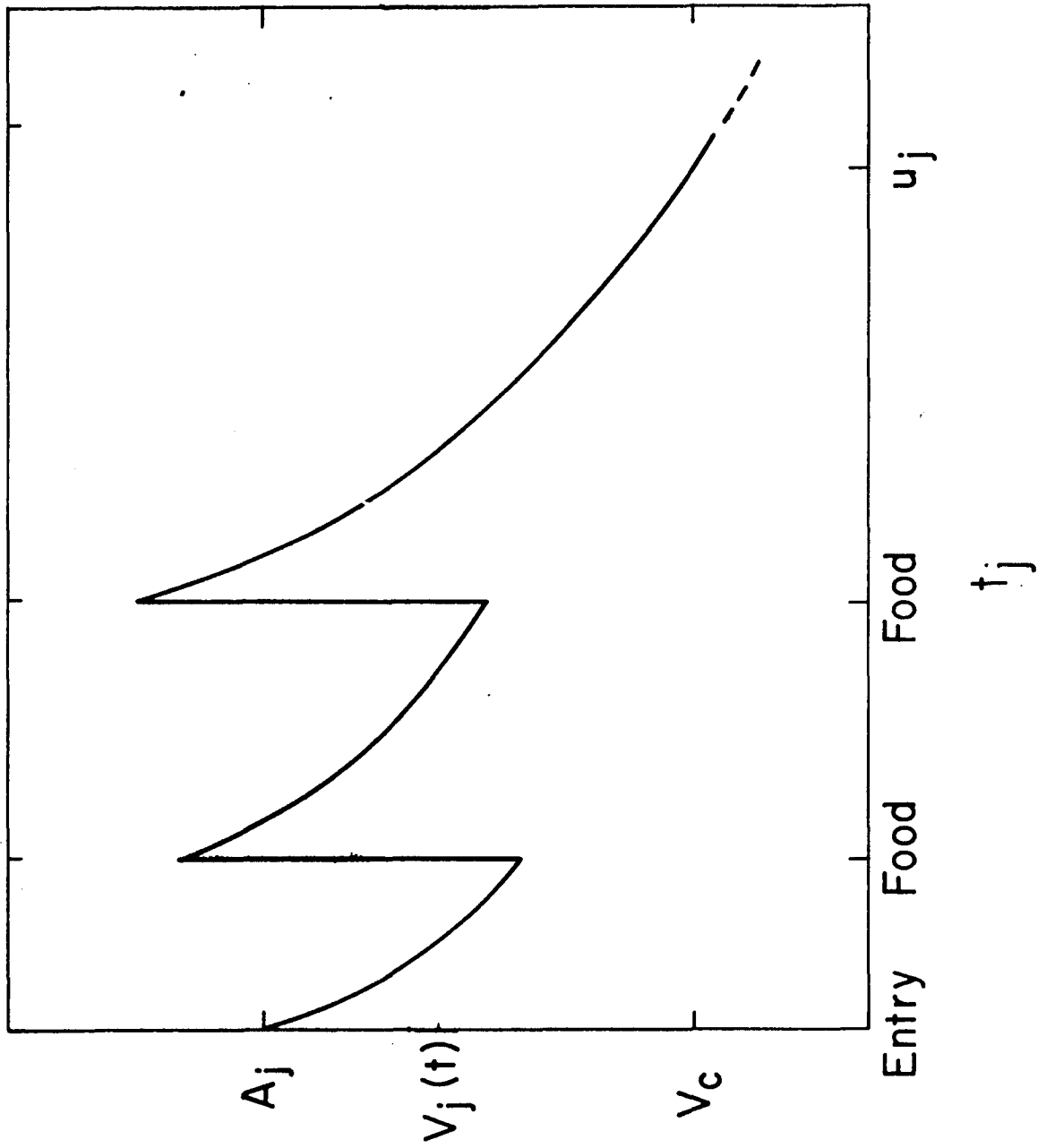
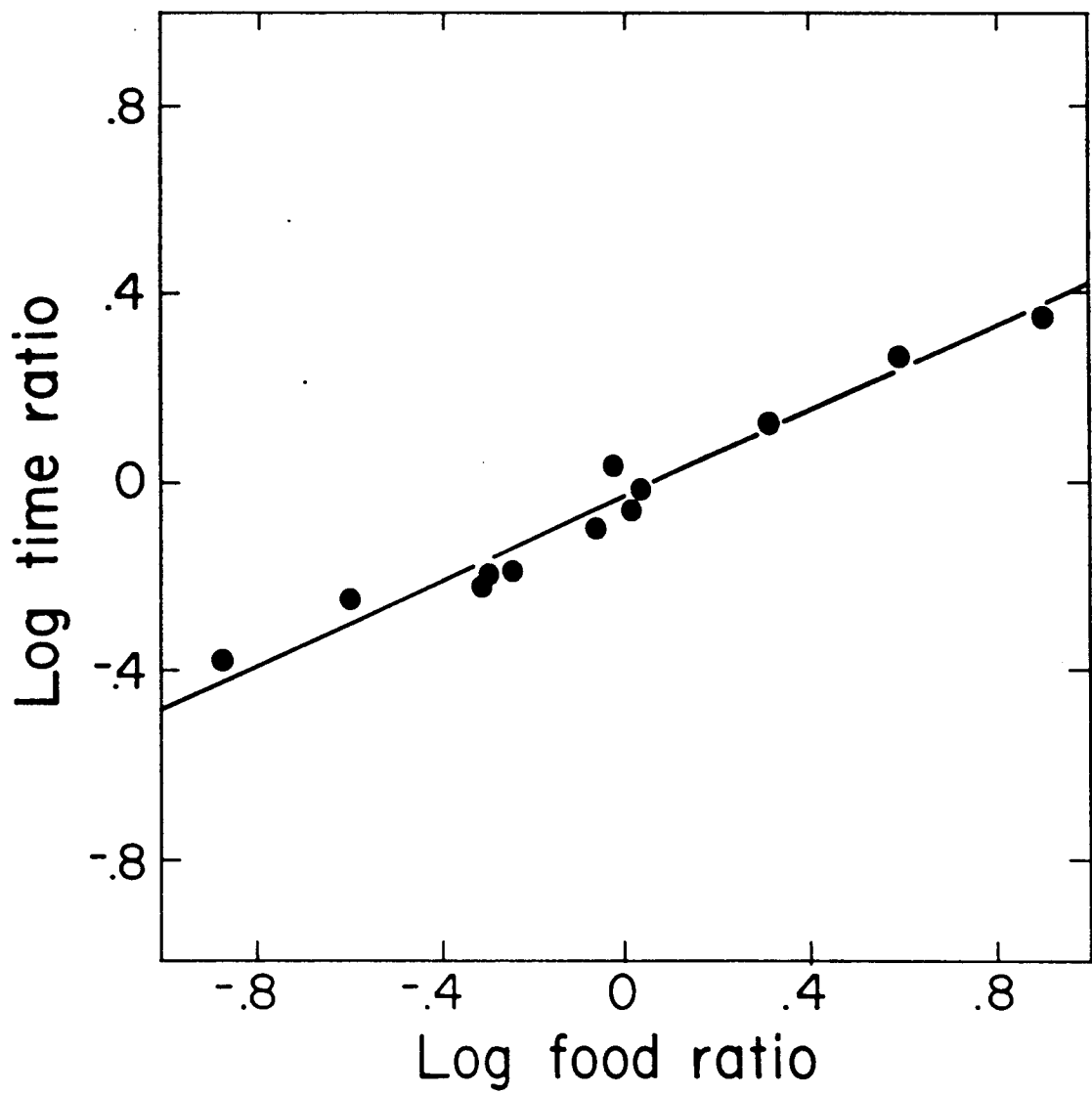


Figure 1.

Figure 2.



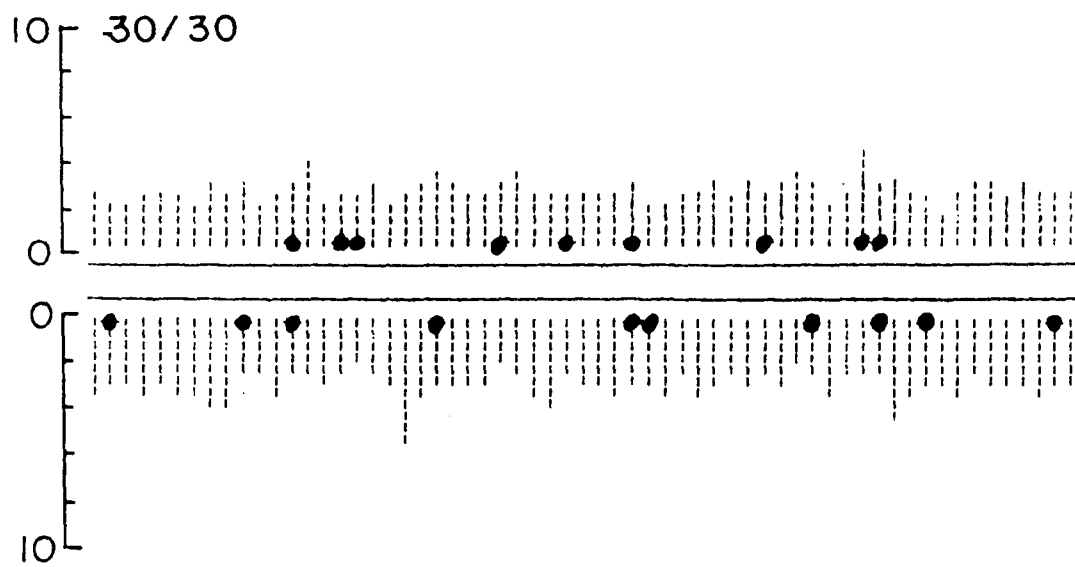


Figure 3a.

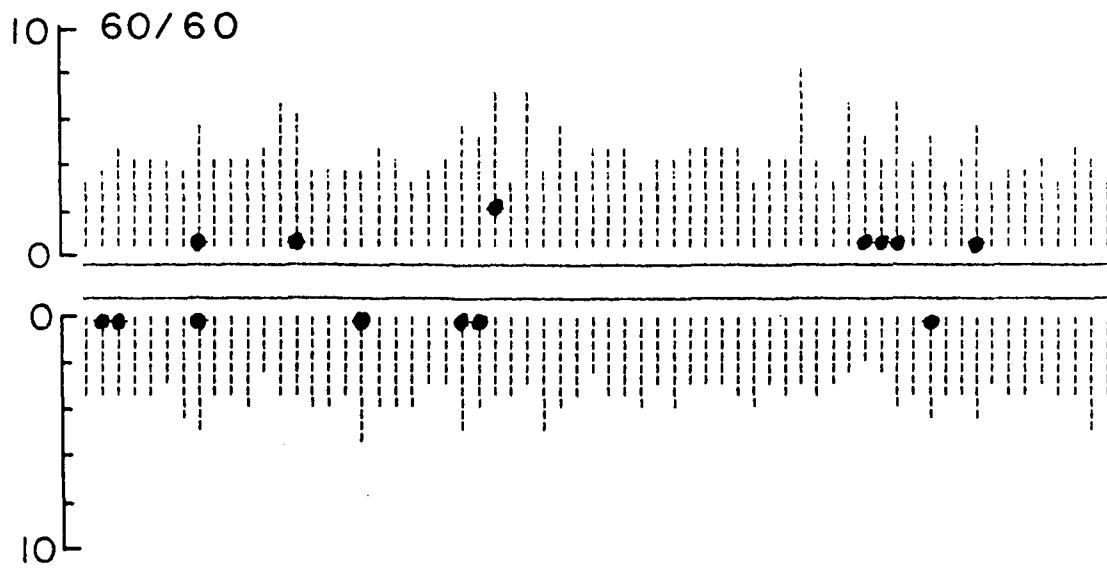


Figure 3b

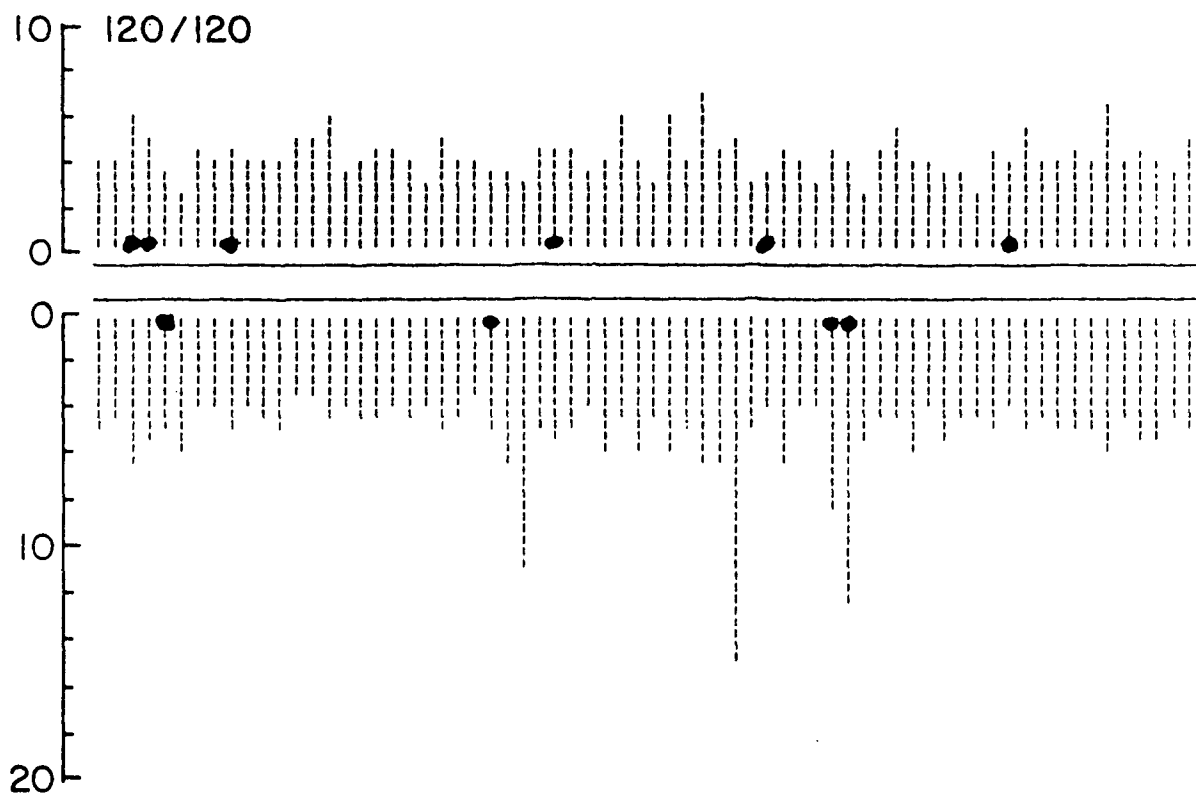


Figure 3c.

