Winter 1995

Molar and local effects of the fixed-ratio changeover requirement on choice, changeovers, and visits: A parametric examination of the fixed-ratio changeover requirement

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Abstract
The distribution of behavior by organisms in choice situations is of long-standing interest to psychologists. The generalized matching relation accurately predicts choice between concurrent variable-interval schedules of reinforcement. Researchers have assumed, on weak grounds, that the effect of the changeover requirement on sensitivity to reinforcement—the exponent in the generalized matching equation—was consistent. This experiment considered the effects of the changeover requirement by parametrically manipulating the fixed-ratio schedule required to switch alternatives. Pigeons pecked either of two side-response keys in a standard three-key operant chamber for food, delivered according to independent variable-interval schedules. No changeover delay was used, instead completion of five fixed-ratio schedules (FR 0, 2, 6, 12, or 20) on the center-response key alternated the active side key. Five reinforcer ratio (1:1, 1:2, 2:1, 1:4, and 4:1) were paired with most FR schedules. A matching relation analysis indicated that for two pigeons response-allocation sensitivity generally overmatched for all but the FR 0 condition, which undermatched. The other two pigeons' sensitivity increased to overmatching when FR 12 was in force. Excepting FR 0 conditions, time-allocation sensitivity, on the other hand, decreased from extreme overmatching toward matching as the changeover requirement increased. Reliable changes in response rates to the two alternatives account for the results.

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Keywords
Psychology, Behavioral, Psychology, Experimental, Biology, Ecology
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MOLAR AND LOCAL EFFECTS OF THE FIXED-RATIO CHANGEOVER REQUIREMENT ON CHOICE, CHANGEOVERS, AND VISITS: A PARAMETRIC EXAMINATION OF THE FIXED-RATIO CHANGEOVER REQUIREMENT

by
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BS, Brigham Young University, 1988
MS, Brigham Young University, 1990

DISSERTATION

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

Doctor of Philosophy
in
Psychology

December, 1995
This dissertation has been examined and approved.

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Date

13 Oct 1997
DEDICATION

Dedicated to my “mothers”: Elodie, the woman who birthed me and seemingly could spell all the words I could not; Deena, the woman who loves me, birthed our children, and taught me that spelling skills are not the only intellectual skills; Blair, Brooke, and Whitney, my daughters who greet me with smiles, hugs, and kisses as they learn the relations between letters, sounds, and ideas, despite Dad’s continual instruction; and Hal Miller, the man who mid-wifed my intellectual birth. May we all one day rejoice in that day of rejoicing.
ACKNOWLEDGMENTS

As with any human endeavor, this project would have never come to fruition were it not for the companionship, encouragement, and tutelage of others.

My academic interest in the experimental analysis of choice began when Harold Miller gave a seemingly simple answer, while walking a dark hall, to what I thought was a profound question. The question: “Why do individuals sin?” The answer: “Because the immediate rewards outweigh the delayed consequences.” Hal’s worldly answer to what I thought was a solely religious question occasioned my awakening to the compatibility, when defined in a particular fashion, of the two Weltanschauungen. Only recently have I begun to realize the full implications of his answer.

The specific questions addressed in this dissertation grew out of discussions with Billy Baum about how we might better understand choice. My questions were facilitated by Tony Nevin’s Graduate Seminar in learning and behavior analysis, and his research grant from the Cambridge Center for Behavioral Studies. My life has been indelibly written upon by Billy and Tony and I am honored to call them my mentors. Along with being scholars and scientists in the strictest senses of the words, they are two of the finest human beings ever to set the occasion for my behavior.

I am fortunate to have had committee members committed to fostering (I promise, Will, only this one time) the development of young academics. Victor was most helpful throughout my years at UNH. Michelle taught a psychology student some things about animal behavior. And Will graciously traveled up from Cambridge twice for merely a dinner and a thank you. I am grateful to them all.

I was privileged to have what amounted to a sixth committee member in fellow graduate student Randy Grace. Our discussions and his willingness to give of his time to assist my work greatly improved this dissertation. Randy was particularly helpful with writing the extraction programs. Without his assistance, I may still be trying to mine the data. Exchanging pigeons will never be as efficient, nor as enjoyable, and few lab discussions will solve as many societal problems.

Other Conant Hall colleagues lent their assistance. Anthony “Ant” Mclean, a visiting scholar from New Zealand, encouraged and instructed at timely moments. Conversation with fellow BYU transplant, Steve Clark, kept religion and science conjoined and me sane. Alex Stevens, Yue Ping Zhang, and Daniel Henderson contributed to the dialogue, and the spice of life. Brad Stone kept the pigeons’ home cages clean. Joy Bryan, a fellow Washingtonian, and I became fast friends soon after arrival. It was fortuitous for our desks to be close in the “bull pen.” Their friendship and support is cherished.

My deepest appreciation and respect goes to Deena, my wife, and Blair, Brooke, and Whitney, our daughters. Few spouses and family members willingly live in the four room box called “married-student housing.” They did so with smiles generally but some
frowns too; both smiles and frowns kept life interesting. My in-laws, Arla and Colonel Ed Beck (Ret.), were most encouraging, even though their grandkids could have been much closer to home had Deena and I settled on Pullman rather than Durham. In a true sense of community, members of our church and Forest Park neighborhood (too many to mention by name) extended their hands in friendship, their arms in support, and their hearts in love. Liz Falvey lent both moral and financial support throughout our stay. If all counseling psychologists were as talented as Liz, they would have much more free time. Thank you is inadequate.

Acknowledgement is given to the University of New Hampshire Psychology Department for funding my graduate education while there and to the Brigham Young University Psychology Department for funding the printing and copying of this dissertation.
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INTRODUCTION

Operant Behavior as Choice

Operant behavior is defined as acts made by organisms that are controlled by the consequences of those acts. The behavior of Thorndike's cats in a puzzle box illustrates operant behavior (Thorndike, 1898). When placed in a small cage outside the reach of appetizing food, cats eventually escaped confinement. The more times the cats were placed in the cage, on average, the shorter the latency to escape. This control by consequences, called the law of effect, typifies much of mammalian behavior. Rachlin (1991) argues that because there are almost always multiple behaviors possible, and since organisms generally engage in only one behavior at a time, essentially all operant behavior is choice behavior. Choice, here, means having more than one option available. Organisms must regularly distribute behavior among a variety of activities including sleeping, foraging, eating, and socializing. The questions of interest for operant psychology concern formulating rules that describe and explain choice; that is, why do organisms do the things they do?

Brief History of Psychology and Choice

The study of choice given multiple alternatives is a long-standing interest of psychologists. The so-called Father of American psychology, William James, wrote extensively on the topic. In an essay titled "The dilemma of determinism" he presented
the classic problem for the study of choice (James, 1962/1896). James gave the example of
leaving the building wherein he is lecturing and walking down Divinity Avenue.
Suppose, he wrote, that “the powers governing the universe annihilate ten minutes of
time with all that it contained, and set me back at the door of this hall just as I was before
the choice was made” (p 155). In this second universe, rather than walking down
Divinity Avenue, suppose James traverses Oxford Street, that is, he chose Oxford over
Divinity. A “passive” spectator observing the two universes could not predict, a priori,
which street James would walk. However, James asserts that any self-respecting
determinist must argue that one of the universes, walking Divinity Avenue say, from
eternity was not possible.

The problem, as set by James, is predicting behavior at every individual choice point.
With Nineteenth-century mechanism as their scientific model, psychologists during the
first half of the Twentieth century vigorously pursued the momentary causes of behavior.
The predominant methodology involved rats running through mazes with several choice
points. Which choice—left or right—the subject made at each choice-point, whether the
choice moved it closer to the goal box, and the latency to run the maze were all recorded.
When a few rats took a novel, more direct route to the goal box after being trained on a
longer route, Tolman (1938), looking for an immediate cause to individual choices,
postulated an internal cognitive map. Inferring a map present in a rat's mind is necessary
only if an immediate cause is sought and the rat’s history is ignored. The rats had a
history of getting food from a particular location. Acknowledging that history frees one
from the need to postulate an internal cause.
The free-operant chamber developed by Skinner (see Skinner 1938, 1956) is an apparatus that allows an analysis of choices made through time while in a relatively stable environment. In the chamber an organism moves about freely, perhaps manipulates an object (a key or lever), and occasionally gets food. The apparatus fosters recording rates of events rather than discrete responses only. Because a rate is the number of target responses that occur during a given unit of time, operant psychologists are not limited to single instances of choice as their fundamental measure; we are freed from the dilemma of determinism, of predicting molecular behavior as cast by James, because now the measured variable occurs through time (Hineline, 1990). It is as if one observed James leave the lecture hall multiple times and then predicted his future course of action based on his past performance. Choice is no longer a single event with one immediate cause. The free-operant chamber allows an analysis of choice extended through time.

The analysis of choice is made explicit when a second manipulandum is added to the apparatus and response rates on both are recorded (Ferster and Skinner, 1957; Findley, 1958). Herrnstein (1961) spawned the experimental analysis of choice when he used two manipulanda and reported a reliable relationship between relative reinforcement rates and relative response rates. Over the past three decades, this line of research has become highly quantitative (Miller, 1984), which encourages connections with other quantitative sciences. Recent years have demonstrated that the mathematical models of choice and their theoretical underpinnings are intimately related with models derived from research on foraging by behavioral ecologists. Chapter I is a review of the matching law with a
particular emphasis on changeover requirements. Chapter II addresses some similarities between foraging and choice. Chapter III presents the methods and procedures. Chapter IV presents the results and Chapter V discusses the results and draws some conclusions.
CHAPTER I

THE MATCHING LAW

Strict and Generalized Matching

The experimental analysis of choice began in earnest when Herrnstein (1961) described a consistent relation between the allocation of pigeons' pecks on two response keys and the relative rate of reinforcement received from the two alternatives. The consistency is expressed mathematically by the strict matching equation:

\[
\frac{B_L}{B_L + B_R} = \frac{R_L}{R_L + R_R}
\] (1)

\(B\) represents behavior (usually measured in number of pecks or time in seconds), \(R\) reinforcers (number of hopper presentations, for example), and the subscripts indicate the alternatives, left and right. Baum and Rachlin (1969) demonstrated that the relation holds whether behavior is measured in units of responses or time. Subsequent research has demonstrated that the matching relation, in either its strict or generalized forms (see below), describes the behavior of many species including rats, cows, wagtails, human, and others. Herrnstein’s results occasioned vigorous research with a variety of hypotheses proposed to explain matching. Some have called the matching relation a fundamental law of choice (for reviews, see Davison & McCarthy, 1988; Williams, 1988).
As investigation continued, consistent deviations from strict matching emerged.

Baum (1974b) developed the *generalized* matching equation to account for these deviations:

\[
\log \left( \frac{B_L}{B_R} \right) = s \log \left( \frac{R_L}{R_R} \right) + \log b \tag{2}
\]

Equation 2 has the form of a linear equation with a slope of \( s \) and a y-intercept of \( \log b \).

Exponentiating both sides of the equation, to express it in power function form, yields the ratio version of Equation 1 with two added terms, a multiplicative constant, \( b \) (*bias*), and an exponent, \( s \) (sensitivity to relative reinforcement or, simply, *sensitivity*):

\[
\frac{B_L}{B_R} = b \left( \frac{R_L}{R_R} \right)^s \tag{3}
\]

Strict matching results when \( b \) and \( s \) both equal 1.0. The bias term captures consistent preferences for a particular alternative regardless of the relative reinforcement rates. The sensitivity term, on the other hand, measures reliable deviations across conditions of behavior ratios from reinforcer ratios. The observation that these two terms are necessary to account for the data—that is that the strict matching equation fails—suggests that either or both of the following are true: a) Strict matching is the norm but current procedures sometimes prevent its observation; b) Reinforcement rates are not the sole determiners of behavior allocation.

In normal procedures, bias seems to remain relatively constant across conditions and generally hovers near zero, although marked deviations do occur particularly when different reinforcement-schedule types are available (Nevin, 1971). Miller (1976)
demonstrated that the bias parameter can be used to measure preferences for different food types. Pigeons pecked a green or red colored key. Each color was associated with one of two magazines containing a particular type of grain. Three types of grain (buckwheat, wheat, and hemp) were successively paired with each other and bias for each pair was used to empirically derive the pigeons’ hedonic scale of the grains. This result suggests and other studies confirm that bias, though malleable, is controlled by straightforward variables. Consequently, bias has produced limited debate.

The sensitivity term has proved to be more theoretically fruitful. The values the term can take on have been categorized into three ranges: matching \((s = 1.0)\), undermatching \((s < 1.0)\), and overmatching \((s > 1.0)\). Undermatching occurs when the behavior ratio is consistently closer to indifference \((b = 1.0)\) than the reinforcer ratio; that is, when relatively more behavior is allocated to the leaner alternative than strict matching predicts, regardless of which alternative is leaner. Overmatching is just the converse of undermatching: when relatively more behavior is allocated to the richer alternative than strict matching predicts, regardless of which is richer.

Different researchers have debated which category, if any, is normative. Originally matching was thought to be normative and recently Williams (1988) supported that view when he concluded that if the "proper" procedures are employed strict matching will be observed. Baum (1979) on the other hand, after reviewing 103 data sets, reported that \(s\) was usually less than 1.0. Later, the results obtained when incorporating a procedure that required pigeons to travel around a partition to switch alternatives led him to conclude
that overmatching may be the norm (Baum, 1982; see Chapter II). Furthermore, he suggested that overmatching may be a sign of an underlying optimizing strategy.

*Theories about Matching*

Several theories have been proposed to explain matching. They can be categorized along two major axes: level of aggregation and type of explanatory theory (see Table 1 below). The first category has two rough sub-categories: molecular and molar. Molecular theories are concerned more with instantaneous events (e.g., an individual lever press and its consequence) and their proximal mechanisms. Molar theories, on the other hand, are based on events that happen over time, at some level of aggregation (e.g., number of presses on a bar per minute). There are two broad levels of the second category also: matching and maximizing. Matching theories are based on some version

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of Equation 1 and accept the matching relation as fundamental to behavior. Maximizing theories are based on utility maximization, often operationalized as maximizing energy
gained per unit time or minimizing time spent in gaining a fixed unit of energy (Stephens & Krebs, 1986).