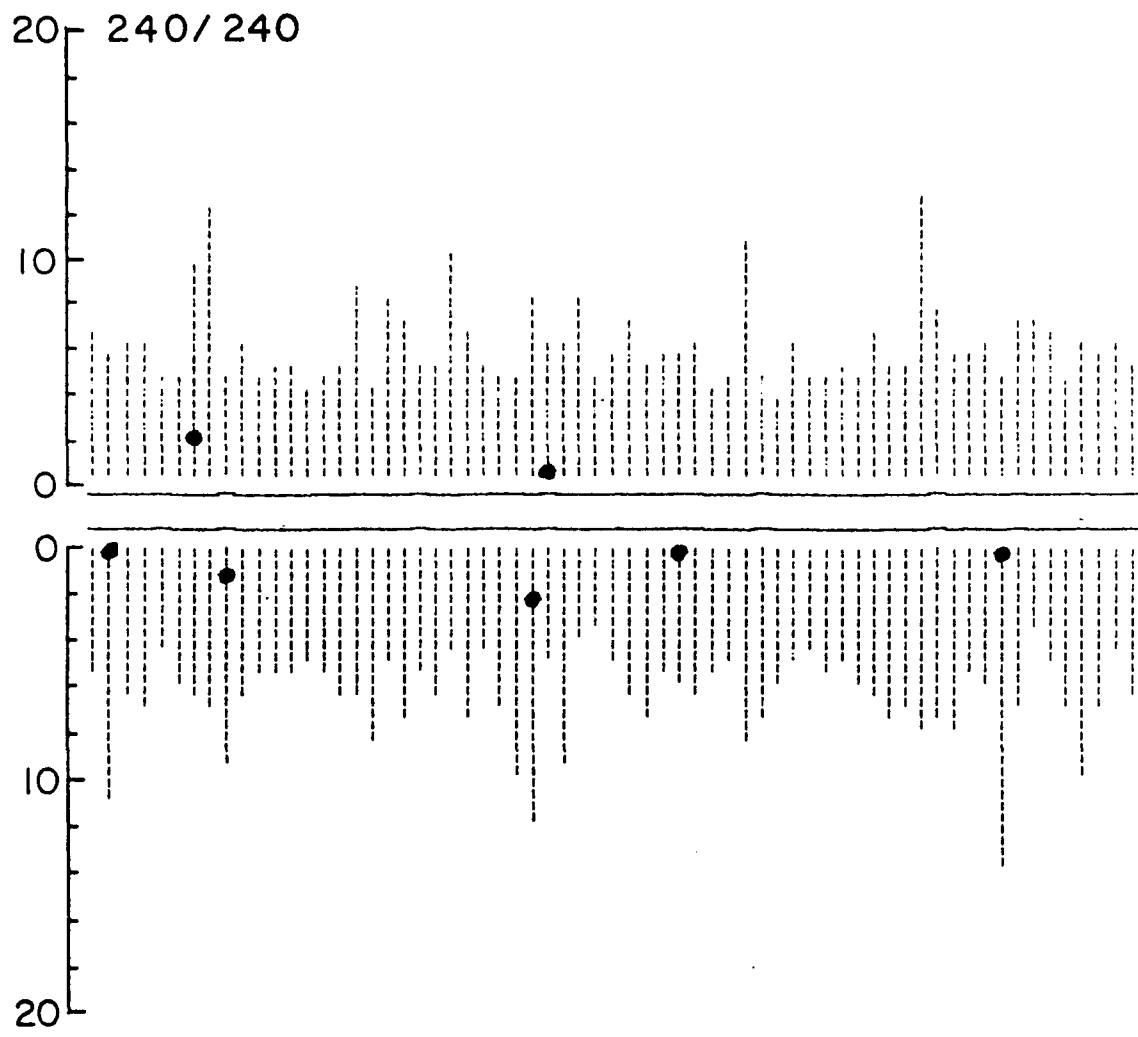


Figure 3d.

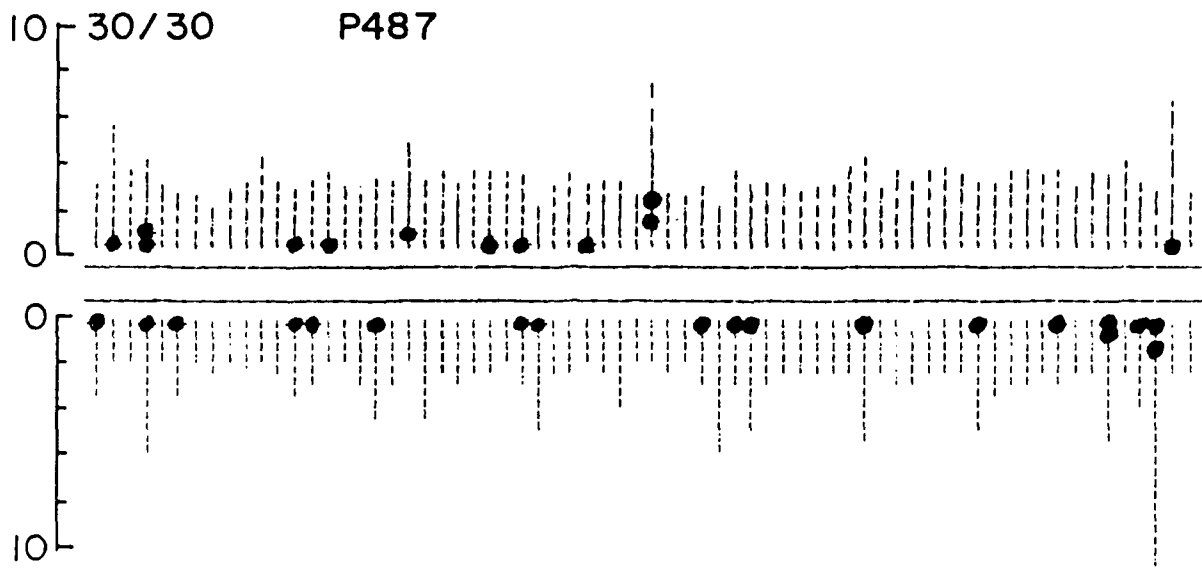


Figure 4a.

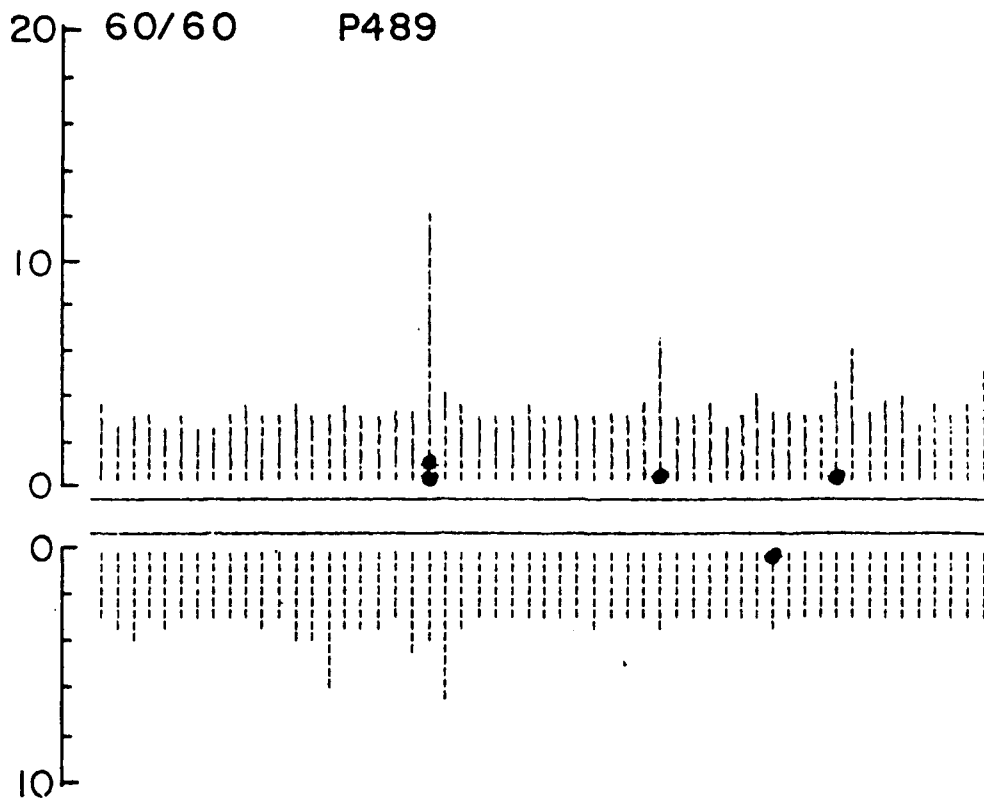


Figure 4b.

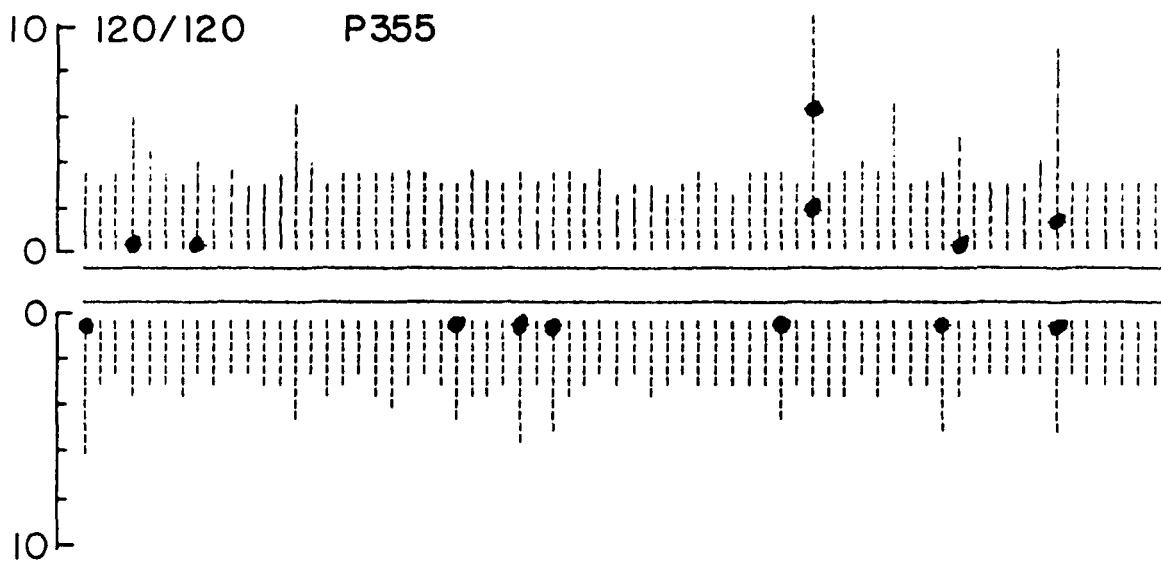


Figure 4c.

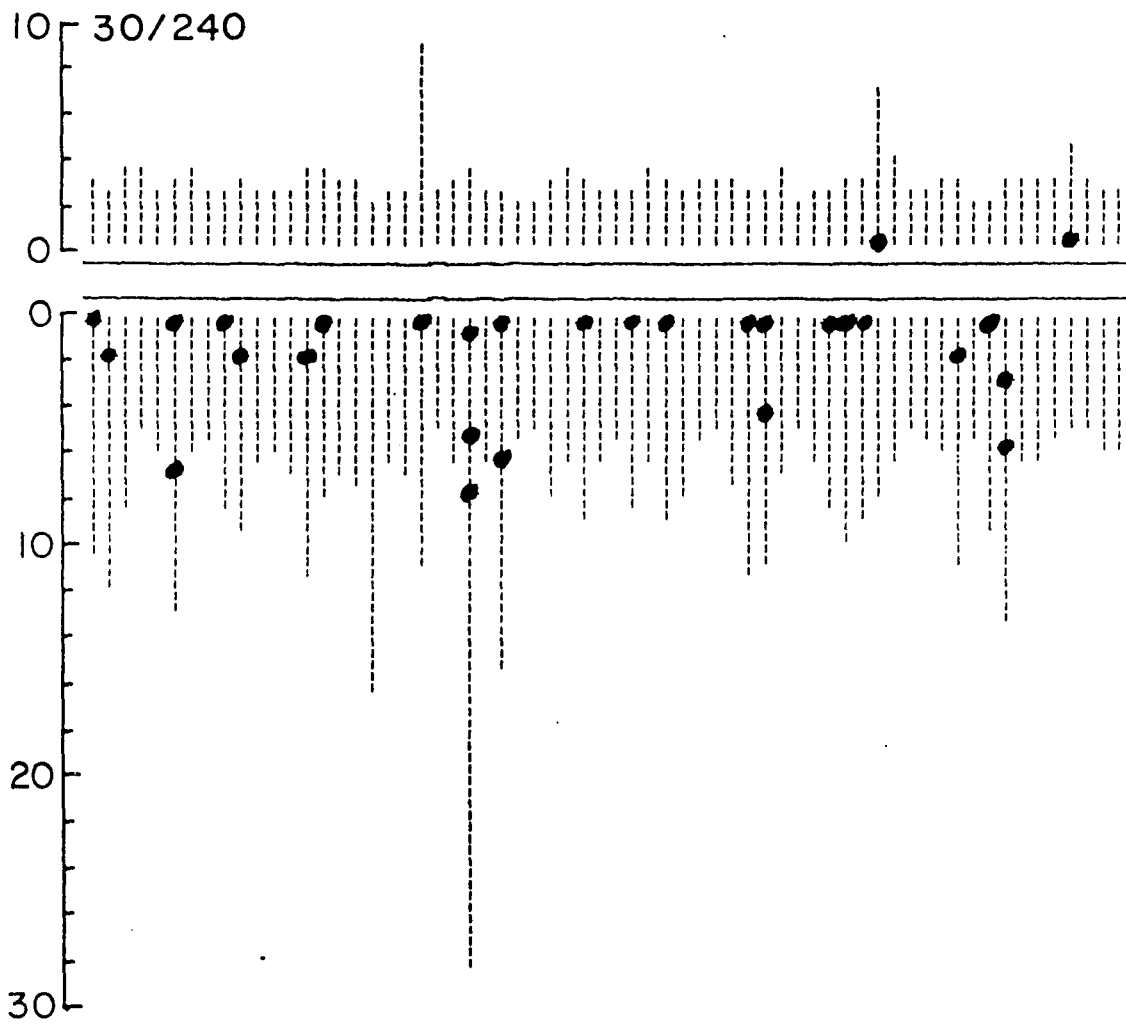


Figure 5a.

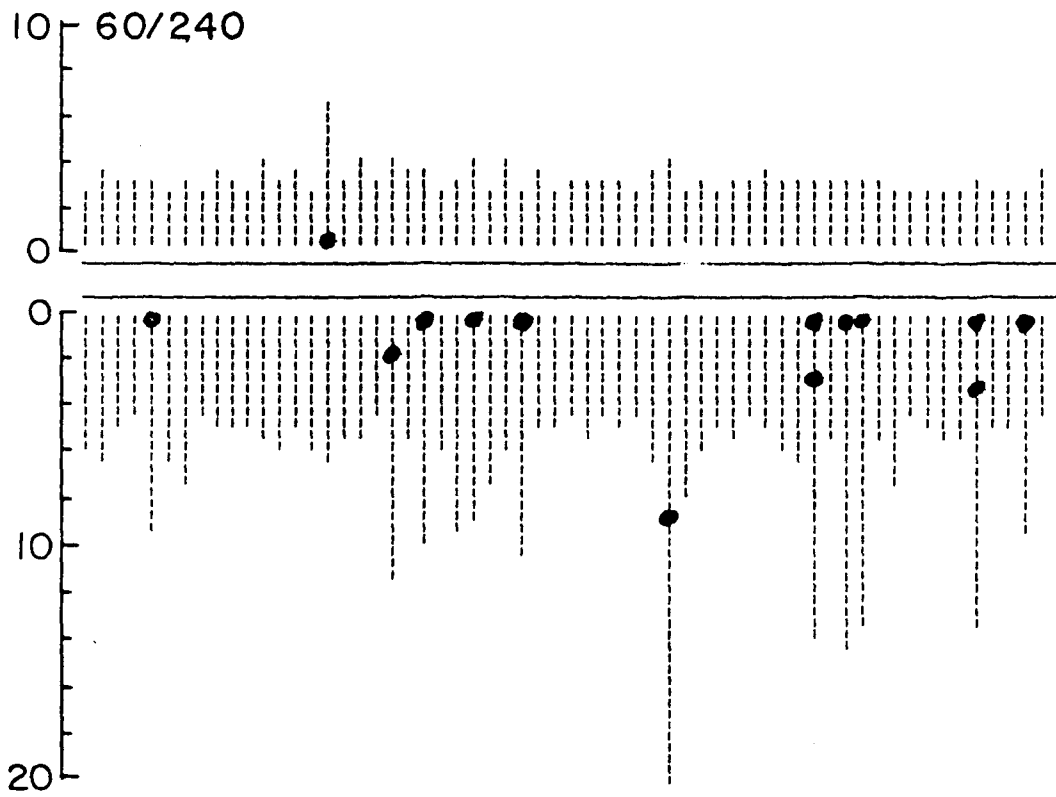


Figure 5b.

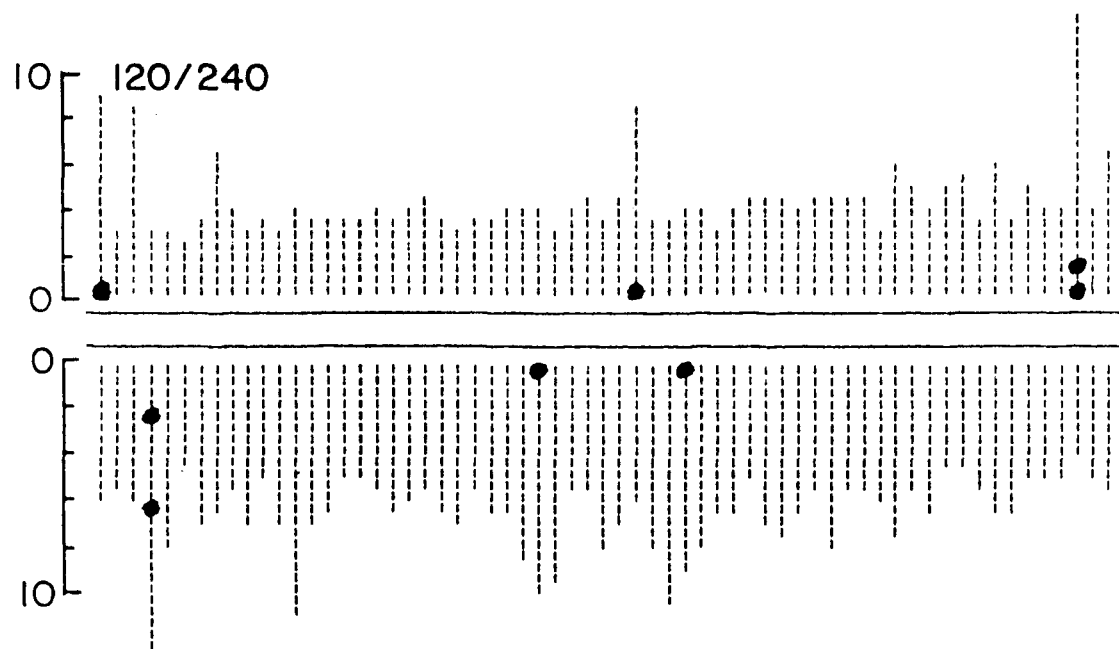


Figure 5c.

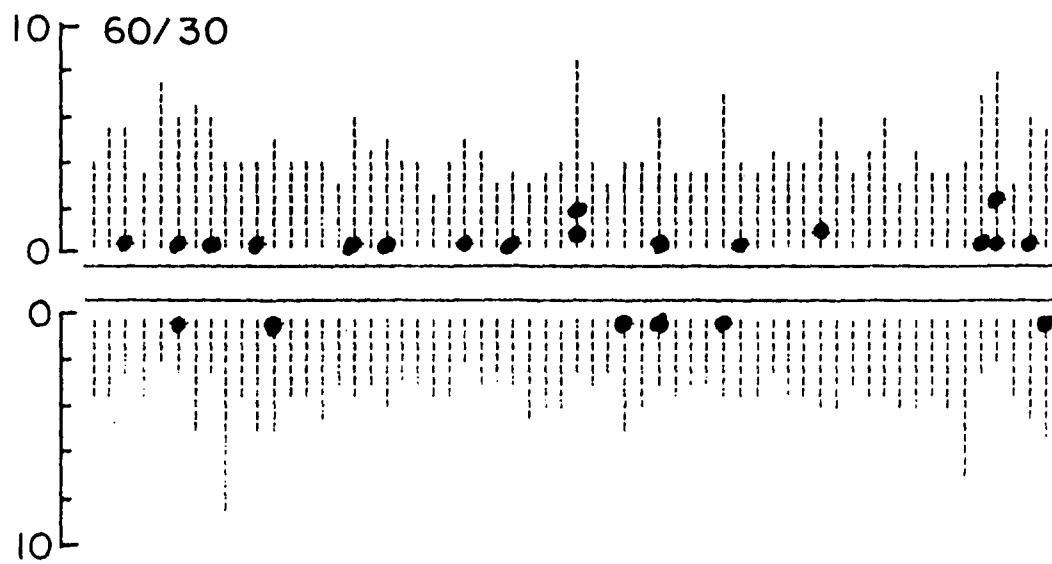


Figure 5d.

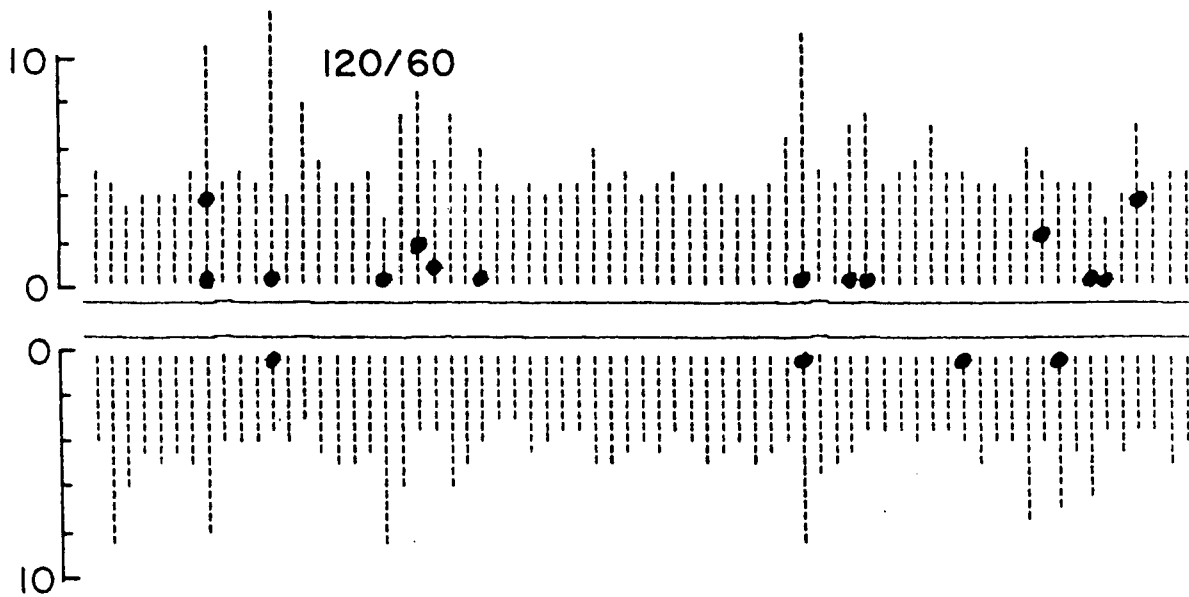


Figure 5e.

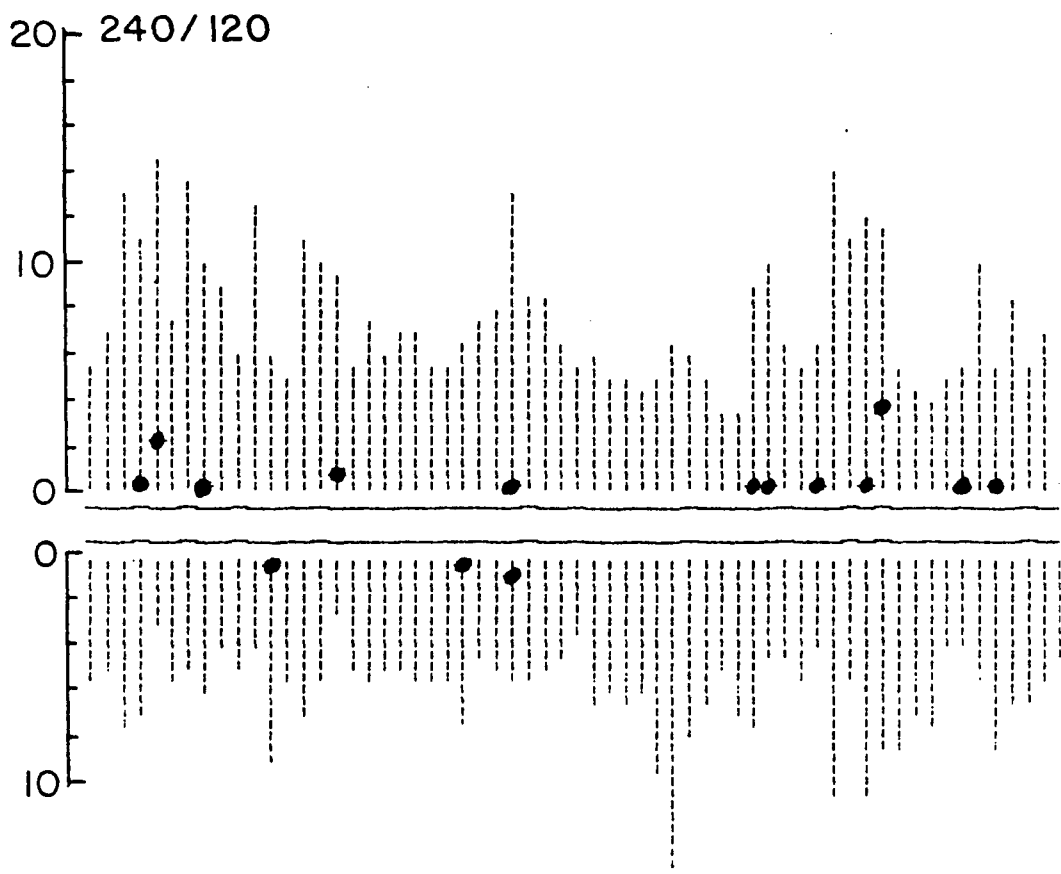


Figure 5f

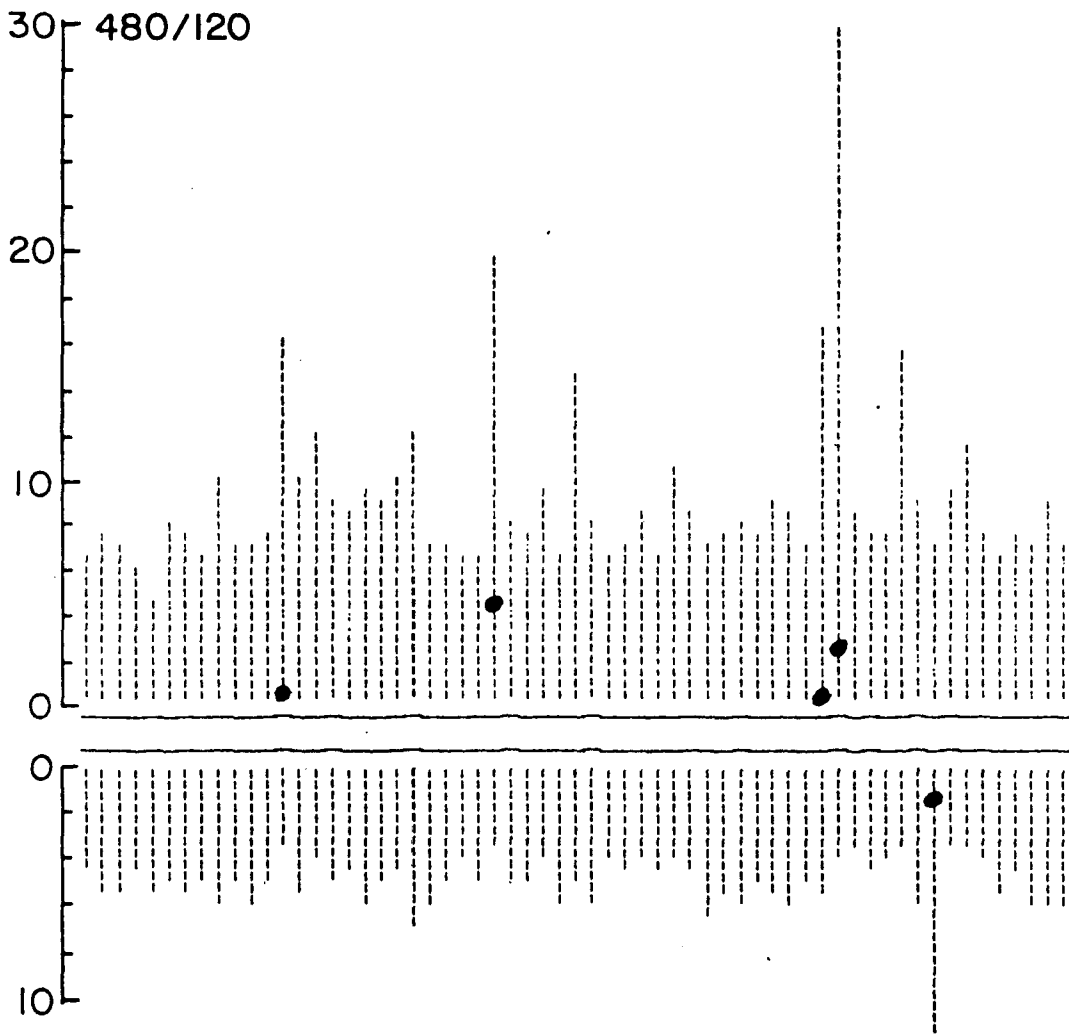


Figure 5g.

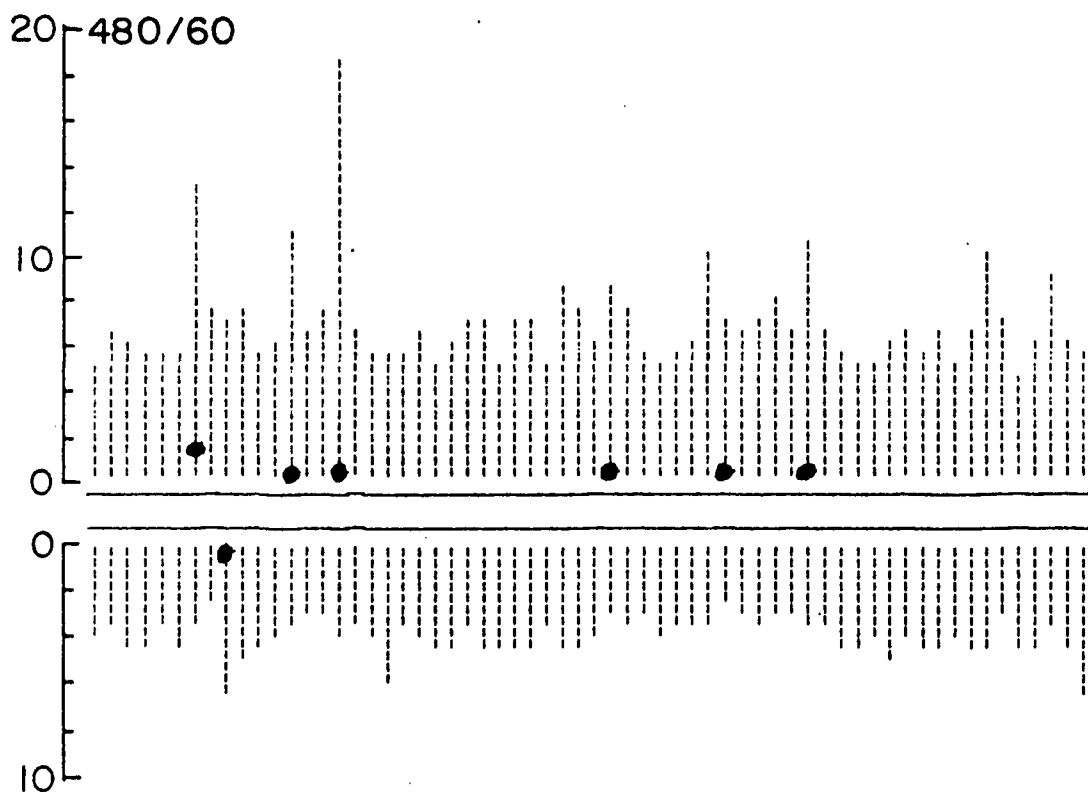


Figure 5h.