*Matching Theory.* The matching equations describe molar behavior and leave unspecified molecular processes. Herrnstein (1970, 1974), however, proposed that molar matching occurs because organisms match at the local level also. Given the momentary possibilities of reinforcement, behavior is distributed according to the organism’s estimates of those momentary rates. Later (see Herrnstein & Vaughan, 1980), Herrnstein reported that the theory failed because it was silent concerning which of two unequal VR reinforcement schedules organisms would prefer. Matching predicts only that one alternative would be preferred exclusively.

*Momentary Maximizing.* Shimp (1966, 1969) and Silberberg, Hamilton, Ziriax, and Casey (1978) suggested that local behavior controlled by momentary reinforcement probability produces molar matching. The specifics of concurrent variable-interval variable-interval schedules of reinforcement (*conc VI VI*) produce an oscillation back and forth between schedules as to which has the higher momentary probability of reinforcement (for elaboration see *Common Procedures* section below). Momentary maximizing theorists reason that, if behavior is sensitive to these oscillations, then an analysis of response sequences should reveal patterns of responding that track these oscillations, called *momentary maximizing*. If, the reasoning continues, matching is observed at the molar level and momentary maximizing at the molecular level, then momentary maximizing is the fundamental process, and matching is an artifact that results from aggregating.
Using both pigeons and computer simulation, Shimp (1966, 1969) and Silberberg et al. (1978) reported sequential dependencies in response sequences that tracked the momentary probability of reinforcement. However, in an empirical study (Nevin, 1969) and a subsequent re-analysis (Nevin, 1979), Nevin reported that the probability of switching remained approximately constant as a function of consecutive pecks to an alternative. Williams (1988) argued that Nevin’s failure to find a correspondence between the probability of changing over and the probability of reinforcement for switching is “prima facie evidence against momentary maximizing as a general explanation” (p. 191). Even so, the role of momentary maximizing in choice continues to be a point of controversy (see Nevin, 1982; Silberberg and Ziriax, 1982).

*Optimization.* Another approach to maximization as the controlling process of matching is called *optimization.* Optimization is based on the assumption that organisms distribute behavior in such a way as to get the best return for their effort. In the *conc* VI VI arrangement, an optimizing strategy is to get the most reinforcers possible within some specified period. Rachlin, Green, Kagel, and Battalio (1976) demonstrated that matching is a special case of maximization because, given the two alternatives, matching maximizes the overall reinforcement rate from both alternatives (in economic language, the rates of return). Complicating the debate, Vaughan (1981) reported that pigeons failed to maintain behavior within an optimizing range (global maximizing) when local reinforcement contingencies lead them away from that range (see *Melioration* below; see also Mazur, 1981; Vaughan and Miller, 1984).
Optimization is an organizing principle in several research areas including economic theory and behavioral ecology. An area of common interest between behavioral ecology and behavior analysis is foraging. Animals responding on manipulanda in operant chambers and obtaining food can be viewed as being analogous to animals foraging for food in the wild. Optimal foraging theory makes specific predictions that can be tested and have been supported, generally (see Hanson and Green, 1989; Stephens and Krebs, 1986). The research reported in this dissertation lends itself to a foraging analysis and, thus, has something to say about foraging in particular and optimization in general. This comparison will be made explicit in Chapter II.

*Melioration.* A theory that crosses the categorical boundaries of both axes is called *melioration* (Herrnstein and Vaughan, 1980; Vaughan, 1981; Vaughan & Herrnstein, 1987). It is at once a molar theory and molecular theory: molecular because it relies on “local” reinforcement contingencies, though not at the micro-level of momentary maximizing; molar because it uses aggregated behavior, though not at the global level of matching. It is also both a matching theory and a maximizing theory: matching because it builds on the assumptions of Equation 1 (see below); maximizing-like theory because the richer local reinforcement rate garners more behavior than the leaner when unequal reinforcement rates are in force. Melioration is represented mathematically by the following equation:

\[
R_D = \frac{R_L}{T_L} \times \frac{R_R}{T_R} \quad (4)
\]
T represents time; the two terms to the right of the equals sign represent the local reinforcement rates for each alternative, indicated by the subscripts; and \( R_D \) represents the difference between the two local reinforcement rates. When \( R_D \) equals 0, behavior stabilizes. Simple manipulation results in the time-allocation ratio version of Equation 1:

\[
\frac{T_L}{T_R} = \frac{R_L}{R_R}
\]

Williams and Royalty (1989) performed three experiments testing melioration theory and argue that their results fail to support the theory. Each condition employed different baseline contingencies but all used probe trials to compare whether local or absolute reinforcement rates controlled behavior. The baseline contingencies were such that, when probes were introduced, if local reinforcement contingencies controlled choice then a specific alternative would be preferred whereas if absolutes reinforcement rates controlled choice then the other alternative would be preferred. Regardless of some inconsistency, Williams and Royalty argue that taken as a whole the three conditions support absolute rather than local control; a result contrary to melioration (For evidence against control by absolute reinforcer rates see Vyse & Belke, 1992).

Evidence both for and against all the above theories proposed to account for matching has been reported. Some theories have been more successful than others, while others have been discarded (e.g., molecular matching). Several researchers have wondered if there are definitive tests between the theories and if, perhaps, all are involved depending on how the question is framed (Miller, Heiner, & Manning, 1990; Nevin 1982). Perhaps one reason for being unable to arrive at an acceptable theory of matching is that we don't
understand the particulars of matching well enough. Baum developed the generalized
matching relation to account quantitatively for systematic deviations from strict equality.
I will now return to the questions surrounding deviations from strict matching.

*Why Deviations?*

Attempting to determine why sensitivity to reinforcement deviates from 1.0 has
motivated much discussion and research. Baum (1974b) presents two possible
approaches. Investigators, such as Williams (1988), could assume that a particular value
of s is normative; that there is a "true" measure of sensitivity and deviations from that
value result from measurement error. The second approach asserts that Equation 1 is
simply a special case of Equation 3 and that the absolute value of s is of no special
importance. What is important is the matching relation as a theoretical framework (see
Killeen, 1972; Rachlin, 1971). Regardless of which rationale one takes, both lead to the
same practice: determining the specific factors that affect sensitivity.

*Sensitivity.* It is possible that sensitivity varies due to random error (Baum, 1979). If
so, across experiments the values of s would fall both above and below the central
tendency and in effect cancel out the variation when data from different experiments are
pooled. However, separate reviews by Baum (1979), Taylor and Davison (1983), and
Wearden and Burgess (1982) conclude that deviations from strict matching are
systematic. One striking result is the consistently different sensitivities obtained from
time- and response-allocation measures. Baum (1979) reported that the mode of time-
allocation sensitivities was 1.0 and the distribution was skewed to values less than 1.0.
The mode of response-allocation measures was .79 and the distribution was slightly skewed toward 1.0. Further, he noted a consistent difference between sensitivity estimates obtained in his own and Davison’s laboratory. Baum’s exponents tended around 1.0 while Davison’s tended to be less than 1.0. Undermatching is the predominant result with time-allocation sensitivities larger than response-allocation sensitivities. However, Wearden and Burgess (1982) point out that, on those infrequent occasions that overmatching occurs, time-allocation sensitivities tend to be less extreme than response-allocation sensitivities. This suggests that deviations are from some anchor and not that response-allocation sensitivities are consistently less than time-allocation sensitivities (see Davison, 1991).

Baum (1974b, 1979) suggested five possible factors that contribute to the exponent deviating from 1.0, in particular toward undermatching. Two factors concern experimental procedures, while the other three are organismic.

One of the suggested procedural factors was that the changeover delay (COD) may not sufficiently separate the alternatives. A COD is a fixed delay to reinforcement following a changeover, commonly employed in concurrent schedules research (COD is discussed in later sections). The second proposed procedural factor was level of deprivation, although McSweeney (1975) reported that it does not affect $s$.

A suggested organismic factor was poor discrimination between alternatives. Animals that discriminate poorly will tend toward indifference which yields undermatching. Davison and McCarthy (1988) considered three possible sources of poor discrimination: stimulus discriminability (cf., Davison & McCarthy, 1994; Miller,
Saunders, & Bourland, 1980), reinforcement rate discrimination, and misallocation of reinforcer origin. Other proposed organismic factors included inconsistency of preference and different response patterns on each alternative. Regarding inconsistency of preference, Nevin (1971) reported that, on concurrent fixed-interval (FI) and variable-interval (VI) schedules, preference for the FI schedule oscillated according to the location in the interval. Preference for the FI increased as the end of the interval approached. Perhaps something similar is occurring in conc VI VI procedures. Regarding different patterns of responding to the two alternatives, the final suggested organismic factor, pigeons may emit different response-to-pause ratios to the rich and lean alternatives. Such a result, in conjunction with low interchangeover times, would have a disproportionate effect on the leaner alternative. Undermatching would be the result. These proposed factors may contribute individually or sympathetically to produce undermatching.

In a more recent review, Taylor and Davison (1983) considered 155 data sets from 18 studies and reported consistent undermatching. Their analysis focused on the progression used to calculate the VI schedules. Traditionally, variable-interval schedules of reinforcement are derived using one of two methods to produce the interreinforcement intervals (IRIs): arithmetic and exponential progressions. The IRIs of arithmetic VI schedules are symmetrically distributed around the mean with the longest interval no more than twice the mean interval (Williams, 1988). Exponentially derived IRIs, on the other hand, are skewed toward the longer intervals and have means and standard deviations that are approximately equal. Whereas Baum (1979) reported differences in s
between time- and response-allocation measures, Taylor and Davison reported that the
means and standard deviations of the two measures of behavior were about the same for
exponential VI schedules; however, the means of the two measures differed by .10 for
arithmetic VI schedules. Taylor and Davison assert that the differences in the slope
obtained in the two labs occurred because Baum usually used exponential VI schedules
while Davison and his associates usually used arithmetic VI schedules. The accuracy of
Taylor and Davison's conclusions need to be reassessed after more appropriate methods
of analysis are performed. They plotted the sensitivity measures on arithmetic scales, but
since sensitivity is always a ratio logarithmic axes should be used (see Robinson, 1992).
Contrary to Taylor and Davison's finding, recent research in our lab indicates that the
methods of constructing the intervals does not produce consistently different values of s
when a within-subject design is used (Ehlert & Grace, 1994).

The general consensus is that the exponent in equation 3 is not invariant. However,
the variation is regular. Reviews indicate that controlling factors responsible for the
variation may be found but more research is needed to determine exactly what they are.
Six sources (Baum, 1974b, 1979; Davison & McCarthy, 1988; Taylor & Davison, 1983;
Wearden & Burgess, 1982; Williams, 1988) suggest that the variation may be due to
procedural\(^1\) differences, with Baum, Wearden and Burgess, and Williams all implicating
the COD as a prime factor. Since procedural details seem crucial to sensitivity, the next
section will describe the two main experimental arrangements used in the experimental

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\(^1\)Wearden & Burgess write that "the degree of undermatching exhibited appears little affected by
\textit{procedural variations} between experiments and occurs in studies using different...values of changeover
analysis of choice. Particular attention will be paid to how the two procedures treat the changeover requirement.

*Common Procedures*

Researchers in the experimental analysis of choice commonly employ one of two experimental procedures. In the *two-key* procedure each manipulandum is directly associated with a reinforcement schedule; responses to either manipulandum (the “side” keys) can be reinforced. In the *changeover-key* procedure one manipulandum (the main key) is associated with two or more schedules, signaled by different discriminative stimuli, while a response to a second manipulandum (the changeover key) changes the stimulus and associated reinforcement schedule on the main key. Herrnstein (1961) used the two-key procedure. Later, Catania (1963) used the changeover-key procedure and obtained close approximations to matching also. The two procedures are considered to be functionally equivalent (Pliskoff, Cicerone, and Nelson, 1978).

Both procedures can handle any combination of schedules. Although other schedule types (e.g., FI, variable ratio (VR)) and other combinations (e.g., VI VR, VI FI, VR VR) have been used since, Herrnstein and Catania used two VI schedules that were simultaneously available. Behavior controlled by other than *conc* VI VI schedules of reinforcement has produced less controversy.

delay” (p.346, italics mine). For this dissertation, the changeover requirement is considered a procedural variation.
VI schedules have a number of characteristics that, when combined with a second VI schedule, foster matching. One characteristic is that scheduled reinforcement probability is independent of time since last reinforcement and is unaffected by behavior (Baum, 1992). In effect, this property allows organisms to switch between alternatives without greatly altering the reinforcement rates. A second property of VI schedules is that reinforcement becomes more likely the longer the time since the last response. A slow response rate, then, yields a high probability that an individual response will be reinforced, and in the lower limit every response will obtain reinforcement (Baum, 1992).

These two characteristics set up a dynamic when two VI schedules of reinforcement are made available concurrently. While working on one alternative, because the reinforcement availability is unpredictable, it is always possible that the next response will yield reinforcement. Yet, because reinforcement probability increases the greater the interresponse time, the longer an organism stays away from the other alternative the higher the probability that switching to it will yield reinforcement. The question an organism working in a conc VI VI preparation must answer is: Should I stay or should I switch? Left unchecked, behavior switches rapidly between the two alternatives, resulting in measured behavior centering around indifference, indicating insensitivity to relative reinforcement rates, and thereby obviating the matching law.

To counter rapid switching, Herrnstein (1961) included a COD. The specifics of the COD depend on whether the two-key or changeover-key procedure is used. The two-key procedure usually initiates the COD upon a response to the other side key (a changeover response). After the delay, another response to the new alternative is required before a
reinforcer may be obtained. This arrangement means that the changeover response, even though it is delivered to a key that usually produces food, can never be reinforced immediately. As commonly arranged, then, the COD begins after the organism responds on the new alternative, and in effect punishes changing over after already having switched alternatives (see de Villiers, 1977; Pliskoff, 1971). The time since the last response on the old alternative, during which the organism travels the distance between the response keys and actually switches, is not a measured component of the COD.