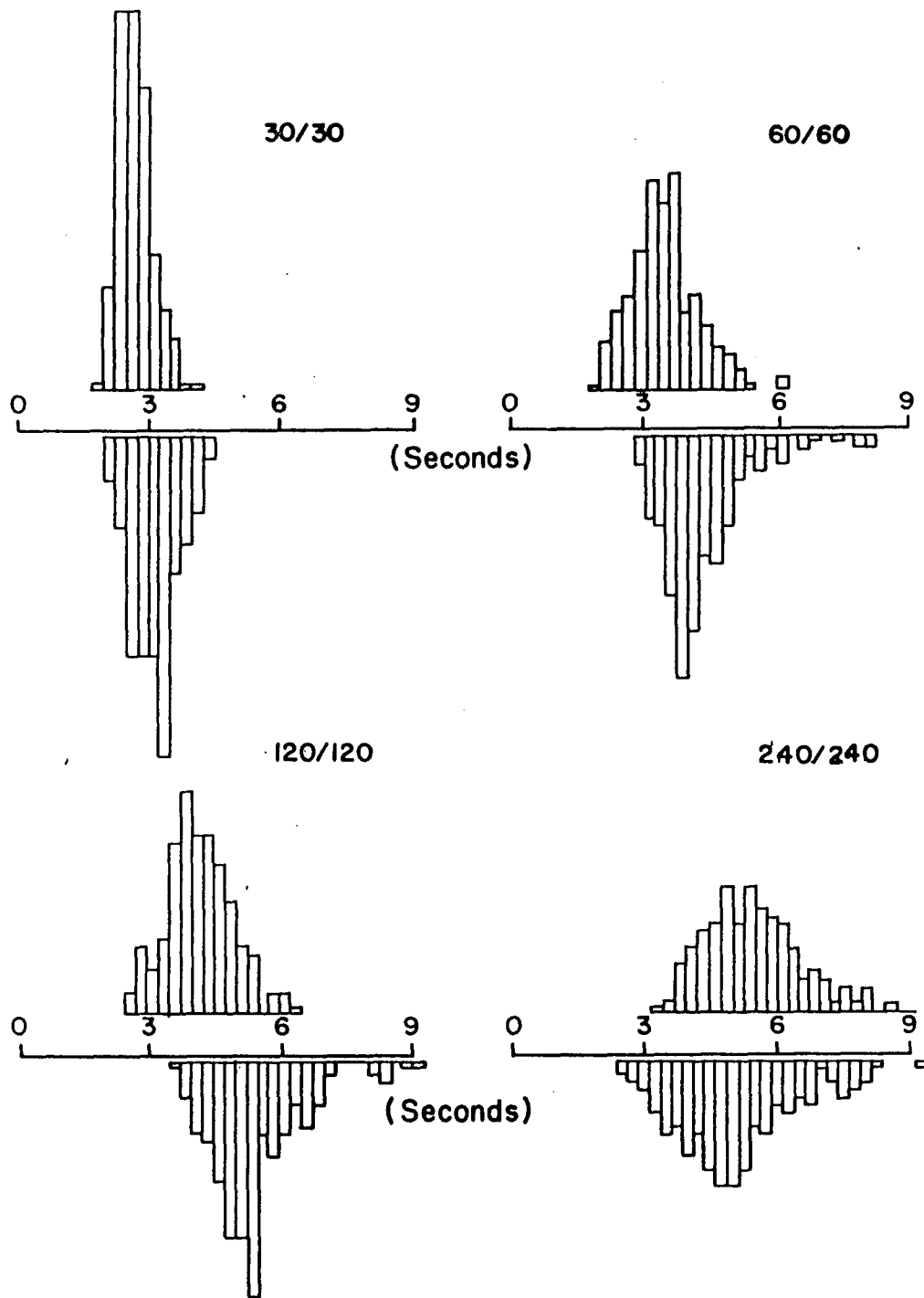


Figure 6

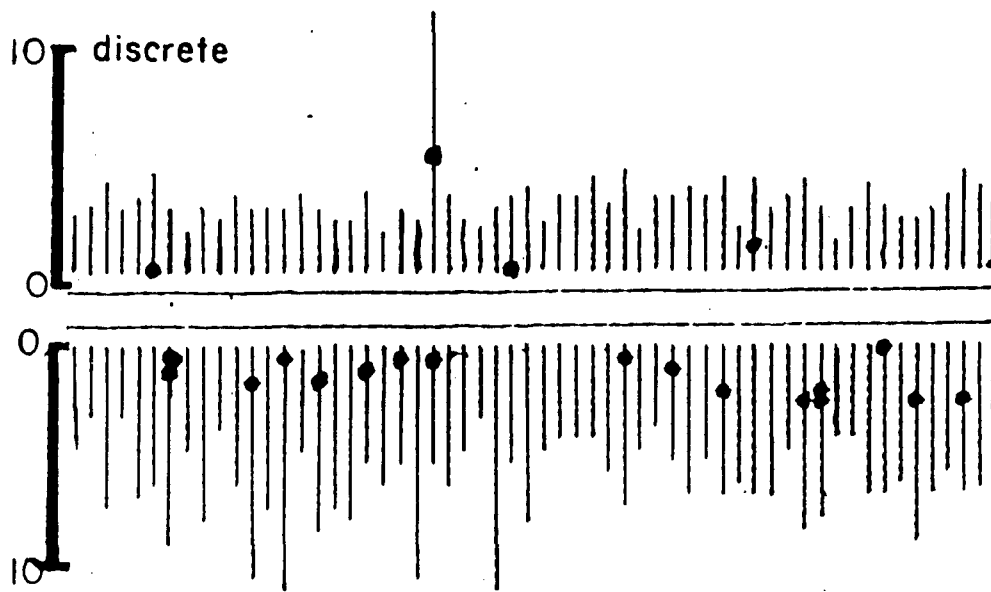


Figure 7.

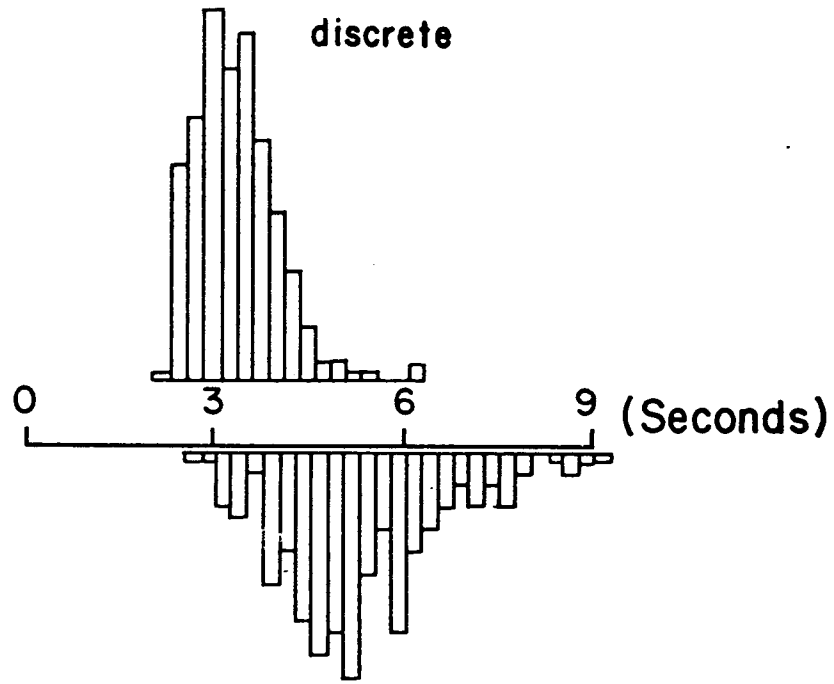
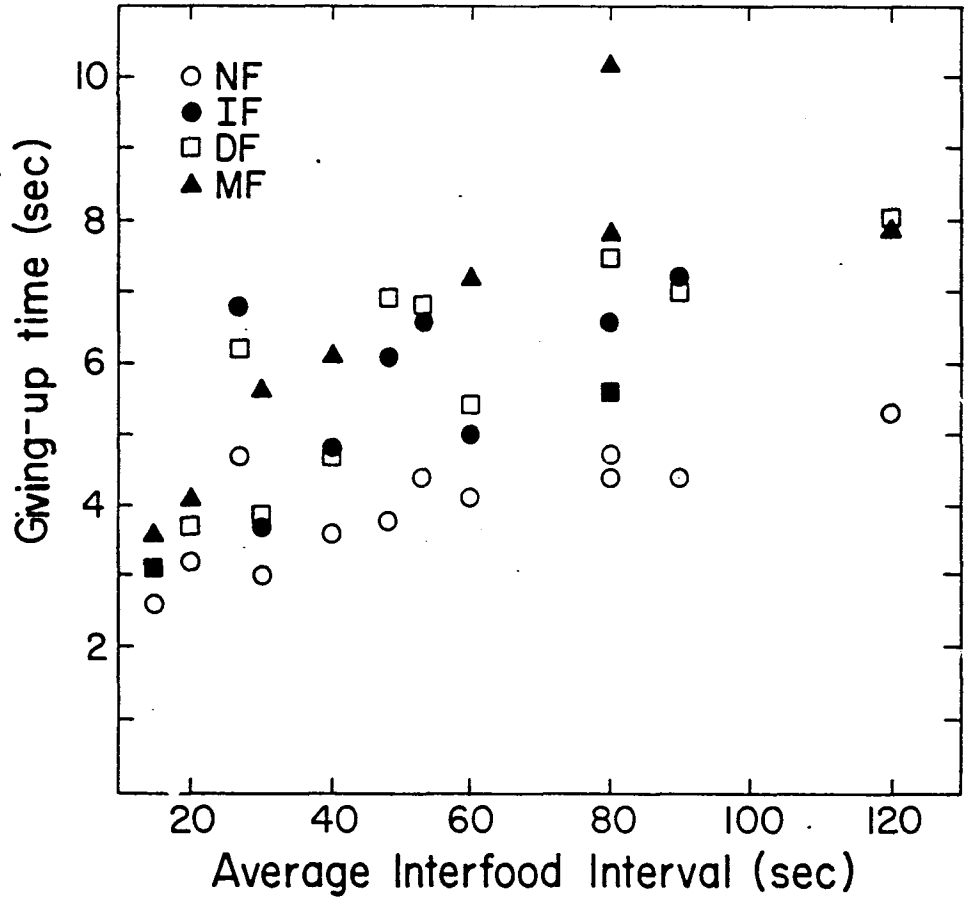


Figure 8.

Figure 9.



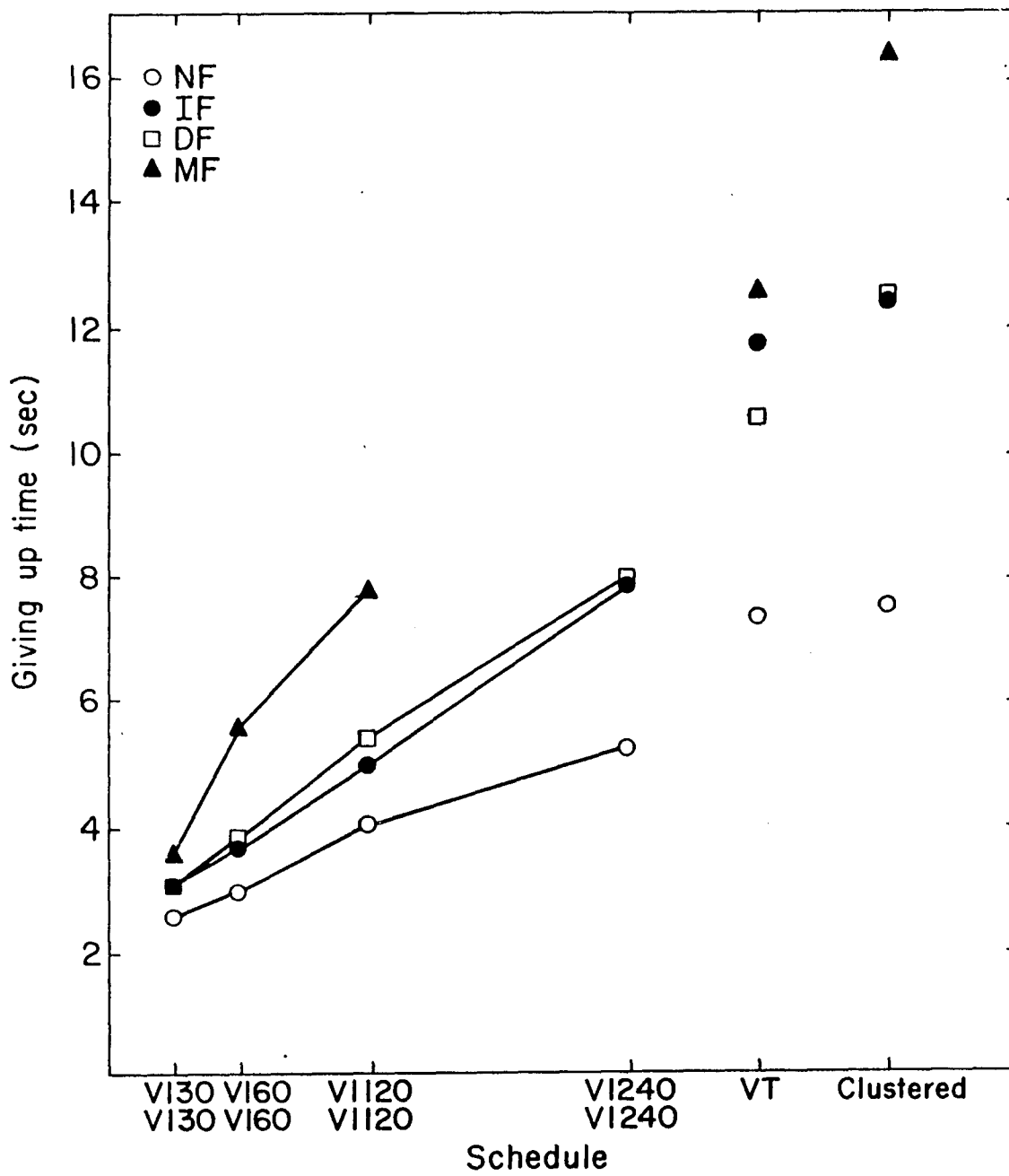


Figure 10a.

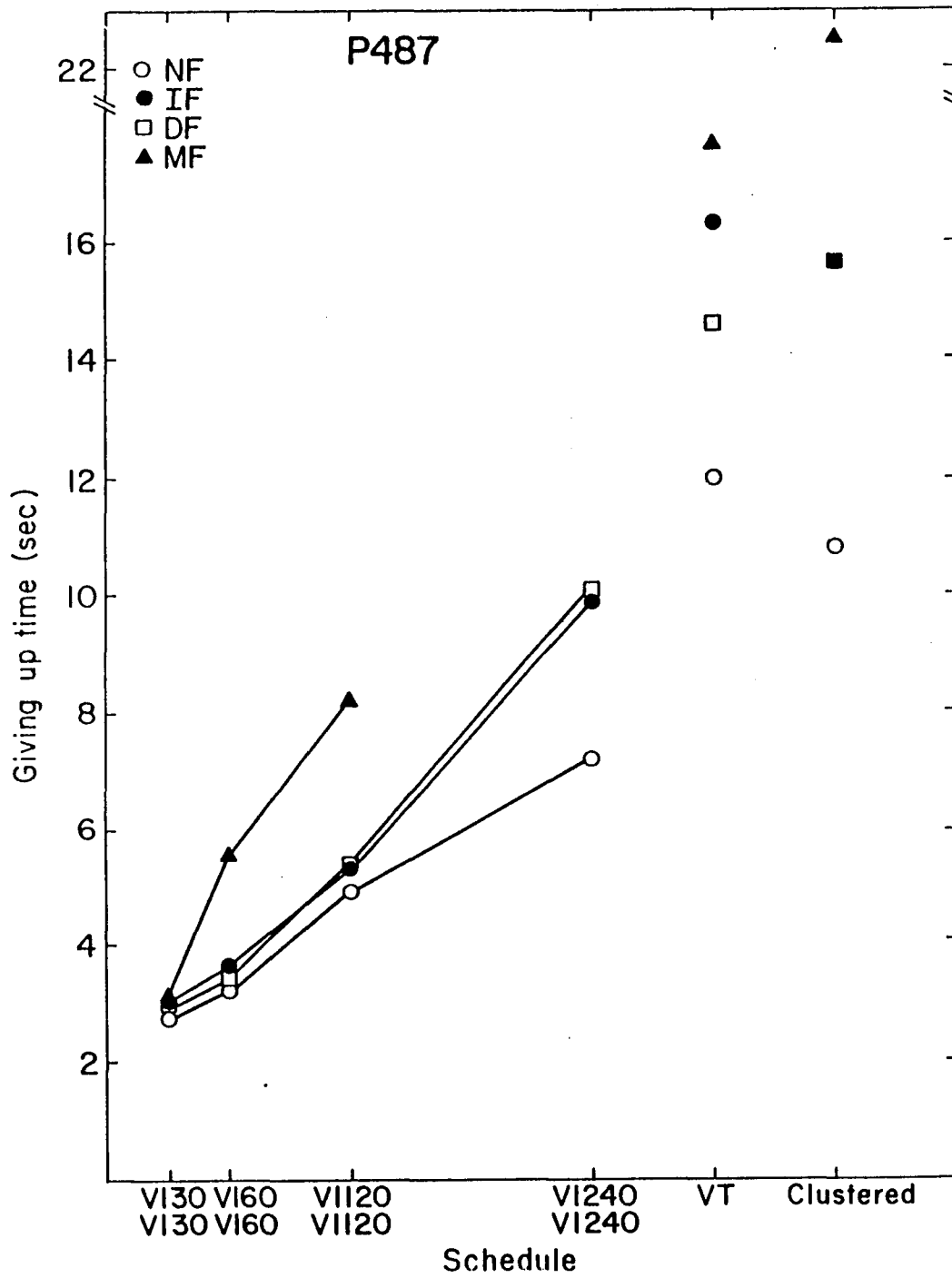


Figure 10b.