The COD in a changeover-key procedure is treated differently mainly due to the location of the changeover response. This procedure has a manipulandum dedicated solely to the changeover response. Responses to the changeover-key change the color of the main key (Findley, 1958) and no response to the changeover-key ever yields food. Generally, the COD begins after a single response to the changeover key. Until the COD times out, responses to the main key cannot produce food. Because the COD for the changeover-key procedure begins with a response to the changeover key, unlike the two-key procedure, a fraction of the time the organism spends switching alternatives contributes to satisfying the COD. But the time traveling to the changeover key is usually not factored into the COD.

The location of the changeover response for the two procedures leads to different treatment of the response. The two-key procedure usually includes the changeover response with total behavior, while the changeover-key procedure excludes the response. Exactly what should be done with the changeover response is not clear. With the changeover-key procedure it makes sense to exclude it, because it is on a never-
reinforced key. With the two-key procedure, it is less clear; the changeover response is on a reinforced key but the response itself is never reinforced. Researchers have discussed what should be done with behavior during the COD. Baum (1974a) analyzed relative responding during and after changeover delay. He reported that COD responding produced extreme undermatching, with some slopes almost horizontal. Should all COD behavior be excluded? Baum (1982) suggested that it should. Davison and McCarthy (1988, pp. 147-48) argue for including changeover behavior because sensitivity measures are more constant when changeover behavior is included than when it is excluded. To settle this question, we must determine how COD procedures affect sensitivity.

The Changeover Delay. Using a changeover-key procedure, Catania (1963) reported that the two sides of Equation 1 better approximated equality when a 2-second COD was included in the procedure than when it was excluded. Also using a changeover-key procedure, Shull and Pliskoff (1967) reinforced rats' lever pressing with electrical brain stimulation, using one pair of VI schedules, and varied the COD across six values from 0-seconds (a single press to the changeover key was required) to 20-seconds. As the COD duration increased relative behavior more closely matched relative reinforcement, but matching performance did not decrease as the COD duration was subsequently reduced. Davison and McCarthy (1988) assert that the Shull and Pliskoff result refutes Baum's claim that the COD affects the exponent. Their conclusion, however, should be accepted with caution. Because Shull and Pliskoff kept each condition in effect for five days only and did not signal the COD, it is unlikely that the rats had sufficient exposure to each
COD duration to alter behavior, particularly in the descending series. Longer exposure may alter the conclusion.

A number of other studies have manipulated the COD (for review, see Stubbs, Pliskoff, & Reid, 1977). Dreyfus, Dorman, Fetterman, and Stubbs (1982) re-analyzed data from Silberberg and Fantino (1970). Silberberg and Fantino incorporated three COD durations (0.88, 1.75, & 3.5 seconds) and varied the relative reinforcement rates. Dreyfus et al. report three main findings. First, as originally reported by Silberberg and Fantino, the pigeons emitted higher rates of responding during the COD than after. If such response rate differences hold for both major procedures, then including or excluding COD responses will have a marked effect on sensitivity. Second, the alternative with the leaner reinforcement rate produced more rapid response rates during COD. This response pattern, by adding relatively more COD responses to the leaner alternative, decreases the values of s for response allocation but not for time, consistent with Baum (1979) and Taylor and Davison (1983). And third, response rate during COD decreased as COD duration increased. Together, these findings indicate that the COD and how the data are treated can have a powerful impact on sensitivity.

*The Fixed-ratio Changeover.* Another method used to impose a changeover requirement is the fixed-ratio changeover (FRCO; see Pliskoff & Fetterman, 1981). Usually the changeover-key procedure requires a single response (FR 1) to switch alternatives; however, increasing the FR required to complete a changeover can be seen as similar to lengthening the COD. An advantage of the FRCO method of programming the changeover requirement is that it requires that the work associated with changing over
be performed *while* changing over rather than, as is the case with a COD, *after* the organism has arrived at the new alternative. Whether the COD merely separates the two schedules (Herrnstein, 1961, 1970) or punishes the changeover response (Pliskoff, 1971) may depend on when during the act of switching the two methods impose the work. As will be discussed below, both methods can produce similar sensitivity measures; nevertheless, the above distinction may have important subtle effects on behavior allocation. In particular, the FRCO method readily produces overmatching.

Stubbs et al. (1977) reviewed and analyzed several studies to consider the effects of the changeover requirement on time at an alternative. Included in the review was an unpublished study by Pliskoff on the effects of increasing the fixed-ratio changeover. Pliskoff used one pair of *concurrent* VI 3-minute VI 3-minute schedules throughout the experiment. The FRCOs were 1, 2, 5, 10, or 20. A power function describes the relation between changeover rates and changeover requirement for both the FRCO and COD preparations. Pliskoff's study is the first I know of that used a FRCO without a COD to impose the changeover requirement. However, the reinforcement rates were not varied for Pliskoff's unpublished study, precluding determining a slope.

Later studies reported that varying the ratio changeover requirement also affects the exponent of Equation 3. Experiment 1 in a study by Pliskoff, Cicerone, and Nelson (1978) used a changeover-key procedure with FRCO 1, 5, and 10. Two replications were performed using three different pigeons for each replication. The first replication contained seven conditions with all conditions using a FRCO 10 except the last one, which used a FRCO 1. The second replication included five conditions, all with FRCO 5.
Pliskoff et al. reported overmatching as the normative result for both replications. The last condition of Replication 1 was an attempt to demonstrate matching using traditional arrangements (i.e., FR 1 on the changeover key); all three birds approximated matching.

Fitting the data from FRCO 5 and 10 separately to Equation 2 confirmed the visual analysis of Pliskoff et al., but not universally. Two conditions from Replication 1 and one from Replication 2 were excluded because extinction was one of the reinforcement schedules. Also excluded was the FRCO 1 condition. For both FRCOs for each bird, response-allocation slopes were always greater than time allocation. The means of the slopes for FRCO 5 ($\bar{X}_{\text{resp}} = 1.25$, $\bar{X}_{\text{time}} = 1.06$) were consistently less than FRCO 10 ($\bar{X}_{\text{resp}} = 1.78$, $\bar{X}_{\text{time}} = 1.54$). For FRCO 5, two of the three birds' time slopes approximated matching. Bias was negligible and the lowest variance accounted for was .91. The re-analysis suggests that a) response-allocation slopes were greater than time-allocation and thus deviated more from matching, b) the larger FRCO produced steeper slopes, and c) contrary to Pliskoff et al.'s claim, overmatching was not the norm for FRCO 5. Perhaps a within-subject design is needed to compare different FRCOs.

A few other studies report similar results when using the FRCO method. Pliskoff and Fetterman (1981) used a FRCO 1, 2, or 4 and reported overmatching with the FRCO 4 and matching with FRCO 2. More recently Dreyfus, DePorto-Callan, and Pesillo (1993) implemented a 2-second COD and a FRCO 5. One or the other changeover method was in effect throughout the first half of a 90-minute daily session. The other method was in effect for the second half. Traditional analyses of the FRCO data obtained results similar to Pliskoff et al. (1978) reviewed above and others (Dunn, 1982): response allocation
overmatched while time allocation matched. However, when time and responses accrued during changeover were included, Dreyfus et al. reported undermatching for both COD and FRCO changeover requirements.

The reviewed results derived from the FRCO procedure indicate that overmatching is the more common result when a fixed number of responses is required to switch alternatives. Taylor and Davison (1983) claim that FRCO-derived overmatching is artifactual because the responses on the changeover key are not included with the total responses. They re-analyzed the Pliskoff et al. (1978) data by adding the changeover-key responses to the alternative to which the pigeons were going, similar to Dreyfus et al. (1993), and found close approximations to matching. However, as pointed out by Dreyfus et al., asserting what should be done with behavior during switching depends on whether one assumes matching is normative.

The indication that the changeover requirement affects sensitivity demands that the procedure be studied in more detail. Developing a procedure that disentangles the various components of changing over would assist in furthering the debate over what should be done with the changeover response(s) and other behavior occurring while switching. This dissertation contributes to our understanding of the intricacies of changing over by: first, testing a procedure that completely separates switching behavior from active-key responding; second, exploring parametrically the effects the FRCO procedure has on Equation 3's exponent in a within-subjects design with extensive training in each condition; and third, looking for local regularities in changeover behavior in relation to reinforcement rates and changeover requirement.
CHAPTER II

FORAGING AS OPERANT BEHAVIOR

The similarity between the experimental analysis of choice by psychologists and research on foraging by behavioral ecologists has been made explicit over the last few decades (see, Green & Kagel, 1987, 1990; Krebs & Kacelnik, 1991; Lea, 1981; Staddon, 1980; Shettleworth, 1988; Stephens & Krebs, 1986). In the 1980s at least three conferences brought together investigators from both disciplines for reports on topics of mutual interest. Each conference published a book containing those reports (Commons, Kacelnik, & Shettleworth, 1987; Kamil, Krebs, & Pulliam, 1987; Kamil & Sargent, 1981). The similarity between the two research veins is evident in this dissertation. Chapter II will briefly review relevant issues from the foraging literature and operant research that has simulated travel between patches.

Foraging

Foraging is the procurement of resources by organisms in the wild. Modern exploration of foraging incorporates an economic analysis of costs and benefits. The behavior of starling parents during breeding season illustrates such cost/benefit analysis (from Krebs & Davies, 1993, Chapter 3, and Krebs & Kacelnik, 1991; see also Stephens & Krebs, 1986). During the height of breeding season, starling parents make up to 400
round trips per day to provide food for their hatchlings. Each of these trips involves a number of important measurable factors: load size, distance of prey from nest, patch density, ease of prey capture, among others. Should the forager bring back the maximum load it can carry on each trip? How far should it travel from the nest? What affect does travel have on load size? Are travel and load size affected by the frequency of encountering prey or the handling time required to access prey once encountered? Using economic models to describe how organisms solve these problems has fostered both research on and theory about animal behavior (Shettleworth, 1988).

Load size is particularly illustrative. With multiple nestlings to feed, parent starlings must balance the cost of each trip with providing sufficient food for the nestlings, called the loading curve. The advantage of foraging until the beak is filled with prey before returning to the nest is apparent, improved ability to meet nestlings’ nutrient requirements. However, any benefits gained from increasing the number of prey returned per trip is counter-balanced by the reduction in foraging efficiency including such costs as greater prey capture time, increased risk of losing already captured prey, and increased load weight. When considered in economic terms, balancing the costs and benefits of an activity is a form of the principle of lost opportunity, the benefits of one option are evaluated in relation to the next-best option (Stephens & Krebs, 1986).

Load size is just one of the possible measurable components of starling’s foraging. One can imagine that all of the factors listed above could influence the offsprings’ survival. Obviously, the parents’ expertise in procuring food will impact that survival. Over evolutionary history, nature will have selected traits that enhance prey procurement
and thereby increased those traits' *relative fitness*. Thus, modern starlings should perform optimally, or close to it, when foraging for their offspring's food. Such reasoning fosters optimal models of foraging.

The starling example also introduces three concepts of foraging that are important for this dissertation: patchy environments, patch profitability, and travel. Prey can be localized in clumps, called *patches*, or be separate from other like items. MacArthur & Pianka (1966) used this feature to form two categories of resource exploitation: prey and patch. Although the distinction between a discrete prey and a patch is somewhat ambiguous (see Stephens & Krebs, 1986), because the alternatives in an operant chamber are locations to which organisms go to obtain food, most operant researchers consider the available alternatives to be patches.

Once a forager is in a patch, one problem of interest to behavioral ecologists concerns when the patch will be vacated. Both patch profitability and travel influence the problem's solution. *Patch profitability* denotes the frequency of prey captures within a patch, analogous to the operant concept of *schedule of reinforcement*. A major influence on when the patch is vacated is the profitability of the present patch relative to the other available patches, or simply *relative profitability*. The picture becomes more complicated when distance between patches, called *travel*, is considered. Ceteris paribus, as distance between patches increases stay time in a patch increases also. Similar results occur as relative profitability increases; stay time in richer patches increases (for review see Shettleworth, 1988). Counter-intuitively, however, as the environment's overall profitability increases, stay time decreases. Such reduction makes sense in light of the
principle of lost opportunity. Persistence in a depleting patch when other patches have high yields decreases prey-capture rate. Therefore, in a rich environment, an organism that stays in a patch loses the opportunity to forage in relatively richer patches.

Mathematical models of behavior, and optimal models of foraging in particular, allow a quantitative analysis of the principle of lost opportunity, an intuitive model. Furthermore, mathematical models benefit scientific investigation in at least two ways: a) the model's assumptions are unambiguous and b) precise predictions are afforded (Krebs & Kacelnik, 1991). These two benefits move behavioral ecology closer to satisfying Williams's (1966) injunction to rigorous rather than intuitive theories.

Organisms working in an operant chamber can be seen as a constrained version of organisms foraging in the wild. Since operant behavior is behavior that is controlled by its consequences, in its most general sense, foraging obviously fits this definition because one consequence of not foraging is starvation, an aversive consequence to organisms formed from selfish genes. Those organisms whose behavior changes relative to the environmental contingencies, prey density say, have a greater likelihood of food procurement and, thus, of survival. Therefore, because foraging is sensitive to consequences, it is operant behavior (see Baum, 1982, 1983, 1987).

The VI reinforcement schedules commonly used in matching law research, though not originally intended to do such, model some types of naturally occurring patch profitability. Variable-interval schedules of reinforcement can be seen as analogous to rapidly depleting food sources that replenish while the predator is away (Stephens & Krebs, 1986). Real-world examples include insects washing on the shore of a lake or
stream and the accumulation of floral nectar. In both instances, resources amass regardless of predator behavior; analogous to the “something-outside-control-of-responding” component of variable interval schedules (Baum, 1992).

Foraging and operant behavior are similar in another sense. Even in a single-manipulandum chamber, a variety of behavior is possible. A rat can press the response bar or not, fall asleep in the corner, explore the chamber, eliminate waste, or scratch an itch. The rat “chooses” among these various options; that is, behavior is distributed between them. A two-manipulanda chamber affords explicit measurement of competing opportunities. A foraging bird is not constrained to merely forage; like a rat in a single-manipulandum chamber it too can engage in other activities. Also, like a rat in a two-manipulanda chamber, foraging organisms choose between multiple patches.