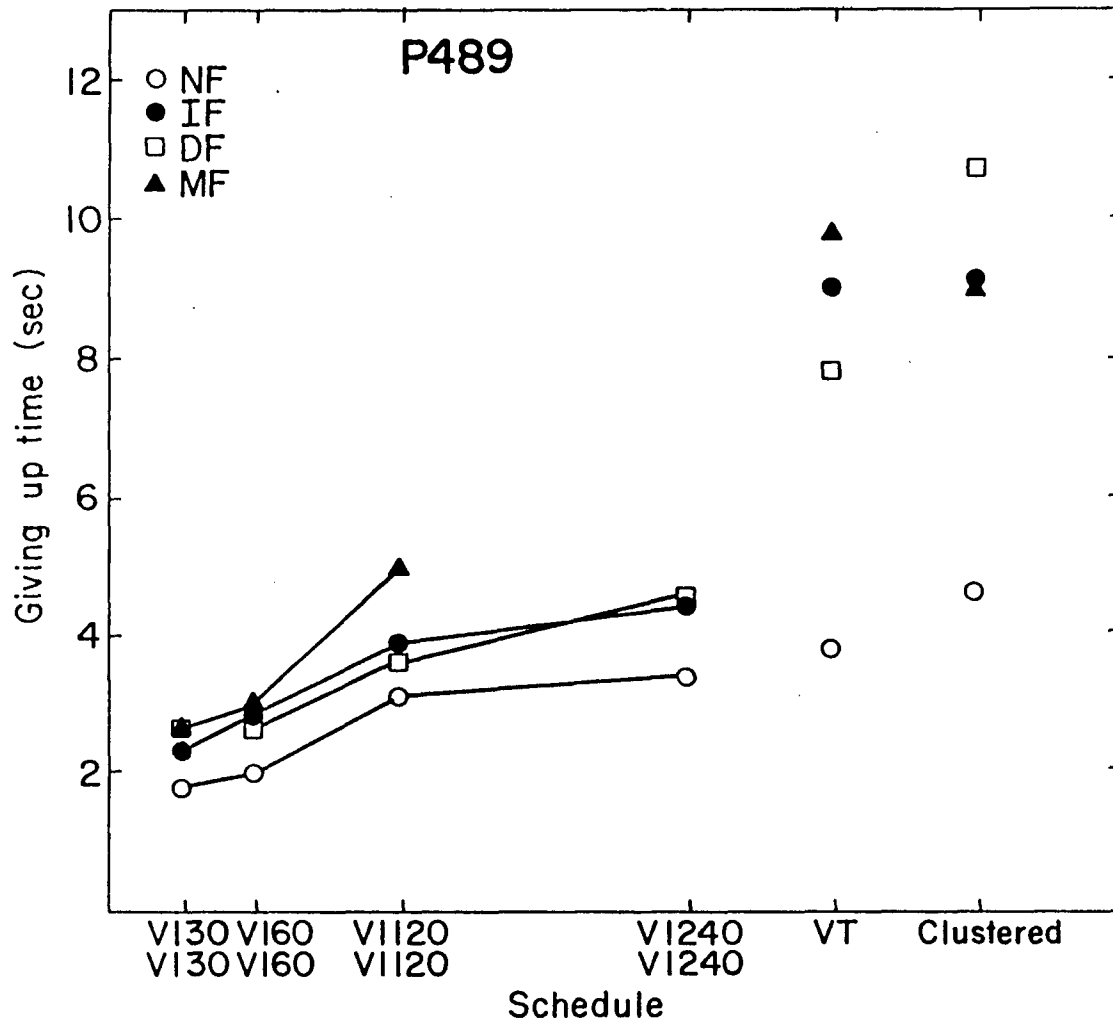


Figure loc.

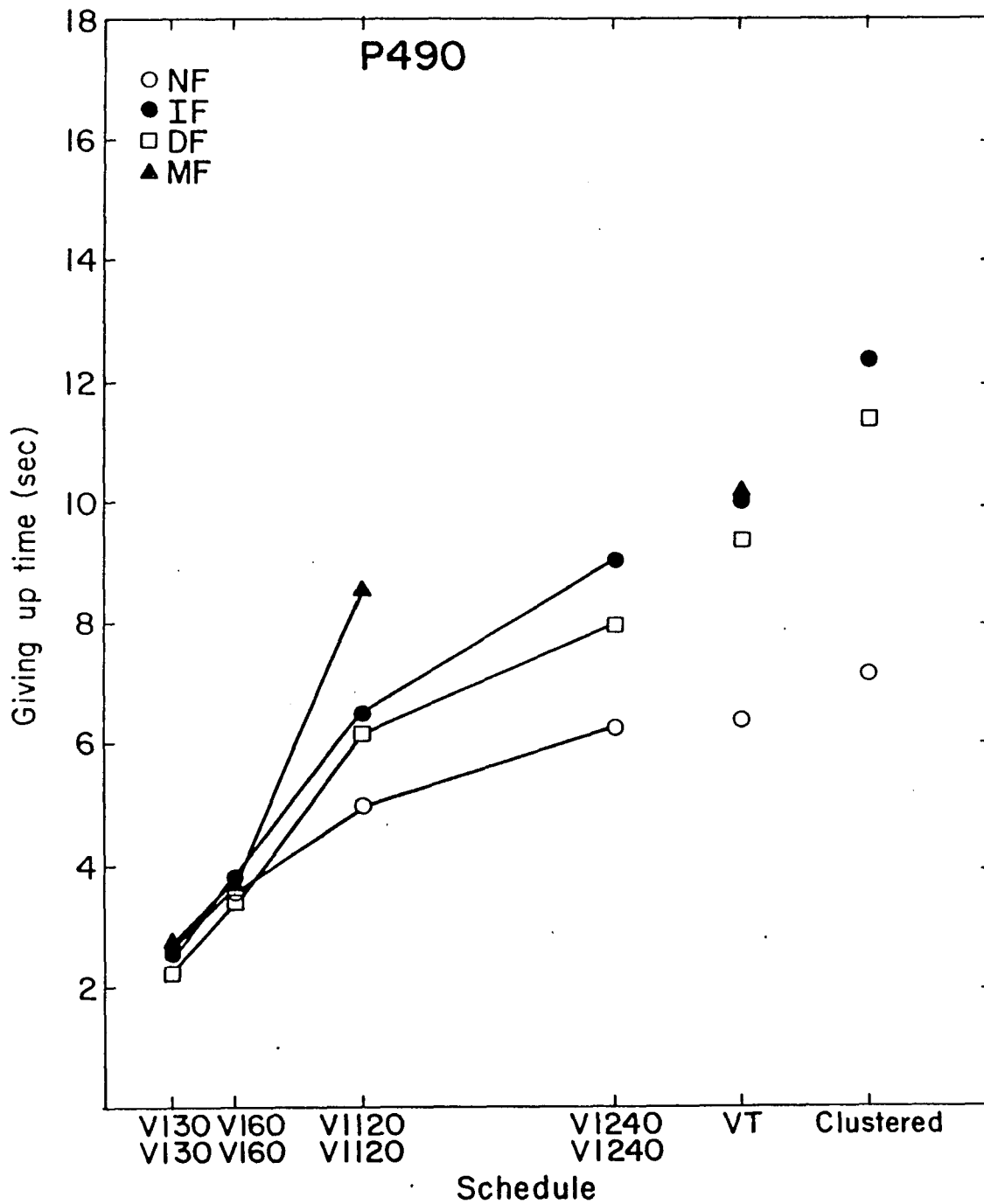


Figure 10d.

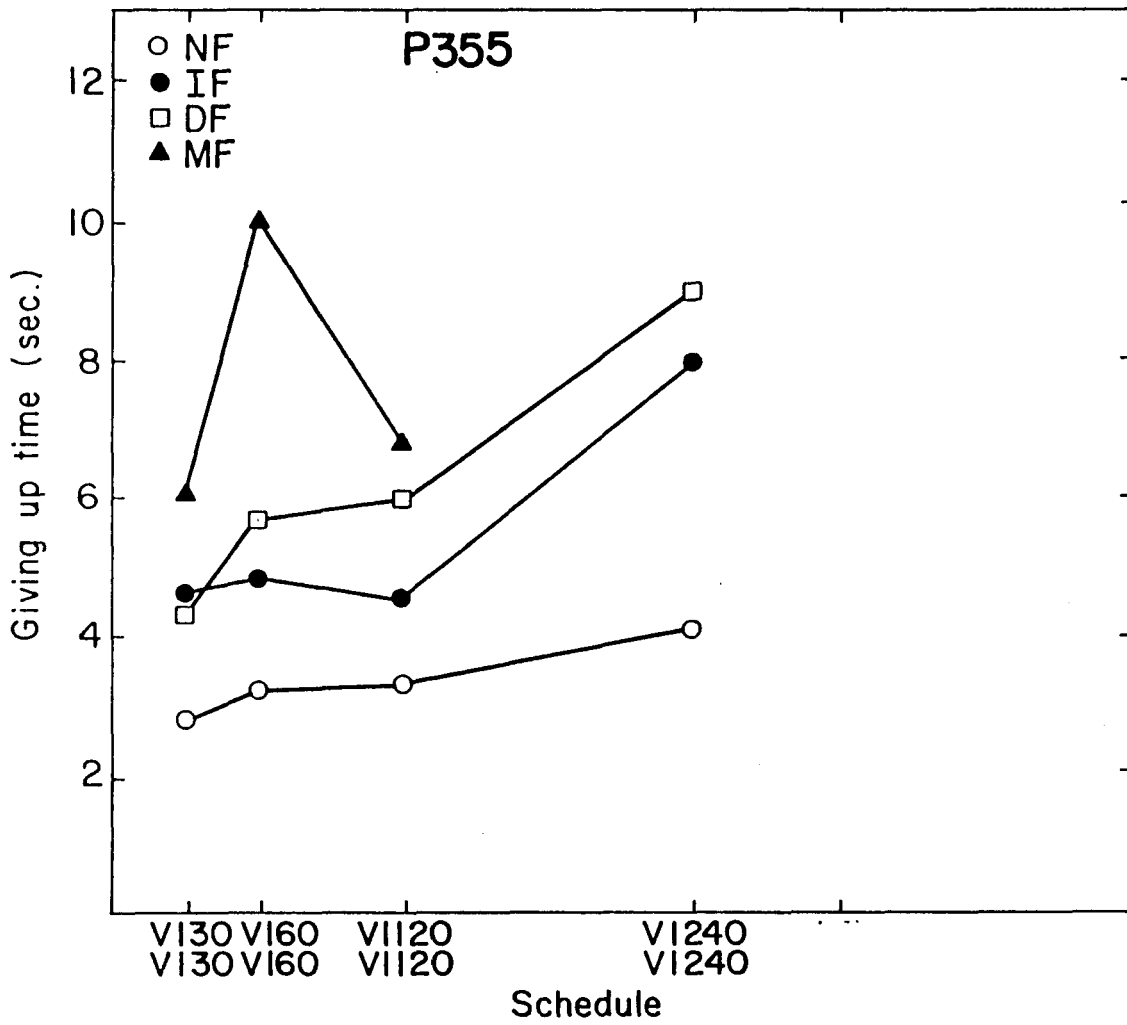


Figure 10e.

Figure 11a.

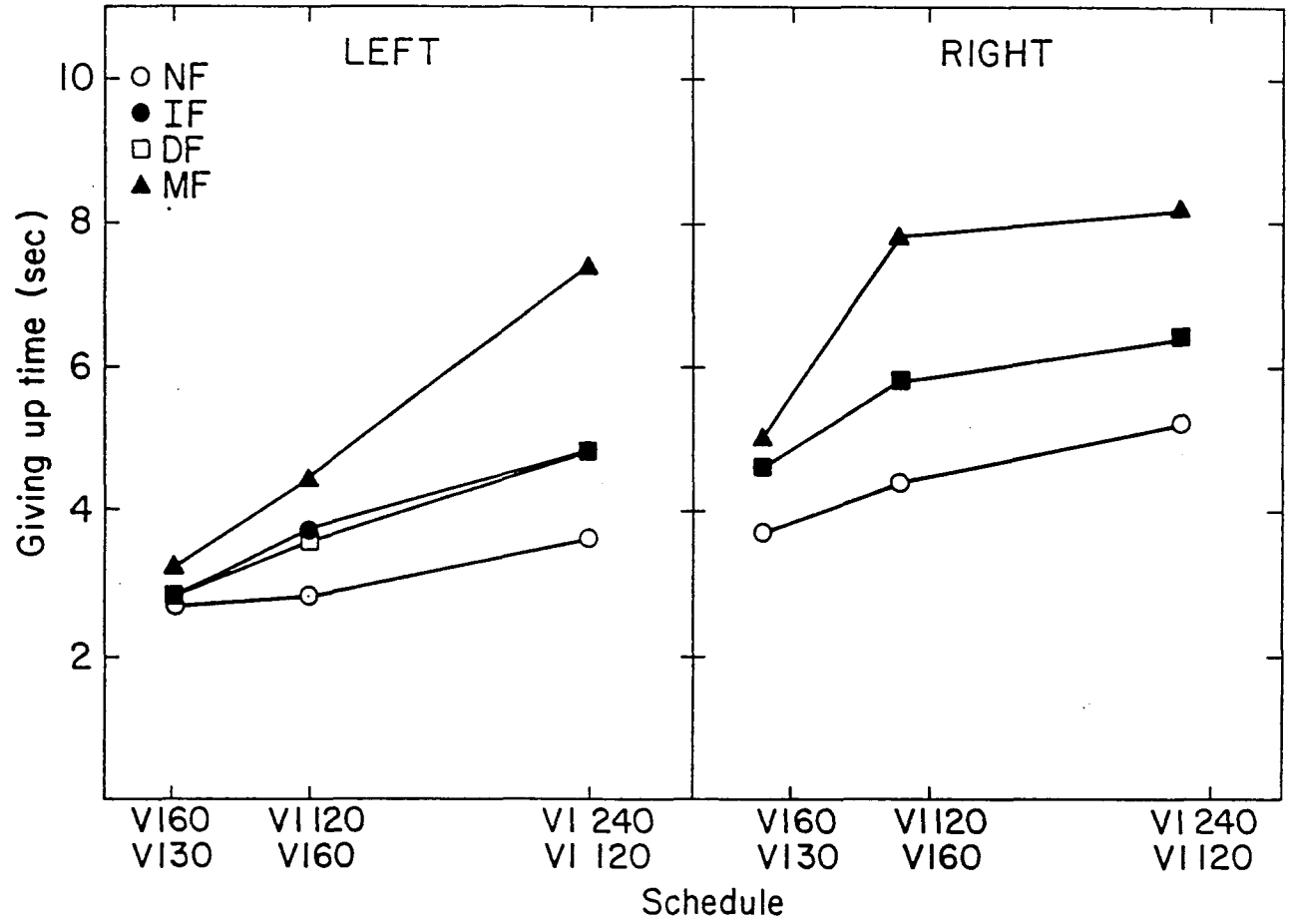


Figure 11b.

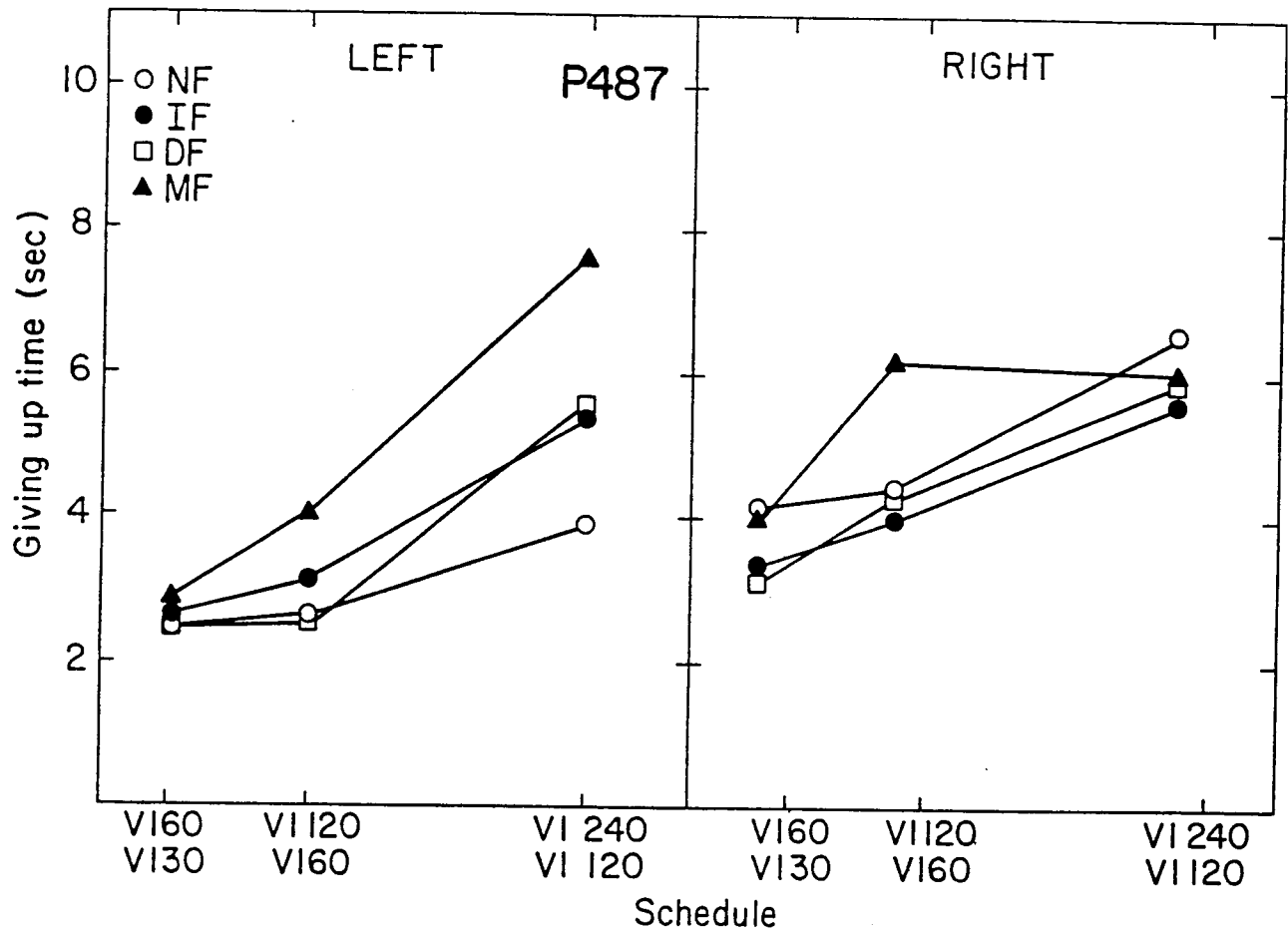


Figure 11c.

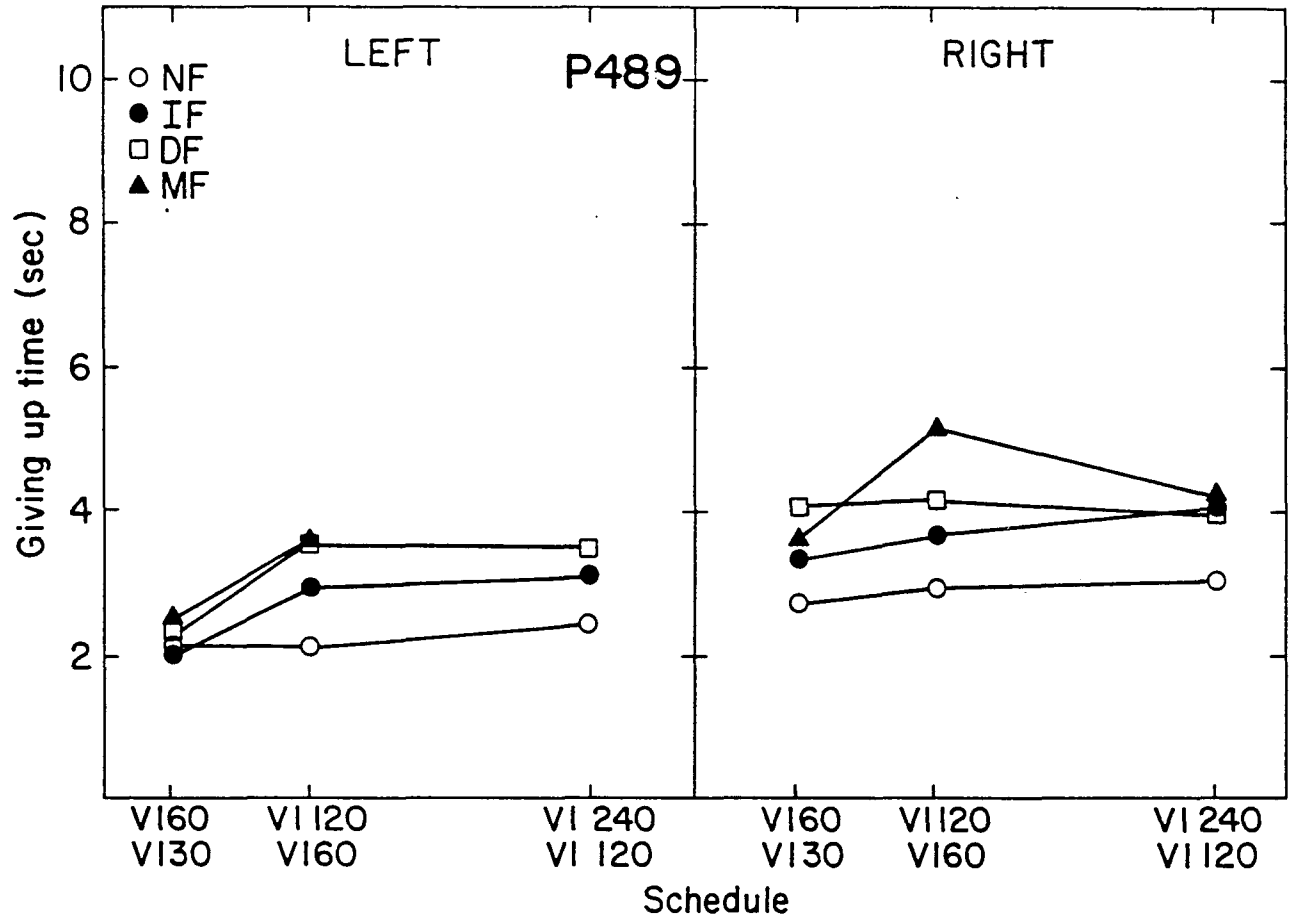


Figure 11d.

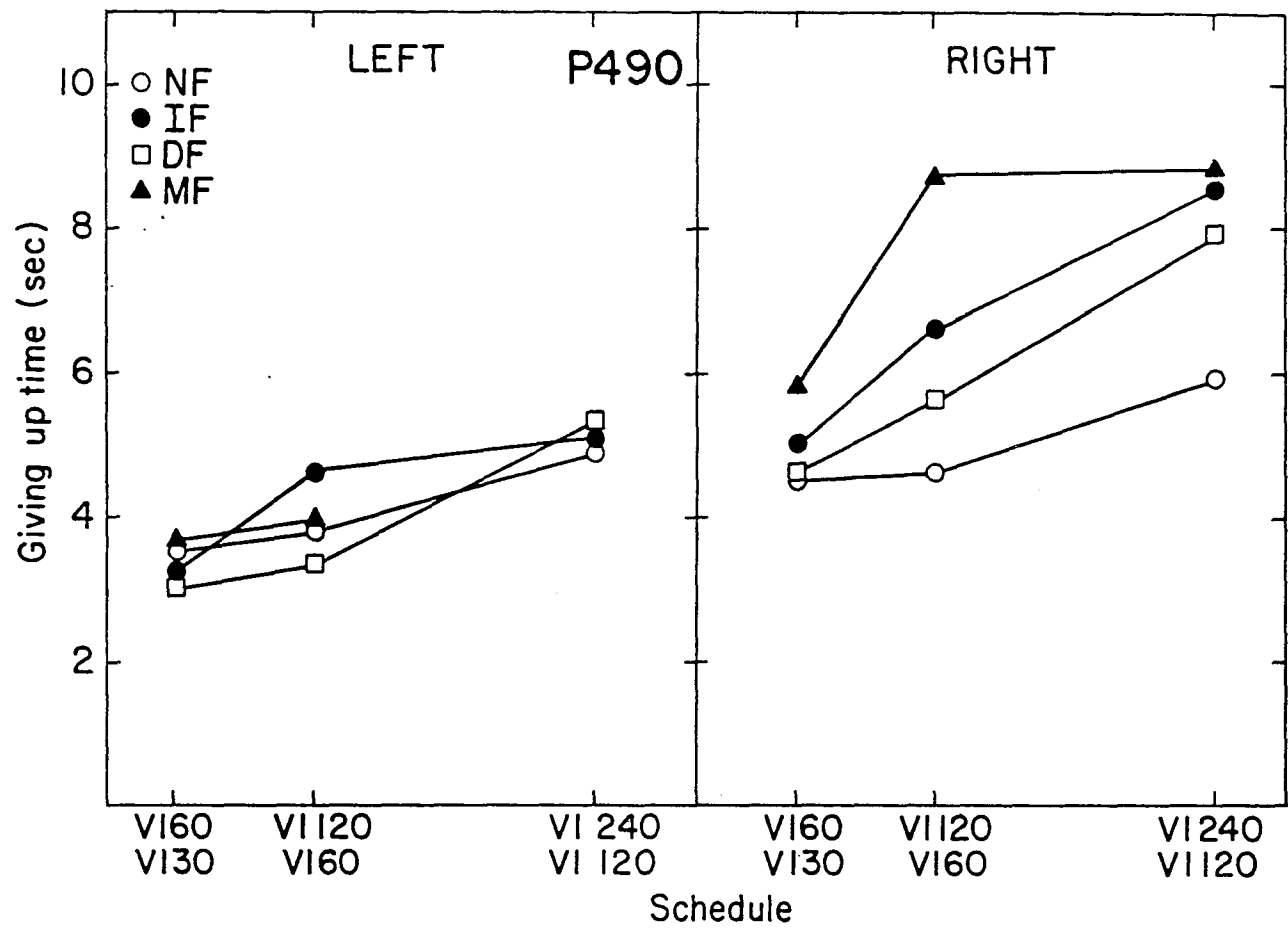
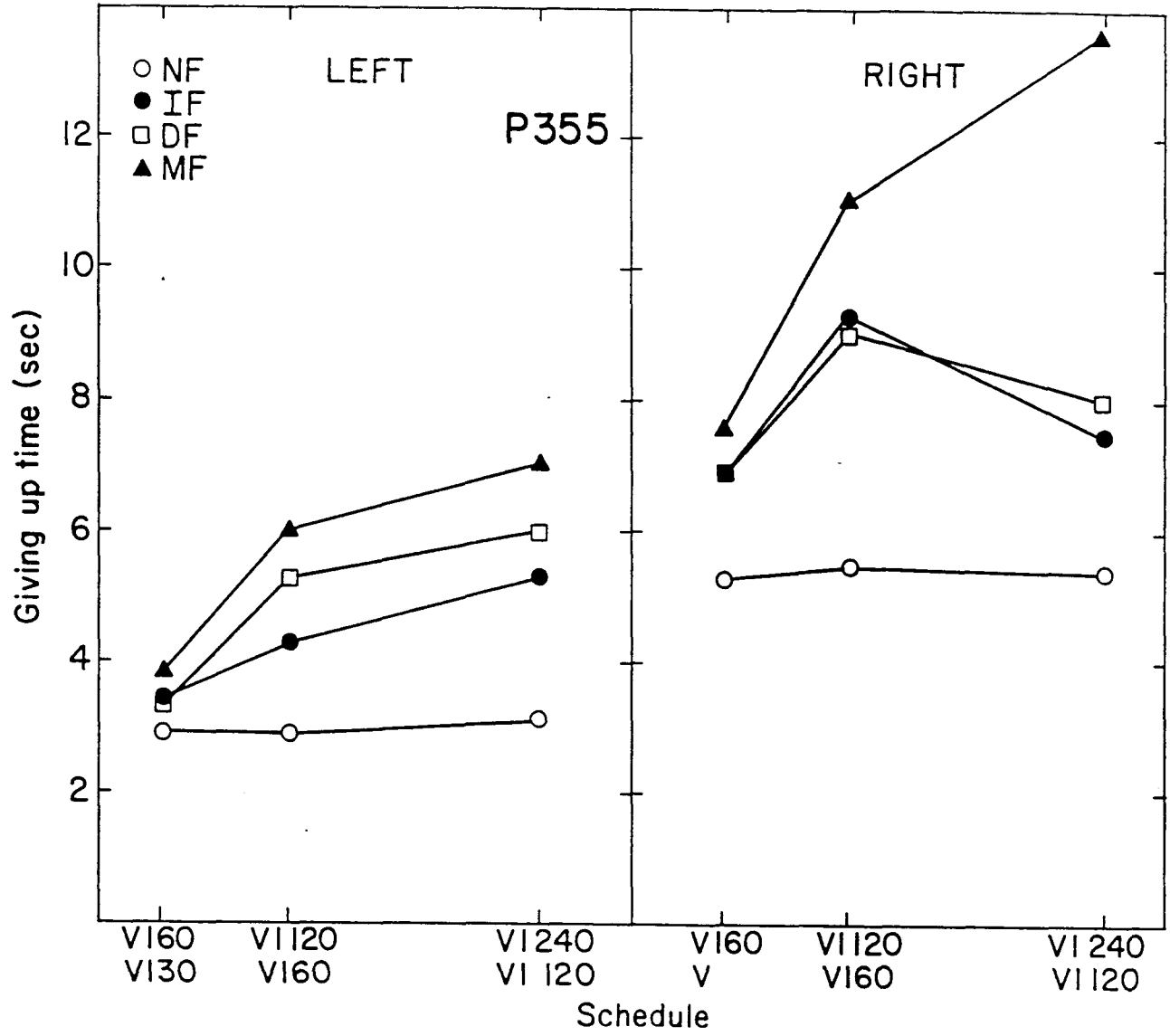


Figure 11e.