Despite the noted similarities, Baum (1983) suggests “three artificialities” of free-operant chamber research: (a) the small size of the chamber, which precludes broad-range foraging typical of non-central-place foragers; (b) the experimental-session time comprises only a small portion of an organism’s day, which forces unusual feeding patterns; and (c) the schedules of reinforcement’s dissimilarity to patterns of prey-capture in free-ranging foraging. Various attempts to ameliorate the differences have met with some success (Baum, 1983; Shettleworth, 1988). In a similar vein, Lea (1981) acknowledges that foraging and operant behavior are not necessarily the same simply because of apparent similarities. However, after an extensive review, he draws three conclusions: (a) the experimental analysis of behavior has advanced our understanding of naturally occurring behavior; (b) research on foraging has increased the range of
behavior analysis to new species, responses, and situations; and (c) the natural selection framework of foraging provides a potential explanation for the regularities formulated in the laboratory. In a more recent review, Shettleworth (1988) concludes that developments in both fields "have considerably enriched this enterprise since it was reviewed by Lea" (p. 41).

*Travel in an Operant Chamber*

Baum (1982) reported an innovative modification to a standard operant chamber that more closely modeled travel between patches, addressing the first "artificiality" (Baum, 1983). Contrary to foraging in the wild, "patches" (response keys) in operant chambers are separated by small distances (e.g., the two-key procedure). Often only a color distinguishes between two patches; the location is identical (e.g., the changeover-key procedure). Baum’s general arrangement was similar to the two-key procedure described above. However, rather than using a delay as the changeover requirement, Baum required the pigeons to travel around barriers of various lengths and, for some pigeons, a hurdle at barrier’s end. The barrier projected perpendicular from the center of the instrument panel with a cut-away that allowed access to the hopper from either side, maintaining the economy of a single feeder. The partition creates a more naturalistic relationship between "patches" in a chamber. The added distance between the patches required the subjects to engage in locomotor activity to switch patches, as if they were in the wild. Baum (1982) reports different average sensitivity values for two groups of pigeons. The group with the larger distance between patches overmatched while the
group with the smaller distance undermatched, consistent with typical results. Related research using rats has been performed by another of Baum’s graduate students, but with even greater distances and vertical climbing (Aparicio, 1992; 1994).

Considering this arrangement from a foraging perspective, the different travel requirements affect sensitivity by altering the duration of patch visits (called *visit duration*, or *dwell, residence, or stay times*). As noted above, increasing distance between patches in naturalistic settings alters load size and other behavior (e.g., Kacelnik, 1984). Baum (1982) reported increasing stay times as distance between patches increased, measured in either pecks or time. Lea (1985) considered stay times using a 21-cm partition and reported relatively constant stay time for each visit except in visits that contained reinforcement. Also, stay times on the richer patch were generally longer than those on the learner.

As reported in the next chapter, this dissertation manipulated travel between patches in a way more common to operant techniques. Rather than adding a partition to the standard chamber, a response key was used to simulate travel between patches (see also Davison & McCarthy, 1994; McCarthy, Voss, & Davison, 1994). Organisms that move from one patch to another engage in work to switch patches. A schedule of reinforcement commonly used to simulate a work requirement is a FR schedule. If a large FR produces results similar to inserting a partition, we could conclude that operant methods can be made to be functionally equivalent to more naturalistic settings and thereby provide even more support for the common interests of behavioral ecologists and operant psychologists. Baum’s (1983) argument that the two fields not only should but
must integrate in order to fully understand behavior will be made an easier task to complete.
CHAPTER III

THE EXPERIMENT

Subjects

Four White Carneaux pigeons, numbered W34, W35, W36, and W37, served as subjects. All had experience with operant chambers and reinforcement schedules prior to beginning this research program. With few exceptions, sessions were conducted daily, approximately 22.5 hours apart. As necessary to maintain each pigeon at approximately 80% of free-feeding body weight, supplemental feedings were given in the home cage after all pigeons finished a session. Water and grit were freely available in the home cage.

Apparatus

Experimental sessions were conducted in four standard three-key operant chambers. The chambers measured 35 cm wide by 35 cm high by 32 cm deep. The distance from the chamber walls to the outside edge of the openings for both side keys measured 80 mm. The outside edges of the center key were 56 mm from the inside edges of both side keys. Each key opening had a 26 mm diameter. The hopper measured 50 mm high by 57 mm wide and the top edge was 90 mm directly below the center key with the bottom
edge 95 mm off the floor. Ambient illumination was provided by a white houselight
centered above the center response key.

Reinforcement consisted of three seconds' access to wheat, provided according to
variable-interval schedules of reinforcement. Each schedule had 16 intervals obtained
from a Fleshler-Hoffman progression (Fleshler & Hoffman, 1962). The mean of the base
intervals was 15.02 seconds with a standard deviation of 15.01. All schedules arranged a
constant minimum interval of .5 seconds. During reinforcement, a white light
illuminated the hopper, house and stimulus lights darkened, and timing ceased. An IBM-
compatible personal computer using MEDPC software controlled all data recording and
scheduling of experimental events. The computer was located in an adjacent room and
connected with the chambers through a MED Associates interface. Turbo Pascal routines
extracted the raw data from MEDPC generated files and data analyses were performed
using Microsoft Excel.

Procedure

The procedure combined elements of the two-key procedure with the changeover-key
procedure. Responding on either side key was reinforced according to independent conc
VI VI schedules. The center key functioned as the changeover key. Pecks to this key
switched the active alternative. To distinguish this preparation from the more standard
ones, I call this the three-key FRCO procedure. The three-key FRCO procedure
completely disentangles active-key responding from imposed changeover requirements.
This allows changeover behavior to be reasonably excluded from a matching relation.
analysis, a common concern of researchers (see Common Procedures above and Dreyfus, et al., 1993).

Sessions began with the two side keys illuminated. A peck to either side key darkened the other key, turned on the houselight, illuminated the changeover key, and began both schedule timers. A peck to the changeover key darkened the active side key and, when the FRCO was satisfied, the changeover key darkened and the other side key illuminated. The first peck to the new side key re-illumination the changeover key and could be reinforced. Schedule timing continued during switching. Data collection terminated on the first changeover after 50 hopper presentations. Terminating data collection after a changeover assured that the visit that contained the last reinforcer ended in the same fashion as all other visits and, therefore, was complete. Thus a recorded session consisted only of complete visits.

Depending on the condition and date, sessions terminated in either of two ways: after the next hopper presentation following data-collection termination, or when the variables reached the computer system's memory limit. Generally, termination due to memory limits only occurred in FRCO 0 conditions, the first FRCO 2 condition, and a few other sessions with many changeovers. During Phase IV or V, depending on the pigeon, a program change ended any need to terminate sessions due to the system's memory limitation (see below for sequence of conditions). Terminating the session after the first hopper presentation after a changeover prevented a session ending on a changeover.

Data were recorded in detail. The changeover was divided into three times: changeover initiation latency (time from last peck on "old" alternative to first peck on
changeover key), FR response duration (time to emit the FRCO), and changeover termination latency (time from last peck on changeover key to first peck on "new" alternative). These three measures allowed a complete record of changeover times. At every event, with event meaning changeover or reinforcer, the active alternative when the event occurred and the number of pecks and time since last event were recorded. Also recorded were the latency to and side of the first peck, and number of pecks and changeovers and duration after formal data collection terminated.

<table>
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<th>0</th>
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<th>6</th>
<th>12</th>
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<td>18</td>
<td>17</td>
<td>16</td>
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<td>2':1' (1:2)</td>
<td>3</td>
<td>W37: 6</td>
<td>19</td>
<td>x</td>
<td>x</td>
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<tr>
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<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
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<td>20</td>
<td>x</td>
<td>x</td>
<td>11</td>
</tr>
<tr>
<td>2':8' (4:1)</td>
<td>5</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>14</td>
</tr>
</tbody>
</table>

**Exceptions**

1. Condition 6 for W37 was the 1:2 reinforcer ratio
2. Between conditions 6 & 7, all pigeons were exposed to a FRCO 1
3. Between conditions 7 & 8, W34 was exposed to a FRCO 4

To investigate the effects on the matching relation of the changeover requirement, two variables were manipulated: reinforcer ratio and changeover requirement. See Table 2 for sequence of conditions. Numbers in cells indicate condition number. Cells containing two numbers indicate repeated conditions. Exceptions are noted at bottom and exceptions 2 and 3 were not included in analyses. The reinforcer ratio was manipulated by varying the reinforcement schedule associated with one of the response alternatives (the "variable" alternative, right key), while pecks on the other alternative
were reinforced according to a VI 2-minute schedule throughout the experiment (the "constant" alternative, left key). The reinforcer rates for the variable alternative included the following schedules: VI 30-second (a 1:4 reinforcer ratio), VI 1-minute (a 1:2 ratio), VI 2-minute (a 1:1 ratio), VI 4-minute (a 2:1 ratio), and VI 8-minute (a 4:1 ratio). Initial order of presentation was determined by random draw.

The second variable, the changeover requirement, was manipulated by varying the number of changeover-key pecks required to switch alternatives. The changeover requirement was one of the following fixed-ratio schedules: 0, 1, 2, 4, 6, 12, or 20. Note that FRCO 0 is identical to the two-key procedure without a COD; the changeover key remained dark and only the side keys were operative. The equal and two extreme reinforcer ratios were combined with all changeover requirements. The 1:2 and 2:1 reinforcer ratios were combined with FRCO 0, 2, & 20.

Preliminary training. Because these were experienced pigeons, preliminary training was minimal. The pigeons were exposed to the three-key FRCO procedure with a FRCO 2 and conc VI 18" VI 18" schedules controlling reinforcement for the initial experimental session. Nineteen additional pre-training sessions were given, in which the changeover key was inactive. Conc VI VI schedules reinforced pecking on the side keys. The VI schedules remained equal and were increased to 27 seconds, then to 63 seconds, and, lastly, to 116 seconds.

Experimental conditions. Conditions in Phase I manipulated the reinforcer ratios while fixing the FRCO at 0 (see Table 2). The first condition had a FRCO 0 with the 1:1 reinforcer ratio. All pigeons then progressed through the four other reinforcer ratios. In
Phase II the reinforcer ratio remained 1:1 while the FR CO was successively increased to the maximum schedule (FR 20). During Phase III the FR CO 20 remained while the reinforcer ratios were manipulated. Throughout Phase IV the reinforcer ratio remained 1:4 while the FR CO progressed down to 2. In Phase V the reinforcer ratios were manipulated while a FR CO 2 was in effect and in Phase VI FR COs 6 & 12 were in effect while the reinforcer ratio remained constant at 4:1.

Stability criteria. Each condition remained in effect at least until, and for some conditions well after, the following criteria were satisfied:

1. Sessions were in effect for a minimum number of days. Usually the minimum was 15, but Phase I conditions were in effect for only 10 days because day-to-day behavior ratios were highly consistent.

2. At least 100 reinforcers needed to have been obtained from the leaner alternative.

In a few of the earlier conditions, some pigeons received only about 80 reinforcers from the lean alternative. Pigeon W36 received only 28 reinforcers from the lean alternative in Condition 5.

3. Behavior ratios were without obvious trends over the sessions used to satisfy the second criterion. A loosely held rule was used to define "obvious": no new high nor low behavior ratios in the sessions wherein the 80 to 100 reinforcements are obtained. The weakness of this rule was evident whenever large variations in choice occurred, usually this accompanied a marked change in the programmed reinforcer ratio. As behavior stabilized after large fluctuations in choice, the "no new high nor low" criterion became ineffective as a stability measure. When such
occurred, the condition was continued until no trends were obvious and day-to-day behavior ratios were relatively consistent.
CHAPTER IV

THE RESULTS

Tables (Appendix I) and figures (Appendices II, III, & IV) of data for each pigeon are shown in the appendices, segregated by analysis and sorted by figure. The results are presented in three major sections. The first section, Molar Results, contains molar analyses. A traditional generalized matching relation analysis is presented. Included are a) fitting the data from individual pigeons to Equation 2 to derive response- and time-allocation sensitivities and log biases for each changeover requirement, b) point estimates of sensitivity measures across conditions, c) response rates across conditions, and d) changeover rates by FRCO and reinforcer ratio.

The second section, Local Results, focuses on local analyses. An analysis of changeover latencies and response rates on the changeover key by FRCO and reinforcer ratio is presented first. Next, what may be the most surprising results from this study are presented: the conditional probability of changing over as a function of pecks since either visit entry (for definition of visit, see below) or last reinforcer. Results show that the probability of switching increases the longer the visit, and the effect becomes more pronounced the greater the changeover requirement.

Finally, the third section, Foraging Analyses, presents results from an extensive analysis of visits, both number of pecks and duration. Visits are categorized into non-
reinforced and reinforced, and reinforced visits are subdivided into single and multiple reinforcers.

*Molar Analyses*

The data used in the molar analyses were obtained by summing across the stable sessions of each condition. Ratios (constant alternative divided by variable alternative) were then calculated for responses, time spent, and reinforcers obtained. All ratios were re-expressed as logarithms (base 10). Response rates on each side key were obtained by dividing number of pecks in a visit by visit duration. Changeover rates were calculated by dividing total number of changeovers in a condition by total time spent pecking on the side response keys. Time and responses that accrued during switching were kept separate from time spent on and responses made to side keys. All molar-analyses figures are in Appendix II.

*Matching Relation Analysis.* Figure 1 displays choice (log response and time ratios) as a function of log reinforcer ratio (obtained) for W37 for each FRCO. Linear equations are listed in the same order as their legend labels. Standard errors of the slope estimate are included beside the equations (see Appendix 1 for other measures).

Figure 2 displays the fitted parameters of the generalized matching relation for all pigeons at all FRCOs. Parameters were fitted using least-squares linear regression. Slopes obtained for FRCO 0, 2, and 20 were taken from five reinforcer ratios while slopes for FRCO 6 and 12 were taken from three (the two extreme ratios and one equality). Because behavior from two pigeons in the repeated conditions was
Figure 1. Log response (left, c/v) and log time (right, c/v) plotted as a function of log reinforcement (c/v) obtained for Pigeon W37. Least-squares linear regression equations, with their standard errors of the estimate for each changeover requirement, are listed in the same order as the lines' identifiers are listed in the legend.
Figure 2. Fitted parameters of Equation 2 for response (left) and time (right) allocation are plotted as a function of log changeover requirement for each pigeon (see legend for symbol). Logarithm (base 10) of the slopes are presented in the top panels and log bias in the bottom panels.
inconsistent with the first condition, only the first condition of repeated conditions was included in the matching relation analyses. The two left panels present response-allocation measures while the two right panels present time-allocation measures. The two top panels depict the logarithms (base 10) of the slopes and the bottom two depict log biases (see Equation 2). The logarithms of the slopes were taken because slopes should be expressed in equal intervals away from matching. Log slopes equate matching with zero, while positive numbers show overmatching and negative numbers show undermatching. The x-axis in each panel is the logarithm of the changeover requirement, with FRCO 0 plotted at 0, equivalent to log 1.