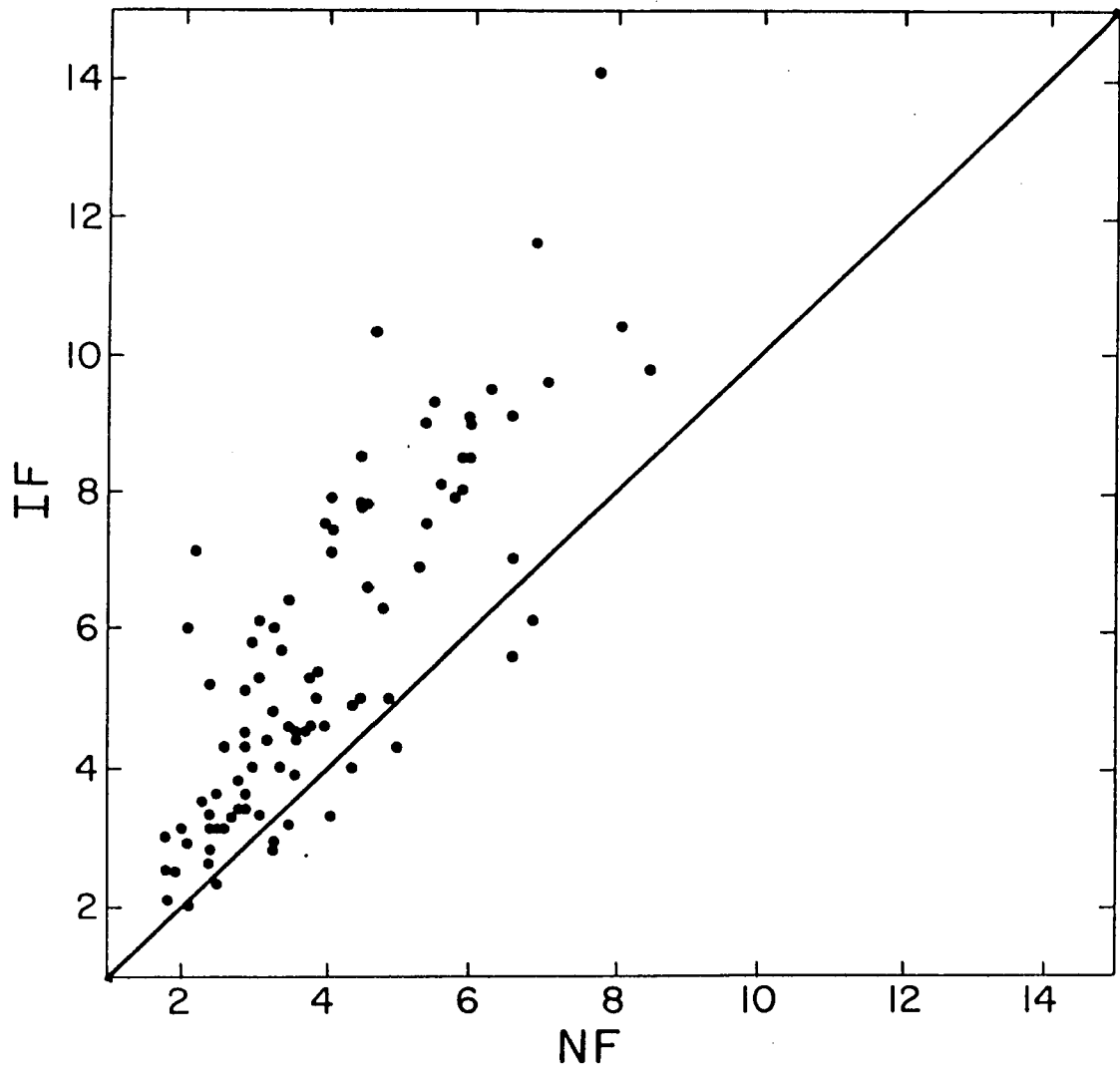


Figure 12a.

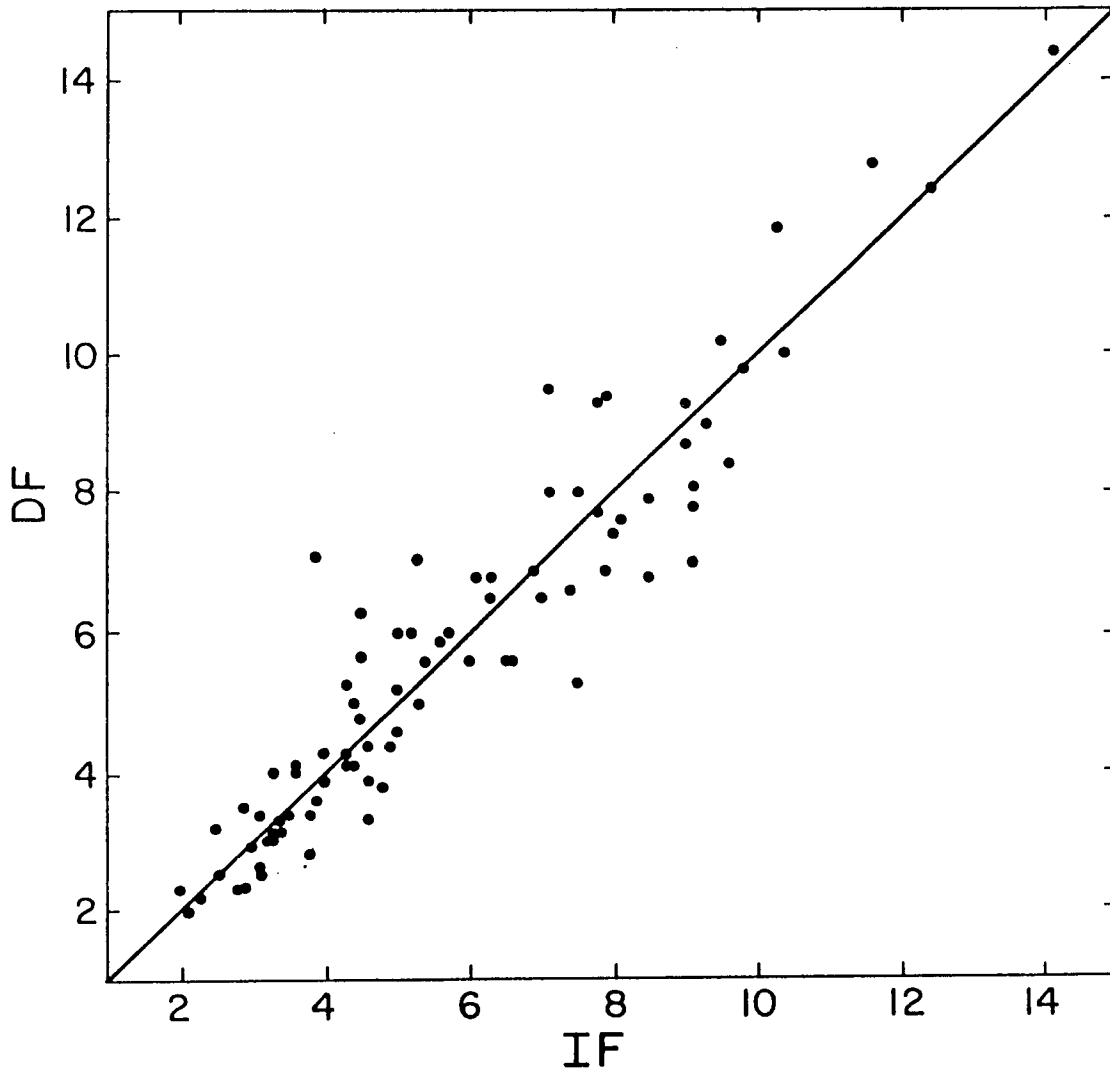


Figure 12b.

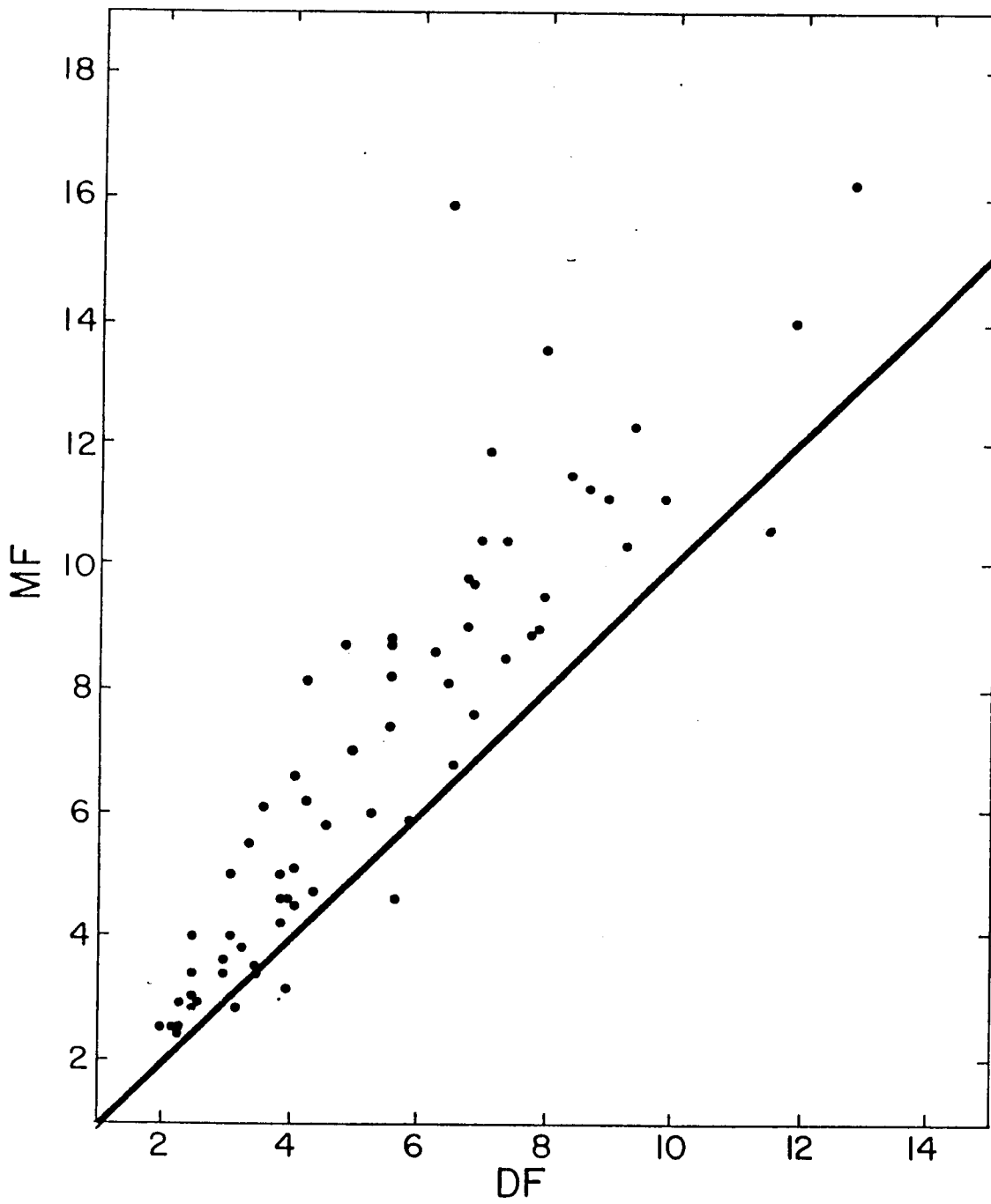


Figure 12c.

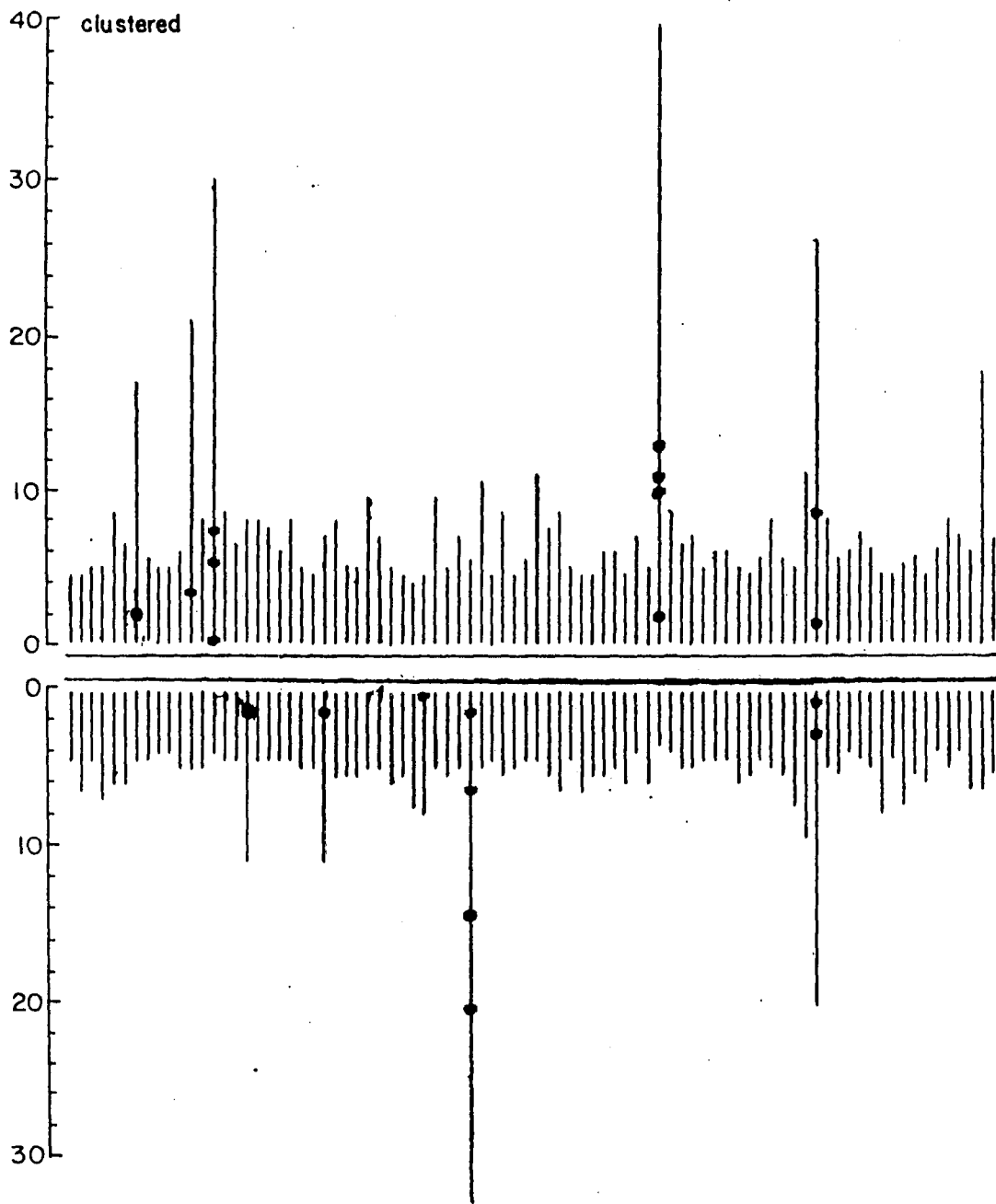


Figure 13.

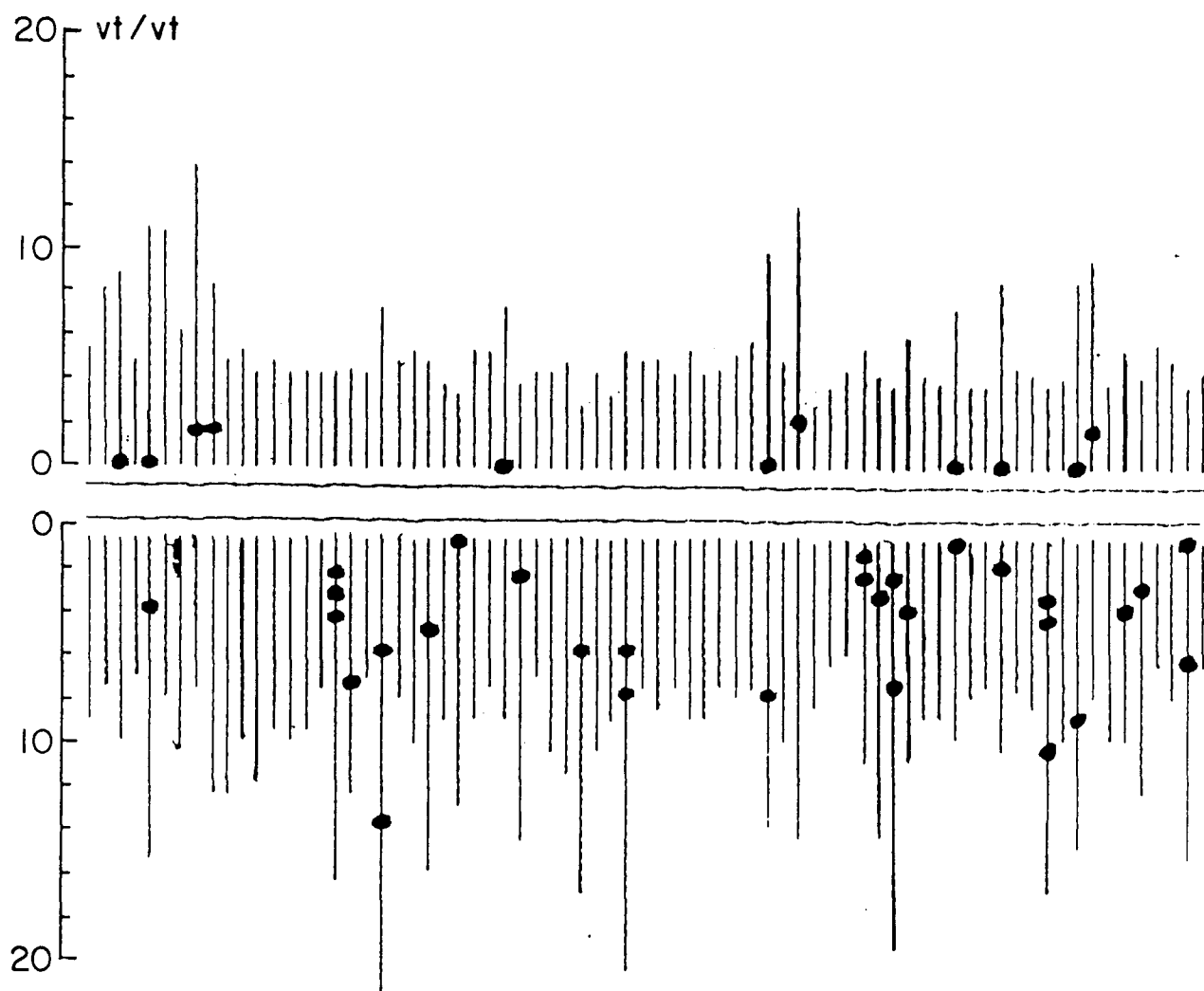


Figure 14.

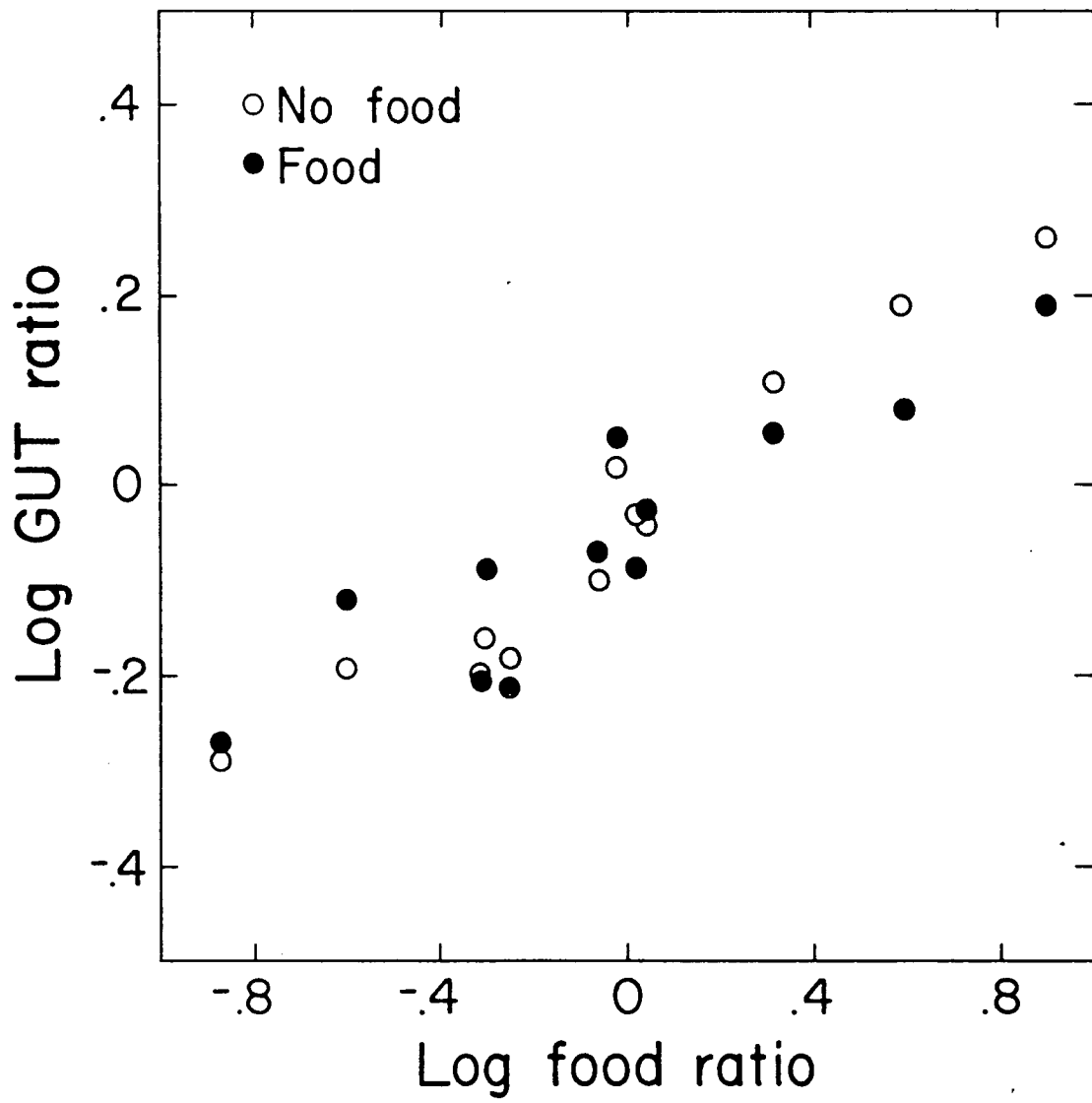


Figure 15.

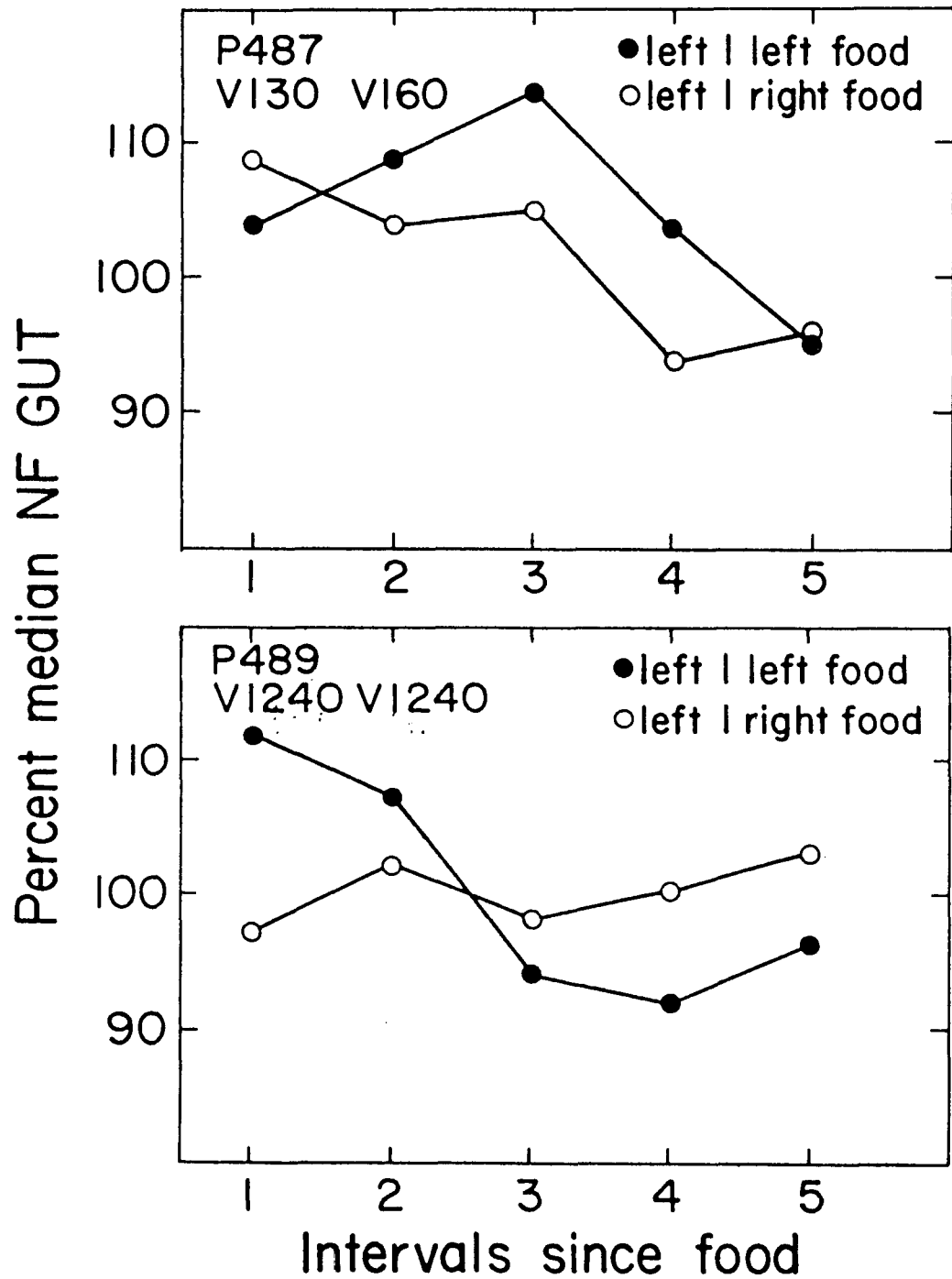


Figure 16a-b.

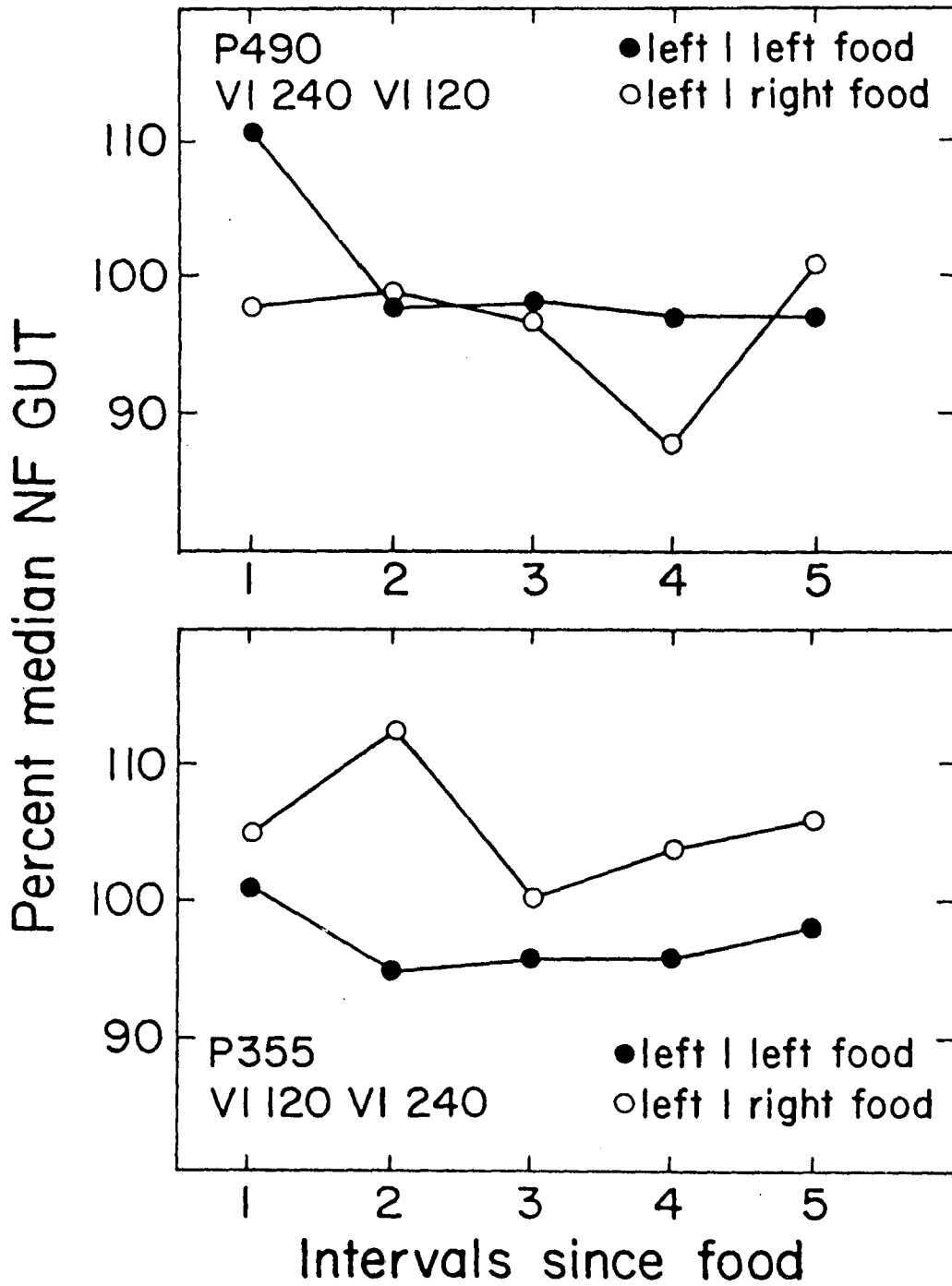


Figure 16c-d.

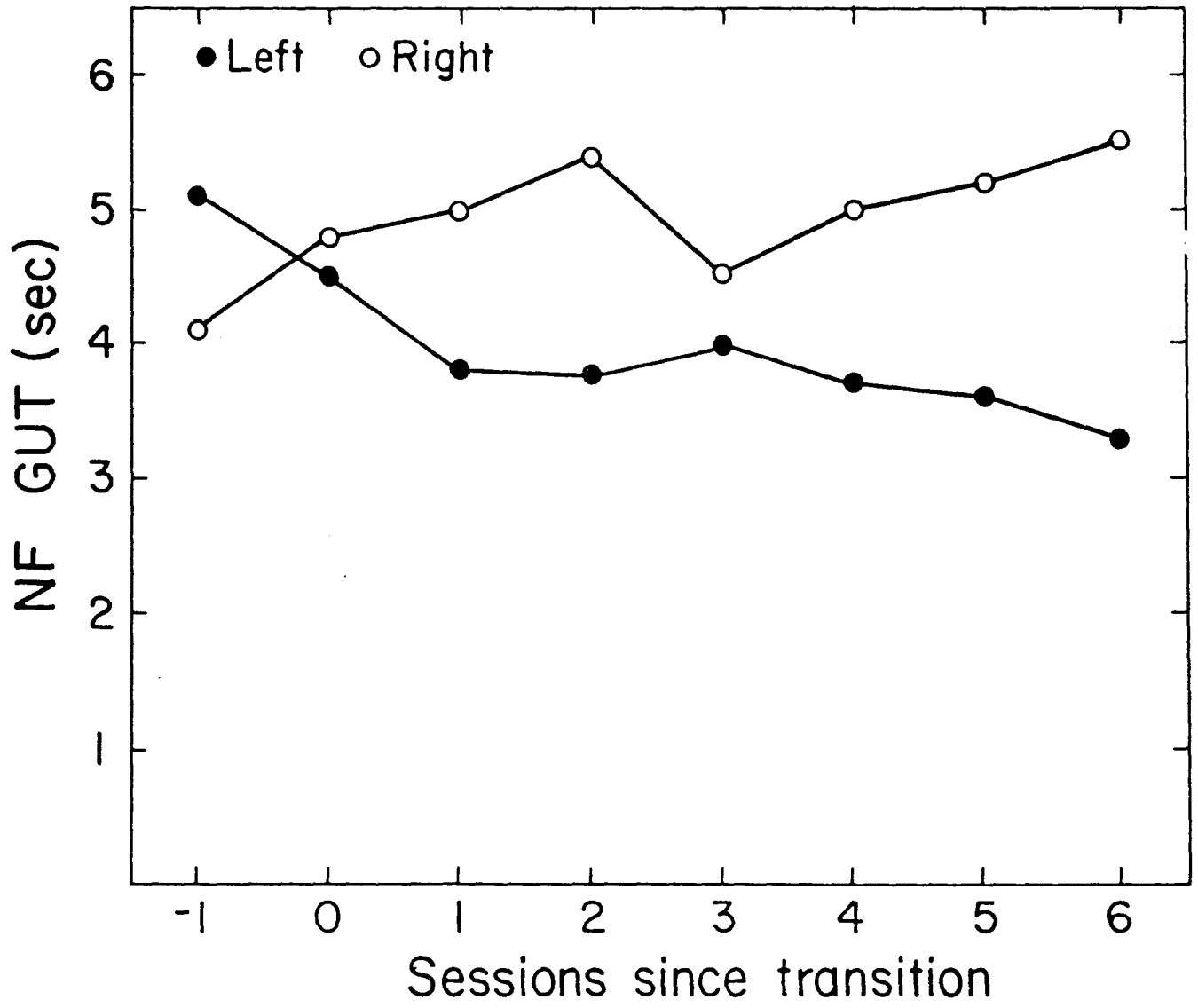


Figure 17.