Since FRCO 0 was essentially a different procedure, in that it was a two-key procedure, whereas the non-zero FRCOs used the three-key FRCO procedure, I treat the data obtained from them separately. First, the response-allocation slopes for FRCO 0 indicate that response ratios undermatch reinforcer ratios (see Table 3 below). All values are well below 1.0 (range = .31 to .76) and are markedly lower than the central tendency ($\bar{X} = .965$) for response-allocation sensitivity obtained using exponential VI schedules reported by Taylor and Davison (1983); however, they are not outside the ranges reported in the three reviews of generalized matching, particularly considering that no changeover-key pecks were required to switch. Except for W36, time-allocation sensitivities, on the other hand, show strong overmatching (range = 1.13 to 2.0); three of the four are higher than the central tendency reported by Taylor and Davison ($\bar{X} = .962$) and sensitivities for Pigeons W35 & W37 are beyond the upper class interval (1.3-1.4; for other ranges of response- and time-sensitivities, see also Baum, 1979; Wearden & Burgess, 1982). Using
a different procedure than FRCO, but one that excluded changeover behavior from
active-key responding also, Baum (1982) reported strong time-allocation overmatching,
within a similar range (.95 to 2.70; see also Chapter II).

The sensitivities obtained from changeover requirements greater than FRCO 0 in
Figure 2 manifest different trends for response- and time-allocation choice. A
nonparametric test for monotonic trends, S (Davison & McCarthy, 1988; Ferguson,
1965), for the two choice measures produced opposite results for three of the four
pigeons. All Ss from the time-allocation sensitivities are negative, indicating a downward
trend, while three of four are positive for the response-allocation sensitivities. Although
none of the statistics for individual pigeons reach two-tailed significance (N = 1, k = 4, p
>.05), S for data pooled across pigeons does exceed significance (N = 4; k = 4, z = 2.21,
p < .05). Since no prior research suggests a negative trend, according to the rules of
significance testing, z-critical must be for a two-tailed test. The medians of the standard
errors of the slope estimate for response and time allocation are .14 and .13, respectively;
however, the maximum for time allocation is much larger (response = .29, time = .50).

The above analysis highlights one other puzzling result: Sensitivity for both
response- and time-allocation shows no consistent increase after FRCO 2. Pigeons W34
and W36 have their largest increases between FRCO 0 and FRCO 2, and remain at about
the same value for all other changeover requirements. Response-allocation sensitivity for
Pigeons W35 and W37 shifted from undermatching to matching as changeover
requirement went from FRCO 0 to FRCO 2, but their sensitivity for FRCO 20 is lower
than smaller changeover requirements. They, also, never reached the same level of
overmatching as the other two pigeons. This effect is even more prominent in time-allocation sensitivity. For all pigeons, sensitivity is lower for FRCO 20 than for FRCO 2. For W35 and W37, it is close to matching. As indicated above, Pliskoff et al.’s data showed response-choice overmatching and time-choice matching, but that was with a FRCO 5. Their results from FRCO 10 showed overmatching for both. However, each replication used different pigeons and sensitivity may be subject specific. Although the ranges for sensitivities are in accord with prior research (see The Fixed-ratio Changeover section above and Table 3), the lower sensitivities from higher FRCOs are surprising.

**Table 3**  
*Individual and Median Slopes and Standard Errors for Response (Top Section) and Time Allocation (Bottom Section) by Changeover Requirement*

<table>
<thead>
<tr>
<th>Response Allocation</th>
<th>Fixed-Ratio Changeover Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
</tr>
<tr>
<td>Bird</td>
<td></td>
</tr>
<tr>
<td>W34</td>
<td>0.55</td>
</tr>
<tr>
<td>W35</td>
<td>0.46</td>
</tr>
<tr>
<td>W36</td>
<td>0.31</td>
</tr>
<tr>
<td>W37</td>
<td>0.76</td>
</tr>
<tr>
<td>Median</td>
<td>0.51</td>
</tr>
<tr>
<td>Median_{SE}</td>
<td></td>
</tr>
</tbody>
</table>

| Time Allocation     |         |         |         |         |         |         |
|---------------------|         |         |         |         |         |         |
| W34                 | 1.13    | 0.12    | 2.15    | 0.27    | 1.78    | 0.11    | 1.86    | 0.07    | 1.83    | 0.08    |
| W35                 | 1.46    | 0.24    | 1.64    | 0.50    | 1.49    | 0.26    | 1.78    | 0.29    | 1.10    | 0.12    |
| W36                 | 0.76    | 0.38    | 1.76    | 0.13    | 1.47    | 0.14    | 1.59    | 0.25    | 1.46    | 0.22    |
| W37                 | 2.00    | 0.50    | 2.32    | 0.30    | 1.36    | 0.13    | 1.17    | 0.10    | 1.06    | 0.08    |
| Median              | 1.30    | 0.31    | 1.96    | 0.28    | 1.48    | 0.13    | 1.68    | 0.18    | 1.28    | 0.10    |
| Median_{SE}         |         |         |         |         |         |         |         |         |         | 0.13     |

The measure of bias (log b in the bottom panels of Figure 2) remained fairly consistent throughout the experiment, except for two FRCOs (0 & 20) for two Pigeons
(W35 & W36, respectively). Time-allocation bias for W36 gradually shifted toward the left alternative as FRCO increased.

Figure 3 presents logarithmic point estimates of response- and time-allocation sensitivity for most conditions in chronological order. Each pigeon's mean log bias was calculated for each FRCO and then used as a constant to solve Equation 2 for \( s \) in each condition that used that FRCO. Conditions with programmed equal reinforcement rates were excluded. The abscissa labels indicate specific conditions. The last digit indicates a particular reinforcer ratio, the first one or two digits indicate the imposed FRCO, and the \( R \) indicates a replication condition (see also Table 2). Pigeon number is noted in each panel.

Todorov, Castro, Hanna, Bittencourt, and Barreto (1983) reported that sensitivity decreases as number of conditions increases. Visual inspection of Figure 3 hints at an increase in sensitivity across conditions. A trend analysis (Ferguson, 1965) across conditions for individual pigeons found no significant trends, however. Pigeon W35's response-allocation estimates approach a significant positive trend (\( z = 1.40, p > .05 \)) and Pigeon W37's time-allocation estimates approach a significant negative trend (\( z = 1.53, p > .05 \)). Comparison with Todorov et al. must be done with caution, however, because the changeover requirements are also changing across conditions.

Visual inspection indicates that the degree of concordance between response- and time-allocation sensitivities is strong. Generally, the greatest disparity occurs at FRCO 0 and the degree of concordance increases as the FRCO increases.
Figure 3. Response- and time-allocation point estimates of slope (base 10 logarithm transform) plotted in order of condition for all pigeons. X-axis labels denote condition. See text for explanation.
Response Rate Analysis. Response rates were calculated by dividing number of pecks on a side by total time on a side for each condition. Then ratios, constant divided by variable, for each category and condition were determined. Figure 4 presents an analysis of response rate ratios for W37. Visits to a side were categorized into those that did (RFT visit) and did not (Non-RFT visit) contain reinforcement. Reinforced visit measures are giving-up measures while non-reinforced visit measures are visit measures (see Local Results section, below, for definitions). The left column presents the data as a function of the obtained reinforcer ratio (base 10 logarithm) sorted by changeover requirement. The top panel contains ratios of visits in which no reinforcement was delivered, while the bottom panel’s data had one reinforcer delivered. The right column presents the same ratios but plotted as a function of the changeover requirement (base 10 logarithm) sorted by reinforcer ratio. By this analysis, dependent measures of log 1 indicate an equal response rate on both alternatives.

Non-reinforced-visit ratios have less consistency across manipulated variables than the reinforced-visit ratios. Plotted as a function of reinforcer ratio (top-left panel), the smaller two changeover requirements have a negative slope, while the three larger FRCOs produce a relatively constant response rate ratio around equality. Except for FRCO 2, the reinforced visits remain relatively constant, whether plotted as a function of reinforcer ratio or FRCO. Most interesting is the convergence of response rate ratios around equality for non-reinforced visits when plotted as a function of FRCO (top-right panel). Generally, all pigeons show similar results (see Appendix II). An exception: W36 produced a slight positive trend as reinforcer ratio increased for reinforced visits.
Figure 4. Response rate ratio (c/v; log scale) plotted as a function of log reinforcer ratio (c/v; obtained; left panels), grouped by changeover requirement, and plotted as a function of log changeover requirement (right panels), grouped by reinforcer ratio. Top panels present data from visits in which no reinforcement was received, bottom panels present data from reinforced visits.
Figure 5. Data from top left panel of Figure 4 (response rate ratio for non-reinforced visits by changeover requirement) for all pigeons are presented.
It is important to note, although difficult to disentangle from relative reinforcer rates in this analysis, that absolute reinforcer rate decreases when moving along the x-axis from left (150 reinforcers per hour) to right (37.5 reinforcers per hour).

Figure 5 presents ratios for the same conditions and category as the top-left panel of Figure 4—as a function of changeover requirement for non-reinforced visits—for all four pigeons. The convergence of response rates to both alternatives as FRCO increased may be seen in all four graphs. The data converge in two ways: first, ratios for different schedule pairs become more similar; and second, ratios approach unity. Also, generally the leaner alternative garners the higher response rate, particularly at FRCO 2. Three of the pigeons consistently show these results, while W36 remains relatively consistent across changeover requirements, except for the VI 2' VI 30" conditions (boxes). These results seem related to the point estimates presented in Figure 3. W36's response and time estimates were similar throughout while the other pigeons had conditions wherein response and time estimates diverged, for smaller FRCOs, and converged, for FRCO 20.

Changeover Rate Analysis. Figure 6 depicts the changeover rates as a function of obtained reinforcer (base 10 logarithm) ratios by changeover requirement. The data support two consistent findings. First, as changeover requirements increase, changeover rate decreases (Baum, 1982; Stubbs et al., 1977; White, 1979). Every pigeon shows this result: Changeover rates are maximal with FRCO 0 and decrease with every increase of FRCO. Second, changeover rates are maximal at equal reinforcer rates and as rates deviate from equality, changeover rate decreases (Alsop & Elliffe, 1988; Catania, 1963; Herrnstein, 1961). This effect is evident from the inverted-U shaped function maintained
Figure 6. Changeover rate (log scale) grouped by changeover requirement plotted as a function of log reinforcer ratio (c/v) for all four pigeons.
with each FRCO in Figure 6. The peakedness of these functions appears to be less than that shown in Alsop and Elliffe’s Figure 4, but their data were plotted on arithmetic scales, had a greater reinforcer ratio range, and changeover time was included in calculations. The lack of any trends across reinforcer ratios, other than the inverted-U, suggests that absolute reinforcer rate had little effect on changeover rates. Pigeons W35 and W36 show the only pronounced deviation from the inverted-U, but only from FRCO 0 conditions. Furthermore, the deviations are inconsistent with each other and thus suggest little about the effect of absolute reinforcer rate.

*Local Analyses*

These analyses used measures obtained by summing across the stable sessions of each condition. Figures for all pigeons are in Appendix III. The following terms will be used:

- **visit**: begins with the first peck to a side key and ends with the last peck to the same side key;
- **non-reinforced visit**: a visit in which the hopper was never presented to the pigeon;
- **single-reinforcer visit**: a visit in which the hopper was presented once;
- **multiple-reinforcer visit**: a visit in which the hopper was presented more than once;
- **visit pecks (VP)**: number of pecks made to the active side key during a visit in which no reinforcement was obtained;
- **visit time (VT)**: the time between the first and last pecks in a visit in which no reinforcement was obtained;
• giving-up time (GUT) or pecks (GUP): the time spent on or the number of pecks made to the active side key following the last hopper presentation before switching;

• changeover initiation latency (CO\text{int}): duration from last peck to the active side key (also terminates a visit) until the first peck to the changeover key;

• changeover termination latency (CO\text{ter}): duration from last peck to the changeover key until the first peck to the new side key (also initiates a visit);

• fixed-ratio response rate (FR Rate): number of pecks made to the changeover key minus one divided by the time between first and last pecks.

Giving-up measures rather than entire visit measures were used because reinforcement extends visit duration artifactually (Baum, 1983; Lea, 1985).

Tables and figures of stable data for each pigeon are in Appendix III. Generally, for each analysis one pigeon’s data are focused on in the text. Marked differences from the example pigeon are noted.

*Changeover Behavior.* Figure 7 presents means of changeover behavior pooled across all four pigeons. The left column of panels depicts measures of leaving the constant alternative and going to the variable alternative, and the right column shows measures for going back. The top six panels show measures as a function of programmed reinforcer ratio, constant divided by variable. The bottom six panels depict changeover measures as a function of changeover requirement. The different symbols, identified in the legends, indicate FRCO (top six panels) or programmed reinforcer ratio (bottom six panels). FRCOs 6 and 12 (top six panels) and 1:2 and 2:1 reinforcer ratios (bottom six panels) are not connected by lines because they were not paired with each other.
Figure 7. Pooled data for three segments of changeover behavior plotted by programmed reinforcer ratio (top six panels) and changeover requirement (bottom six panels). See text for details.
Changeover latency measures were obtained by summing across stable sessions and dividing by total number of visits (presented in hundredth of a second). The CO_{ter} panels include mean total changeover time for FRCO 0. The FR rate (presented as responses per second) was obtained by multiplying the number of visits by the changeover requirement minus one, yielding the number of interresponse times, then dividing by the sum of the time between first and last peck on the changeover key.

The top two panels show the CO_{int} measures. The 4:1 and 1:4 conditions had higher latencies when leaving the relatively leaner alternative (VI 2’ when paired with VI 30”, left most symbols of leaving constant, and VI 8’ when paired with VI 2’, right most symbols when leaving variable). And the panels depicting CO_{int} as a function of changeover requirement indicate that latency for leaving the leaner alternative remains higher across all changeover requirements, except FRCO 2 (squares in leaving constant panels and asterisks in leaving variable panels). Because the effect is evident for leaving both alternatives, absolute reinforcer rates seem not to affect it (Alsop and Elliffe, 1988; Davison and McCarthy, 1988). This result holds for all pigeons, generally (see Appendix III).

The CO_{ter} panels show that reinforcer ratio had little effect on the latency to terminate switching while the changeover requirement had a small affect on CO_{ter}. The pooled data show a small increasing trend in termination latency as FRCO increases. Pigeon W36 accounts for most of the increasing trend (see Appendix III).

Contrary to response rate during COD, which decreases as COD increases (Stubbs et al., 1977), the FR rate shows an increase between FRCO 2 and 6 and little change
thereafter as changeover requirement increases. The increase between FRCO 2 and 6 may result from the FRCO 2 having only one interresponse interval per changeover.

Nevin (1973) indicated that the relation between average response rate and FR requirement is nonmonotonic. Boren (1953, 1961) reported that for small FRs (i.e., FR-1 to FR-36) response rate negatively accelerates as FR requirement increases. Felton and Lyon (1966), on the other hand, report that for larger FR requirements (i.e., FR-25 to FR-150) response rate tends to decrease as FR requirement increases. Contrary to Boren and Felton and Lyon, the response rates shown here change little across FRCO. Also, there was a small increase in FR response rate across reinforcer ratios when leaving the variable alternative. It was most apparent for W36 (see Appendix III).

**Conditional Probability of Switching.** To calculate the conditional probability of switching as a function of time, separate frequency distributions (bin size was 3 pecks) were constructed for VPs, GUPs in a single-reinforcer visit (GUP_s), and GUPs in a multiple-reinforcer visit (GUP_m). Prior studies performed separate analyses for reinforced and non-reinforced trials also (see Nevin, 1969, 1979; Silberberg et al., 1978). Then, for each bin, the frequency in a bin was divided by the cumulative frequency of that bin and greater (see Anger, 1956, interresponse time per opportunity analysis). A minimum of 20 opportunities was required for the probability to be calculated. A count in the first bin (labeled 0) indicates that no pecks were made to the active side key following a reinforcer. Except for 0, the x-axis’s labels are the upper bounds. This type of analysis asks the question: given that a pigeon has made a number of pecks to the
alternative, what is the probability that it will switch alternatives? Appendix III contains
figures for all conditions and all pigeons.

Figures 8a-j present 10 conditions selected from the twenty-three possible conditions
for Pigeon W37. The left column depicts the constant alternative while the right column
shows data from the variable alternative. Programmed reinforcers per hour and FRCO in
effect are noted at the top of each figure. Most figures have two rows of charts, however
some have three. The top row depicts data from non-reinforced visits; the second row,
data from single-reinforcer visits; and the third row, if any, data from multiple-reinforcer
visits.

Figures 8a-e are all from FRCO 20 conditions, richest (a) to leanest (e) overall
reinforcer rates. Figure 8a indicates that almost all reinforcers from the right side key
were obtained during multiple-reinforcer visits (lower right panel) and there were no non-
reinforced visits. Conditional probability of switching increased as a function of number
of pecks since last reinforcer. The range of GUPs was between 4 and 53. The
conditional probability of switching out of the constant alternative rose also, although it
was only over two bins.

Progressing through Figures 8b-e suggests similar trends in the conditional
probability of switching. As the overall reinforcer rate decreases, the increases in
conditional probability of switching become more pronounced.

Comparing Figure 8a with Figure 8e allows evaluation at the two extreme absolute
reinforcer rates. Both figures depict data from the same relative reinforcer rate (1:4, a,
vs. 4:1, e), but with the richer and leaner schedules reversed and at leaner absolute rates
(150 per hour, a, vs. 37.5 per hour, e). At the leaner absolute reinforcement rate, the richer alternative (Figure 8e, left column) shows the same effect as the rich alternative at the richer absolute rate (Figure 8a, right column). Though the effect is not as steep, it is distributed across more bins with the highest conditional probability of switching in the 96-peck bin for the non-reinforced visit, 72-peck bin for the single-reinforcer visit, and 60-peck bin for the multiple-reinforcer visit. As with the richer absolute reinforcement rate, the sharply increasing conditional probability to exit is evident on the lean alternative in the leaner absolute rate also (Figure 8e, right column), though it occurs across more bins. Comparing down the left column in Figure 8e, the richer alternative, indicates a modest increasing tendency to exit.

Figures 8f-j present the conditional probability of switching as a function of the changeover requirement, FRCO 0 to 20, successively for one pair of schedules. Figure 8j is a duplicate of Figure 8e. Focus, first, on the non-reinforced visits on the richer alternative, top-left panels. At FRCO 0, the highest conditional probability of leaving occurs early in the visit and decreases with longer visits. FRCOs 2 and 6 produce peaked distributions, with the peak in a later bin for FRCO 6 (12-peck bin vs. 24-peck bin). FRCO 12 produces a rise and then a plateau while FRCO 20, as noted above, produces a steady rise.

Scanning down the left column of each figure reveals that the same tendency found in Figure 8e holds for all changeover requirements: the tendency to exit increases. Visits to the lean alternative (right panels) tend to end quickly until FRCO 20 where the conditional probability of switching steadily rises.
Figure 8a. Conditional probability of switching plotted as a function of visit pecks (bin size = 3, excluding zero bin). Left panels present leaving constant while right panels present leaving variable alternative. Data were separated into non-reinforced visits (top panels), single reinforcer visits (middle panels), and multiple reinforcer visits (bottom panels). Programmed reinforcer rates and changeover requirement noted at top.
Figure 8b. Conditional probability of switching plotted as a function of visit pecks (bin size = 3, excluding zero bin). Left panels present leaving constant while right panels present leaving variable alternative. Data were separated into non-reinforced visits (top panels), single reinforcer visits (middle panels), and multiple reinforcer visits (bottom panels). Programmed reinforcer rates and changeover requirement noted at top.
Figure 8c. Conditional probability of switching plotted as a function of visit pecks (bin size = 3, excluding zero bin). Left panels present leaving constant while right panels present leaving variable alternative. Data were separated into non-reinforced visits (top panels), single reinforcer visits (middle panels), and multiple reinforcer visits (bottom panels). Programmed reinforcer rates and changeover requirement noted at top.
Figure 8d. Conditional probability of switching plotted as a function of visit pecks (bin size = 3, excluding zero bin). Left panels present leaving constant while right panels present leaving variable alternative. Data were separated into non-reinforced visits (top panels), single reinforcer visits (middle panels), and multiple reinforcer visits (bottom panels). Programmed reinforcer rates and changeover requirement noted at top.
Figure 8c. Conditional probability of switching plotted as a function of visit pecks (bin size = 3, excluding zero bin). Left panels present leaving constant while right panels present leaving variable alternative. Data were separated into non-reinforced visits (top panels), single reinforcer visits (middle panels), and multiple reinforcer visits (bottom panels). Programmed reinforcer rates and changeover requirement noted at top.
Figure 8f. Conditional probability of switching plotted as a function of visit pecks (bin size = 3, excluding zero bin). Left panels present leaving constant while right panels present leaving variable alternative. Data were separated into non-reinforced visits (top panels), single reinforcer visits (middle panels), and multiple reinforcer visits (bottom panels). Programmed reinforcer rates and changeover requirement noted at top.
Figure 8g. Conditional probability of switching plotted as a function of visit pecks (bin size = 3, excluding zero bin). Left panels present leaving constant while right panels present leaving variable alternative. Data were separated into non-reinforced visits (top panels), single reinforcer visits (middle panels), and multiple reinforcer visits (bottom panels). Programmed reinforcer rates and changeover requirement noted at top.
Figure 8h. Conditional probability of switching plotted as a function of visit pecks (bin size = 3, excluding zero bin). Left panels present leaving constant while right panels present leaving variable alternative. Data were separated into non-reinforced visits (top panels), single reinforcer visits (middle panels), and multiple reinforcer visits (bottom panels). Programmed reinforcer rates and changeover requirement noted at top.
Figure 8i. Conditional probability of switching plotted as a function of visit pecks (bin size = 3, excluding zero bin). Left panels present leaving constant while right panels present leaving variable alternative. Data were separated into non-reinforced visits (top panels), single reinforcer visits (middle panels), and multiple reinforcer visits (bottom panels). Programmed reinforcer rates and changeover requirement noted at top.
Figure 8j. Conditional probability of switching plotted as a function of visit pecks (bin size = 3, excluding zero bin). Left panels present leaving constant while right panels present leaving variable alternative. Data were separated into non-reinforced visits (top panels), single reinforcer visits (middle panels), and multiple reinforcer visits (bottom panels). Programmed reinforcer rates and changeover requirement noted at top.
Generally, the other pigeons' data show similar results (see Appendix III). Particularly interesting is W36's data from Condition 11 (VI 2' VI 4', see Table 2) which shows an increasing conditional probability of leaving even in extended visits, out to the 237 peck bin. The data from W35 show the effects but not as clearly.

Figures 9 a-b present a summary of the prior analyses. Using least-squares linear regression and excluding the 0-peck bin, slopes were determined for each conditional probability of switching distribution, again separated by visit type (non-reinforced, top panels; single reinforcer, middle panels; and multiple reinforcer, bottom panels) and plotted as a function of log reinforcer rate (obtained; Figure 9a) and log changeover requirement (Figure 9b). The most obvious result was that nearly all slopes were positive thereby supporting the general finding of the analyses presented in Figure 8 of an increasing probability of switching. The most frequent violations of this result occurred when FRCO 0 was in effect. When plotted as a function of log reinforcer rate (Figure 9a), the slopes tended to peak at the equal reinforcer rates, when changeover rates are maximal (see Figure 6). When plotted as a function of FRCO, all slopes tended to remain positive. The absolute value of the slopes should be regarded with some caution, however. The number of bins used to determine each slope was commonly quite different for each changeover requirement and reinforcer ratio. Generally, the larger changeover requirements produced longer visits (see the Foraging Analyses section below) which increases the number of bins. To compensate for this, another analysis would need to be performed constraining the visit pecks and GUPs within a fixed number of bins. These general tendencies hold for all four pigeons, generally (see Appendix III).
Figure 9a. Slopes of conditional probability of switching for each changeover requirement (see legend) plotted as a function of log reinforcer rate (obtained). Grouped in same manner as Figure 8. One point in the middle-right panel is off the scale.
Figure 9b. Slopes of conditional probability of switching for each reinforcer rate (see legend) plotted as a function of log changeover requirement. Grouped in same manner as Figure 8. One point in the middle-right panel is off the scale.
The results portrayed in Figures 8 and 9 indicate that the shape of the conditional probability function is a joint function of absolute reinforcer rate and the changeover requirement.

Foraging Analyses

Representative Statistic. The foraging analyses required determining a statistic that represented the central tendency of the measures. Frequency histograms for data from each pigeon were constructed of the peck and duration measures for non-reinforced, single-reinforcer, and multiple-reinforcer visits for each condition. A minimum sample size of 10 was required to be included in the analyses. \( \text{GUP}_m \) were affected the most by this requirement. Usually the distributions were symmetrical around a mode. Means and medians were calculated.

Figures 10a-b present the means (left column) and medians (right column) of visit pecks (a) and visit times (b) for Pigeon W36 and are presented to show that there are only little differences between the two statistics. First, consider the relationship between the two columns. Usually the forms have the same shapes: Both means and medians for both visit pecks and visit time show a crossover of performance on the two alternatives. (The slopes are considered in the next figure.) The means, however, tend to be somewhat smoother (see top panels, FRCO 0). Usually the means were smoother for all pigeons and all three categories of visits (non-reinforced, single-reinforcer, and multiple-reinforcer visits; see Appendix IV). For some conditions, the median visit was 0.0 and,
Figure 10a. Mean (left panels) and median (right panels) log visit pecks for constant and variable alternatives (see legend), categorized by travel requirement, plotted as a function of log reinforcer ratio (c/v; obtained).
Figure 10b. Mean (left panels) and median (right panels) log visit time for constant and variable alternatives (see legend), categorized by travel requirement, plotted as a function of log reinforcer ratio (c/v; obtained).
since the logarithms are undefined, could not be plotted. The mean is used throughout the remainder of the foraging analyses.

A second feature of Figures 10a-b to note is where along the abscissa the crossovers occur. Both pecks and time show this effect but in slightly different ways. Consider first the pecks. For FRCOs 0, 2, 6, & 12 the point of crossover is consistently to the right of equal reinforcer rates and that point for the higher three changeover requirements is consistent. The crossover point for FRCO 20, however, is to the left of equal reinforcer rates. The same effect holds for the visit times except that as the changeover requirement increases the crossover point progressively shifts to the right on the x-axis. These results are directly correlated with the measures of bias for this pigeon in Figure 2 (triangles in the bottom panels). Response allocation bias was constant for the smaller changeover requirements and switched for FRCO 20. Time allocation bias showed a more gradual shift and then a small jump as changeover requirement increased. The large shift in W35's bias measure when FRCO increased from 0 to 2 (Figure 2) is also evident in the visit pecks and visit time charts (see Appendix IV).

This analysis suggests a slight effect of the absolute reinforcer rate, most evident in Figure 10b. When FRCO 20 was in effect (bottom two panels), the points for the 4:1 reinforcement ratio (far right) are greater than the corresponding points for the 1:4 ratio (far left). Many of the panels for all four pigeons, for non-reinforced visits particularly, support this inverse relation between visit pecks or time and absolute reinforcer rate, consistent with the principle of lost opportunity (see Chapter II & Appendix IV).
Figure 11a. Log mean visit pecks and giving-up pecks for constant (left panels) and variable (right panels) alternatives, categorized by travel requirement, plotted as a function of log reinforcer ratio (c/v; obtained).

Equations are least square linear and are listed in the same order as in the legend.
Figure 11b. Log mean visit time and giving-up time for constant (left panels) and variable (right panels) alternatives, categorized by travel requirement, plotted as a function of log reinforcer ratio (c/v; obtained). Equations are least square linear and are listed in the same order as in the legend.
Visit Analyses. Figures 11a (pecks) and 11b (time) depict data similar to Figure 10. (Note that not all y-axis scales are identical, but all are the same length.) The logarithms of the mean visit pecks and giving-up pecks are plotted as a function of the obtained log reinforcer ratio for both the constant (left column) and variable (right column) alternatives by changeover requirement (FRCO 0 on top, increasing changeover requirement downward). The least-squares regression equation for each visit type is included, and these are listed in the same order as the label in the legend. Some \( \text{GUP}_m \) and \( \text{GUT}_m \) have fewer than five points due to small sample size.

The most striking observation is the positive slope for the constant alternative and the negative slope for the variable alternative for all FRCOs and for both pecks and times. This result indicates that visit pecks and time and giving-up pecks and time are related to relative reinforcer rate more so than absolute rates. As the constant alternative became richer relative to the variable alternative and absolute reinforcer rates decreased, visits became longer (left panels), consistent with prediction for both relative and absolute reinforcer rates. Conversely, as the variable alternative became leaner relative to the constant alternative and absolute reinforcer rates decreased, visits became shorter (right panels), consistent with prediction for relative reinforcement but inconsistent with prediction for absolute rates. The effect of absolute reinforcement may be evident from the negative slopes being less negative than the positive slopes are positive. Similar results for relative reinforcement rates were reported by Dreyfus et al. (1993). The only exceptions are the positive slope for \( \text{GUP}_m \) and \( \text{GUT}_m \) in FRCO 2 on the variable
alternative, but those slopes are derived from only two points. And the slopes for the GUTₜ when FRCO 0 was in effect are close to zero.

Figures 12a (peck) and 12b (time) are the same points as Figure 11 but the manipulated variables are reversed: that is, pecks and time are plotted as a function of the logarithm (base 10) of the changeover requirement by programmed reinforcer ratio (1:4, top panel, to 4:1, bottom panel). (Note that not all y-axis scales are equal.) With high reliability, as changeover requirement increased so did the measured variable. Baum (1982) and McCarthy, Voss, and Davison (1994) showed the same relationship. All pigeons show similar results (see Appendix IV).

Figure 13 presents a comparison of time measures (visit time, top panels, or GUTₜ, bottom panels; y-axis) as a function of response measures (visit pecks, top panels, or GUPₜ, bottom panels; x-axis) separated by alternative (constant, left column; variable, right column) with each changeover requirement depicted by different symbols (see legend) for W36. Lines are best fitting lines of each changeover requirement with their equations listed in the same sequence as the sequence of the line’s identifier in the legend. The equation at the bottom of each panel is for all points combined, except FRCO 0, with the variance accounted for below it. All y-intercepts are positive and, with the exception of FRCO 0, are fairly consistent at about 2.0. Because time was measured in hundredths, a y-intercept of log 2.0 means a y-intercept of 100, if the slope is close to 1.0, corresponding to a response rate of one peck per second. Excepting FRCO 0, only three slopes approximate 1.0; the remaining are consistently less than one. Furthermore,
as FRCO increases the more similar the slopes, generally. These results hold regardless of alternative and for both non-reinforced and single-reinforcer visits.

The slopes for each category of visit for all pigeons are presented in Figure 14. Logs of the slopes, sorted by alternative and reinforced or non-reinforced visits, are plotted as a function of travel requirement. W34 and W35 each have one point for the FRCO 0 condition that is off the scale (constant alternative, single-reinforced visits and variable alternative, non-reinforced visits, respectively). Most prominent is the slopes’ convergence as travel increases. W34 and W35 tend to converge around slopes of 1.0 (log 0) while W36 and W37 tend around slopes slightly less than 1.0 (negative logs). In addition, when the slopes are different (i.e., smaller travel requirements), the slopes for the non-reinforced visits tend to be greater than reinforced visits. The convergence of the slopes as travel increased is similar to the convergences depicted in Figures 4 and 5.
Figure 12a. Log mean visit pecks and giving-up pecks for constant (left panels) and variable (right panels) alternatives, categorized by reinforcer ratio, plotted as a function of log travel requirement.
Figure 12b. Log mean visit time and giving-up time for constant (left panels) and variable (right panels) alternatives, categorized by reinforcer ratio, plotted as a function of log travel requirement.
Figure 14. Response by time slopes (from Figure 13) plotted as a function of log travel requirement. Symbols indicate alternative and non-reinforced or reinforced visits (see legend). Pigeon indicated in each panel.
CHAPTER IV

DISCUSSION AND CONCLUSIONS

The motivating issues for this dissertation revolved around the factors that affected choice, generally, and switching, specifically. Research investigating the matching relation has demonstrated that relative reinforcer rates reliably influence behavior. Whether or not reinforcement sensitivity is a constant is currently debated. Research suggests that reinforcement sensitivity is affected by the changeover requirement (Baum, 1974a; 1974b; 1979; Temple, Scown, & Foster; 1995; Wearden & Burgess, 1982; & Williams, 1988), but until recently no parametric examination of its effects had been reported. Temple et. al parametrically manipulated the changeover delay. This present dissertation physically separated the imposed changeover requirement from main-key responding and manipulated it. The results further our understanding about switching. This chapter reviews and discusses the key results.

Molar Findings

The effect of the changeover requirement has been debated since Herrnstein’s (1961) report. Research with other than COD changeover requirements (i.e., FR schedules and barriers) suggests that sensitivity increases with changeover requirement and that overmatching becomes the norm. Figure 2 demonstrates that, after some minimal
changeover requirement, response-allocation sensitivity remains relatively constant for individual subjects, consistent with Temple, Scown, and Foster’s (1995) recent report which varied COD. Pigeons W34 and W36 (see Figure 2) maintained similar response-allocation sensitivity measures for all changeover requirements larger than FRCO 0. Pigeon W37’s sensitivity was fairly constant over the larger three FRCOs, while W35 reached a maximum at FRCO 12. Also consistent with Temple et al. and contrary \(^2\) to Herrnstein (1961), behavior is sensitive to reinforcement contingencies even without a COD, although the slope is less than 1.0.

Time allocation sensitivity, on the other hand, has a pronounced negative trend as the changeover requirement increases. This result is contrary to previous findings. All prior reviews and studies reported that time sensitivity deviated less from matching than response sensitivity (Chapter 1, Why Deviations?), suggesting that deviations are from some anchor. Figure 15 depicts the sensitivity difference scores for log response sensitivity minus log time sensitivity plotted as a function of changeover requirement. At FRCO 0 time sensitivity was greater than response and, since response sensitivities undermatch, this is in keeping with earlier reports. However at FRCO 2 and larger, all sensitivity measures, except one of W35’s response measures, are overmatching; nevertheless, Figure 15 indicates that time sensitivities are more extreme than response sensitivities. Larger FRCOs produced larger difference scores indicating that response sensitivities became relatively greater than time sensitivities as changeover requirement

\(^2\) \text{...relative frequency of reinforcement on Key A was about 66%. The relative frequencies of responding on Key A were 50% and 56% for the two pigeons} \text{ (Herrnstein, 1961, p. 270).}
Figure 15. Difference in sensitivity of response and time allocation plotted as a function of log changeover requirement. Symbols denote pigeon (see legend).
increased. This reversal of the sensitivities's deviation from 1.0 as FRCO increased may indicate that time sensitivity is more firmly anchored than response sensitivity (Wearden and Burgess, 1982).

One way to understand the decreasing trend in time sensitivity is to consider what is happening to response rates on each alternative as the changeover requirement increases. Recall the three noted features from Figure 5. First, as changeover requirement increased the response-rate ratios for the different schedule pairs converged, meaning that larger FRCOs produced more similar response rates. Second, almost all ratios converge at 1.0, equal response rates on each alternative regardless of reinforcer rate. And third, at smaller FRCOs the leaner alternative garnered the higher response rate. Baum (1982, p. 42) noted a divergence in response rates to the preferred and non-preferred alternatives. Like Figure 5, Figure 14 suggests similar changes in response rates also. Taken together, these results indicate that response rates on the two alternatives changed reliably with changeover requirement. More specifically, as changeover requirement increased, response rate on the leaner alternative relative to the richer alternative slowed down. This means that the changeover requirement increases the amount of time spent on an alternative more than the number of responses given. Such results reflect the crucial property of VI schedules: quantity of responses is less important than a well placed peck.

The results support the different-response-topography hypothesis proposed by Baum (1979). Clearly, with lower changeover requirements the richer and leaner schedules garnered different response rates. As FRCO increased, the response ratios approached unity. Increasing the time on the lean alternative with responses remaining
proportionally constant would produce the negative trend for time-allocation sensitivity while at the same time keeping response sensitivities constant. The changes in response rate may result from changes in the response-to-pause ratio due to the increased visit durations and pecks that occurred as the changeover requirement increased (see Figure 12b). If the richer and leaner alternatives do obtain different response rates, attempts to mathematically model the effects of unequal changeover requirements (Davison, 1991) need to account for changing response rates.

Central to recent investigations of the matching relation is the question of what is the normative value of $s$: matching, undermatching, or overmatching? For other than the lowest changeover requirement, both response and time allocation do not show undermatching here; overmatching is the norm, although matching occurs in a few instances (W35's response allocation and time allocation for W35 and W37 when FRCO 20 was in force). Using chickens as subjects, Temple et al. (1995) reported mostly matching for all but the lowest CODs, when response- and time-allocation measures included changeover behavior. When response-allocation sensitivities excluded changeover responses, they tracked sensitivities that included changeover responses but at higher values, sometimes matching and sometimes overmatching.

The consistency in the FR response rate depicted in Figure 7 indicates that including changeover behavior would add a constant to both alternatives. This would have a proportionally larger effect on the leaner alternative thereby reducing sensitivity. Given that changeover responding occurs on a separate key in this dissertation, including changeover behavior in the calculation seems unwise. Furthermore, supporting Baum
(1982), Temple et al. argue that changeover behavior should be excluded because doing so homogenizes the sensitivity measures derived from different procedures. Perhaps comparing absolute sensitivity values is less important than considering the effects specific procedures have on sensitivity, particularly considering that COD responding is essentially insensitive to reinforcement rates (see Baum, 1974a; 1982; Temple et al.; Figure 1).

*Conditional Probability of Switching*

The properties of *conce* VI VI schedules (see Chapter I, *Common Procedures*) lead to the intuitive conclusion that the probability of returning to an alternative should increase the longer one is away from that alternative. However, Nevin (1969; 1979), using a discrete-trials procedure, reported that the probability of a changeover response remained constant or decreased slightly as a function of run length; at the same time, the probability of reinforcement for switching increased steadily. Using a two-key changeover procedure (FR 1), Heyman (1979) also reported no increase in the conditional probability of switching. Heyman used a variety of concurrent schedules, both richer (VI 33.3 seconds) and leaner (VI 300 seconds), which allowed run lengths much longer than Nevin obtained. Nevin's (1969) longest run lengths were in the 6-10 bin while Heyman's longest runs were near 50 when a VI 33.3 second schedule was paired with a VI 300 second schedule. Experiment 1 of Silberberg et al. (1978) replicated Nevin and Shimp (1966) and claimed evidence supporting sequential
dependencies. Silberberg et al. claimed that their other experiments confirmed this conclusion, although not without theoretical complexity.

Figures 8a-j show an increasing probability of switching the more consecutive pecks on an alternative, particularly when the changeover requirement is large. Why was evidence for an increasing probability of switching so clearly evident in Figures 8 and 9? The most obvious reason is the changeover requirement. When the FRCO 20 was in force (Figures 8a-e), almost every panel shows the increasing trend and Figure 9b indicates that all slopes are positive. When FRCO 0 was in effect (Figure 8f), however, non-reinforced visits show the more typical pattern, constant or decreasing conditional probability of switching. As the changeover requirement increases, the positive trend becomes more pronounced.

The changeover requirements imposed in the reports that tested for momentary control of switching were nothing or minimal. Only three experiments\(^3\) included a changeover requirement: Shimp (1966; Experiment IV) required two pecks, Silberberg et al. (1978; Experiment 2) had a 1.5 second COD, and Heyman (1979) imposed an FR 1.

These experiments tended to be the most difficult to fit into the momentary maximizing models. Silberberg et al. admit that “the presence of the COD complicated any attempt to identify the concurrent response rule for free-operant choice allocation” (p. 385). Perseveration on an alternative, fostered by changeover requirements, confounds

\(^3\) The 6-second intertrial interval that Nevin (1969) included could be considered analogous to a COD, but with a potentially crucial difference: Each peck was separated by the intertrial interval, thereby decreasing the likelihood of prolonged perseveration, opposite the effect of travel here.

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momentary maximizing; so much so that Silberberg et al. developed it as a component of
their model.

Exactly what momentary maximizing theorists should do with behavior occurring
during switching is unclear. It seems that changeover behavior would reduce the
momentary probability of reinforcement from the other schedule and, thus, actually
decrease the schedule’s momentary control; exactly opposite of the results reported here.
Perhaps large changeover requirements allow a more clear discrimination of the molar
reinforcer rates. Working in conjunction, then, the changeover requirement, by
suppressing switching, and the molar reinforcement rates, by exerting more control on
behavior the longer the time since last visit, produce the increasing conditional
probability of switching observed. An interesting test would be a Nevin-like procedure,
but with a changeover requirement.

Foraging

Baum (1982) demonstrated that travel between alternatives in an operant chamber
reliably affected not only the matching relation but also “stay time”. The data presented
in Figures 12a-b confirm Baum’s results: as the changeover requirement increased all
measures of residence time and pecks increased. These results also support similar
findings using different procedures (see McCarthy et al., 1994). Also, the results
confirm other reports that residence measures increase as relative reinforcer rates increase
(Davison, 1991; Temple et al., 1995). The modestly increasing trends of visit measures
(i.e., visit pecks, giving-up pecks) as absolute reinforcer rates decreased supports the
principle of lost opportunity: As the richness of overall environment decreases, there is less of a cost for staying in a patch because the probability of obtaining reinforcement from another patch is low (see Chapter II).

Various authors (see Baum, 1983; Lea, 1981; Shettleworth, 1988) have considered the similarities of foraging in the wild and operant behavior. Baum (1983) noted three artificialities of the operant chamber (see Chapter II). Baum (1982) addressed the first artificiality. He made the operant chamber more “natural-like” by adding a physical barrier between the two “patches”. The results confirmed the previous assumption that the operant chamber is a viable laboratory option to naturalistic research, and that the matching relation can accommodate such data.

This present research progresses the other way, in a sense. Fixed-ratio schedules are commonly used to model work requirements in operant research. And, rather than needing to add an “artificiality” to the operant chamber to make it more natural-like, the tools forged from the operant lab can be considered sufficient to model the natural world. Namely, data that resulted from an FR travel requirement produced results highly similar to Baum’s physical travel, and thus an FR schedule sufficiently models the physical distance between patches in the wild. McCarthy et al. (1994) argue that it is not the work associated with traveling, per se, that controls behavior as much as it is the time away from reinforcement. It would be extremely difficult to test such questions in the wild.

My argument merely intends to assert that the tools of operant psychologists need not be rejected because they are contrived. Both operant psychology and behavioral ecology
can work cooperatively, confident with their respective tools, to more fully understand the behavior of organisms.

Additional Analyses

The means employed to record these data lend themselves to other analyses. Two come to mind presently. Determining the location during a visit that reinforcement is delivered may help explain the increasing conditional probability of switching as run length increases. One way to investigate this is by determining the proportion of reinforcers received for the first peck following a changeover, categorized by richer and leaner alternatives. Perhaps reinforcement works in different ways depending on whether delivered from the richer or leaner schedule. Leaner schedules may reinforce time away from them by yielding reinforcement upon return, while richer schedules may reinforce active responding. Thus, the longer one is away from the leaner alternative, encouraged by the larger changeover requirements, the more probable switching to it becomes. Also, reinforcement soon after switching to the leaner alternative may contribute to maintaining behavior on it, thereby affecting the exponent of Equation 3.

Perhaps there is some optimal (that is, molar maximizing) time away from the leaner alternative or, more specifically, some optimal time since last reinforcement from the lean side. This time would possibly approximate the mean and depend on travel requirements. The second analysis would seek to answer the following question: What is the function between the probability of switching and time since the last reinforcement from the rich or lean alternative? The method of data recording employed lends itself to
such a question; both the time and number of changeovers between reinforcers can be extracted from the data.

Conclusion

The matching relation as a framework for understanding choice is in its fourth decade. Evidence presented in this document supports using the generalized matching relation to understand choice measured at a molar level. Three major conclusions seem warranted. First, once a changeover requirement is implemented, response-allocation sensitivity remains relatively stable in the overmatching range. Time-allocation sensitivity, however, decreases as the changeover requirement increases—a trend that may be related to changing response rates on the richer and leaner alternatives. Second, as changeover requirements increase, the conditional probability of switching increases the longer one remains on an alternative. And third, operant tools of modeling foraging in the wild can be considered functionally similar to foraging in the wild.

In the opening chapter of the book, *The Limits of Rationality*, Jon Elster (1990) asserted that theories fail for two reasons: indeterminacy and inadequacy. The first occurs when a theory fails to make unique predictions, the second, when predictions fail. Elster asserts that inadequacy is a more serious problem. At this point, the matching relation as a theory of choice seems to fail in the first instance: sensitivity depends on procedures and therefore may not have a unique value. But then again, should we be surprised that procedures affect sensitivity? No one would claim that the law of gravity is void if, without accounting for wind resistance, predictions failed. Before we reject
matching as a framework for choice we need to unify our procedures; or at least attempt
to determine sensitivity values for specific procedures (see Baum, 1979; Taylor &
Davison, 1983).

More generally, have we learned anything more about William James' choosing
Oxford Street over Divinity Avenue? Just as a physicist would shy away from predicting
the path of a particular falling leaf, so too would a psychologist hesitate to predict a
priori which street James would walk on a particular night. However, allow an operant
psychologist to make predictions using multiple observations, the pay-offs associated
with each street, and the obstacles (e.g., travel?) that accompany each one and perhaps
even James himself might admit that determinism, of a particular kind, is feasible.
Perhaps he would have even felt less compulsion to opt for free will.
LIST OF REFERENCES


APPENDIX I

Tables of Raw Data
The following tables contain data from stable sessions. Pigeon number is indicated on the first page of each table. The first column, labeled FR CO, indicates the fixed-ratio changeover requirement. The second column, labeled VI Vari, indicates the variable-interval reinforcement schedule in seconds for the variable alternative (always the right alternative). The constant alternative maintained a variable-interval 120 second schedule throughout. Responses, times (in seconds), reinforcers, and visits for constant (Const) and variable (Vari) alternatives are included. The Leaving Constant and Leaving Variable columns present mean changeover times in seconds for that session. These times are categorized into changeover initiation (Init), time on the changeover key (FR T), and changeover termination (Term). When FR CO 0 was in effect, all changeover time was recorded in the columns headed Term.
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APPENDIX II

Molar Analyses
The following four figures present log response (c/v) by log reinforcer (c/v) and log time. Pigeon number is noted on each figure. Linear equations and standard errors of the slope estimate are listed in the same order as their legend labels.
The following four figures present response rate ratio (c/v) as a function of log reinforcer ratio (c/ν; left panels) and log changeover requirement (right panels). The top row of panels are measures from non-reinforced visits, while the bottom row are from reinforced visits. Legends indicate symbols for the other manipulated variable. Note logarithmic scale on y-axis.
APPENDIX III

Local Analyses
The following four figures present means of changeover measures as a function of programmed reinforcer ratio (top six panels) and changeover requirement (bottom six panels). Symbols of the other manipulated variable are noted in the legends. Left panels depict measures of leaving the constant alternative and going to the variable alternative, and right panels show measures for going back. The top row of each set of panels present changeover initiation latency (last peck active key to first peck changeover key), middle-row panels of each set present response rate on the changeover key, and bottom-row panels of each set present changeover termination latency (last peck changeover key to first peck new alternative). Pigeon number is noted on each figure.
The following 92 figures present the conditional probability of switching as a function of run length categorized by non-reinforced, single reinforcer, or multiple reinforcer (on some figures) visits (rows) and left (left panels) and right (right panels) alternatives. Pigeon number, changeover requirement (FRCOR) and reinforcement schedules are noted at the top of each figure. Figures are grouped by pigeon, then by changeover requirement and, within each changeover group, proceed from richer to learner overall reinforcer rate.
W34
Constant: 30/hr
Variable: 120/hr
Non-reinforced visits

Single Reinforcer Visits

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W34

Constant: 30/hr

Non-reinforced visits

Single Reinforcer Visits

Multiple Reinforcer Visits

Variable: 60/hr

Giving-up Pecks

Giving-up Pecks

Showing
Appendix III
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W34
Constant: 30/hr
FRCCO: 02
Variable: 15/hr

Non-reinforced visits

Single Reinforcer Visits

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W34
Constant: 30/hr

Variable: 7.5/hr

Non-reinforced visits

Single Reinforcer Visits

Multiple Reinforcer Visits
W34

Constant: 30/hr

FINDO: 12

Variable: 30/hr

Non-reinforced visits

Single Reinforcer Visits

(Bar charts showing probability distribution for non-reinforced and single reinforcer visits.)
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page 172

W34

Constant: 30/hr

FRCCX: 12

Variable: 7.5/hr

Non-reinforced visits

Single Reinforcer Visits

Multiple Reinforcer Visits

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Non-reinforced visits

Single Reinforcer Visits

Multiple Reinforcer Visits
W34

Constant: 30/hr

FRDD: 20

Variable: 7.5/hr

Non-reinforced visits

Visit Pecks

Conditional Probability of CD

Single Reinforcer Visits

Giving-up Pecks

Multiple Reinforcer Visits

Giving-up Pecks

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W35
Constant: 30/hr
FRICQ 00
Variable: 30/hr

Non-reinforced visits

Single Reinforcer Visits

Conditional Probability of CD

Visit Packs

Giving-up Packs

1.0
0.8
0.6
0.4
0.2
0.0

W35

Constant: 30/hr
FRDO: 00
Variable: 15/hr

Non-reinforced visits

Conditional Probability of GO

Non-reinforced visits

Single Reinforcer Visits

Conditional Probability of GO
W35
Constant: 30/hr

Non-reinforced visits

Single Reinforcer Visits

Multiple Reinforcer Visits

Variable: 7.5/hr
Appendix III
page 186

W35
Constant: 30/hr
FR00: 02
Variable: 60/hr

Non-reinforced visits

Single Reinforcer Visits

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W35
Constant: 30/hr
FRDO: 06
Variable: 120/hr

Non-reinforced visits

Single Reinforcer Visits

Multiple Reinforcer Visits

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W35

Constant: 30/hr

FR50: 20

Variable: 120/hr

Non-reinforced visits

Single Reinforcer Visits

Multiple Reinforcer Visits

Giving-up Packs

Conditional Probability of CD

Giving-up Packs

Conditional Probability of CD

Giving-up Packs

Conditional Probability of CD

Giving-up Packs
W35
Constant: 30/hr
PROC 20 R
Variable: 120/hr

Non-reinforced Visits

Single Reinforcer Visits

Multiple Reinforcer Visits

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W35
Constant: 30/hr
FRIO: 20
Variable: 60/hr

Non-reinforced Visits

Single Reinforcer Visits

Multiple Reinforcer Visits
Non-reinforced visits

Single Reinforcer Visits
Non-reinforced visits

Single Reinforcer Visits

Multiple Reinforcer Visits

Variable: 7.5/hr

Constant: 30/hr
Non-reinforced visits

Single Reinforcer Visits
W36
Constant: 30/hr  FRIC: 20  Variable: 120/hr

Non-reinforced visits

Conditional Probability of OD

Visits Peck

Single Reinforcer Visits

Conditional Probability of OD

Giving-up Pecks

Multiple Reinforcer Visits

Conditional Probability of OD

Giving-up Pecks
W36  
Constant: 30/hr  
FRIO: 20  
Variable: 30/hr  

Non-reinforced visits

Single Reinforcer Visits

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W36
Constant: 30/hr
FRCC: 20
Variable: 7.5/hr

Non-reinforced visits

Conditional Probability of CI

Visit Pecks

Single Reinforcer Visits

Conditional Probability of CI

Giving-up Pecks

Multiple Reinforcer Visits

Conditional Probability of CI

Giving-up Pecks
W37
Constant: 30/hr

FROC: 00
Variable: 120/hr

Non-reinforced visits

Single Reinforcer Visits

Multiple Reinforcer Visits
Constant: 30/hr
Variable: 30/hr

Non-reinforced visits

Single Reinforcer Visits

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Appendix III
page 230

W37
Constant: 30/hr
FRIOO, 00
Variable: 7.5/hr

Non-reinforced visits

Visit Packs

Single Reinforcer Visits

Giving-up Packs
W37

Constant: 30/hr

FR10: 02

Variable: 30/hr

Non-reinforced visits

Single Reinforcer Visits

Conditional Probability of CD

Visit Packs

Giving-up Packs
W37

Constant: 30/hr

FRCCO: 20

Variable: 30/hr

Non-reinforced visits

Conditional Probability of CO

Visit Packs

Single Reinforcer Visits

Conditional Probability of CO

Giving-up Packs
Constant: 30/hr
FRIO: 20
Variable: 7.5/hr

Non-reinforced visits

Single Reinforcer Visits

Multiple Reinforcer Visits
The following eight figures present summaries of data presented in the immediately prior figures. Slopes, derived using least-squares linear regression and excluding the 0-peck bin, for each conditional probability of switching distribution are plotted as a function of log reinforcer rate (obtained; first four figures) and log changeover requirement (last four figures). As in the prior analysis, slopes were categorized by non-reinforced, single reinforcer, or multiple reinforcer (on some figures) visits (rows) and left (left panels) and right (right panels) alternatives.
APPENDIX IV

Foraging Analyses
The following 24 figures present log mean (left panels) and median (right panels) peck measures (visit pecks or giving-up pecks; first 12 figures) and duration measures (visit time or giving-up time; last 12 figures) as a function of log obtained reinforcer ratio. Ordered by pigeon (number is noted on each figure), measures are categorized by non-reinforced (first figure), single reinforcer (second figure), and multiple reinforcer visits (third figure) as noted at the top of each figure. Changeover requirement increases from top to bottom panels. Within each panel, measures present both constant and variable alternatives (see legends for symbols).
Appendix IV
page 268

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The following 16 figures present the means presented in the prior figures separated into constant (left panels) and variable (right panels) alternatives. The first eight figures plot peck measures (first four figures) and time measures (last four figures) as a function of obtained log reinforcer ratio. The least-squares regression equations for each category of visit are given in each panel in the order listed in the legend. The last eight figures plot peck measures (first four figures) and time measures (last four figures) as a function of log travel requirement.
The following four figures present the relation between the time measures (y-axis) and the response measures (x-axis) presented in the immediately prior figures. Left panels present constant alternative measures and right panels present variable alternative measures. Top panels are data from non-reinforced visits and bottom panels are data from single reinforcer visits. Lines are best fitting lines of each changeover requirement with their equations listed in the same sequence as identified in the legend. The equation with the variance accounted for below it is for all points combined, except FRCO 0.
W34

Constant (Left)

- FR0
- FR2
- FR6
- FR12
- FR20
- Series 6
- Linear (FR 20)
- Linear (FR 12)
- Linear (FR 6)
- Linear (FR 2)
- Linear (FR 0)
- All Points

y = 1.0615x + 1.6134
y = 1.2506x + 1.3149
y = 1.3653x + 1.2035
y = 1.4177x + 1.2459
y = 1.9359x + 0.7656

y = 1.2345x + 1.3732
R^2 = 0.9908

Variable (Right)

y = 0.6536x + 1.9239
y = 0.6045x + 1.8542
y = 1.0721x + 1.6169
y = 1.3872x + 1.3007
y = 2.2023x + 0.8426

y = 1.1647x + 1.5053
R^2 = 0.968

Log Time Measure

Log Response Measure

ft sing