RESPONSE STRENGTH AS BOUT INITIATION: AN ANALYSIS OF INTERRESPONSE TIMES ON CONCURRENT SCHEDULES OF REINFORCEMENT

Tracy G. Taylor

A Thesis Submitted to the University of North Carolina Wilmington in Partial Fulfillment of the Requirements for the Degree of Master of the Arts

Department of Psychology
University of North Carolina Wilmington
2011

Approved by

Advisory Committee

Christine E. Hughes
Carol A. Pilgrim
Wendy Donlin-Washington
Raymond C. Pitts
Chair

Accepted By
Dean, Graduate School
# TABLE OF CONTENTS

ABSTRACT ................................................................................................................................. iv  
ACKNOWLEDGMENTS .............................................................................................................. vi  
LIST OF TABLES ....................................................................................................................... vii  
LIST OF FIGURES ..................................................................................................................... viii  
INTRODUCTION ....................................................................................................................... 1  
  Response Strength as Response Rate ................................................................. 2  
  Response Strength as Choice ............................................................................. 5  
  Response Strength as Resistance to Change .................................................. 16  
  Response Strength, Units, and Rate as a Composite Measure ....................... 19  
  The Present Experiment .................................................................................... 37  
METHOD ................................................................................................................................... 38  
  Subjects .................................................................................................................. 38  
  Apparatus .......................................................................................................... 39  
  Procedure .......................................................................................................... 39  
    Preliminary Training .................................................................................... 39  
    Concurrent Schedule .................................................................................... 40  
  Data Analysis .................................................................................................... 43  
RESULTS .................................................................................................................................. 45  
DISCUSSION ............................................................................................................................ 82  
  The Pigeon Problem ....................................................................................... 86  
  The Broken-Stick Appearance: Necessary and Sufficient Conditions ............ 88  
  Effects of Reinforcement on Operant Behavior ........................................... 91  
  The Isolation of the Behavioral Unit ............................................................... 93
The Log-Survivor Analysis as a Measure of Response Strength .................. 96

Future Directions and Limitations ................................................................. 98

REFERENCES .................................................................................................. 103
ABSTRACT

Previous research has shown that nose poking by rats maintained by variable-interval (VI) schedules of reinforcement is organized into bouts, and responses that initiate bouts of behavior show a more orderly relation to changes in rate of reinforcement than within-bout responses. A log-survivor analysis of interresponse times (IRTS) has been useful for revealing the bout pattern of behavior. This analysis plots the logarithmic proportion of IRTs that are longer than t (s). The functions generated by rats nose-poking under VI schedules typically have a broken-stick appearance with a steep, shorter initial limb representing within-bout responses and a longer, shallower second limb representing bout initiations. Changes in reinforcement rate have been shown to affect the slope of the second limb, indicating they primarily affect the probability of initiating a bout of responding. Attempts to replicate this finding with keypecking in pigeons have failed, calling the generality of the finding and of the analysis into question. One possibility is that pigeons experience a lower rate of reinforcement for engaging in behavior other than the target behavior relative to rats and therefore, do not disengage from the target response long enough for a bout pattern to emerge. The present experiment tested this hypothesis by exposing pigeons to sets of concurrent VI, VI schedules of reinforcement in the absence of a changeover delay. In this arrangement, one option is conceptually the target behavior while the other option provides reinforcement for engaging in other behavior. Log-survivor analyses failed to produce a broken-stick appearance in most cases, indicating a bout pattern of behavior did not develop. Relative IRT-frequency distributions and relative visit-length distributions suggest that when rate of reinforcement was relatively lean, visits were not long enough for a broken-stick appearance to develop. When rate of reinforcement was relatively rich, changeover IRTs were not different enough from within-visit IRTs for a broken-stick appearance to develop. These
results are possibly due to the absence of a COD which likely would have increased visit length to the lean alternative; it may be that single-alternative situations generally involve natural CODs. The present experiment does suggest, however, that the log-survivor analysis is useful when making judgments regarding the strength of a behavior. Future experiments should use a changeover delay to lengthen visits to the leaner option.
ACKNOWLEDGEMENTS

I would like to thank my mentor, Ray Pitts, for his teaching, his support, and his shaping of my scientific and verbal behavior. I would also like to thank Chris Hughes, who has truly been a second mentor. Thanks to the two of you, I feel that I have grown immensely as a writer, a thinker, and a scientist over the past two years. I would like to thank the other members of my committee, Carol Pilgrim and Wendy Donlin-Washington, for their guidance, insight, and support. All of the behavior-analysis faculty members have truly been instrumental in my learning as a graduate student, and the experience would not have been the same without any of them. I am also very grateful for the insight and thoughtful comments provided by Rick Shull in the design and implementation of this experiment. I was very lucky to have someone with such expertise in this area available to me. Thank you to the other members of the behavioral pharmacology lab including Amanda Rickard, Emily Baxter, Shelley Moore-Murawsky, Ashley Aikman, Carol Cummings, Brian Coleman, Sarah Edwards, and Meghan Burns, who assisted me in conducting experimental sessions over the course of this study. Your help is greatly appreciated.

I would like to thank my mom and dad for their ongoing support as I continue in my pursuit of a career as a researcher. I am very lucky and grateful to have such loving and encouraging parents. Finally, I would like to thank Frank for being my best friend, an engaged soundboard, and an invaluable support system.
LIST OF TABLES

1. Concurrent VI, VI Conditions................................................................................................................. 41
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sample even record of rat’s nosepoking behavior over time</td>
<td>22</td>
</tr>
<tr>
<td>2. Model of operant responding</td>
<td>23</td>
</tr>
<tr>
<td>3. The log-survivor functions produced by Shull el at.’s (2001) simulations</td>
<td>25</td>
</tr>
<tr>
<td>4. Log response ratios as a function of log reinforcement ratios for each bird</td>
<td>46</td>
</tr>
<tr>
<td>5. Log-survivor functions from the last session of Condition 1</td>
<td>47</td>
</tr>
<tr>
<td>6. Relative frequency distributions for visit length from the last session of Condition 1</td>
<td>51</td>
</tr>
<tr>
<td>7. Relative IRT distributions for each option from the last session of Condition 1</td>
<td>53</td>
</tr>
<tr>
<td>8. Log-survivor functions from the last session of Condition 2</td>
<td>57</td>
</tr>
<tr>
<td>9. Relative frequency distributions for visit length from the last session of Condition 2</td>
<td>60</td>
</tr>
<tr>
<td>10. Relative IRT distributions for each option from the last session of Condition 2</td>
<td>61</td>
</tr>
<tr>
<td>11. Log-survivor functions from the last session of Condition 3</td>
<td>63</td>
</tr>
<tr>
<td>12. Relative frequency distributions for visit length from the last session of Condition 3</td>
<td>64</td>
</tr>
<tr>
<td>13. Relative IRT distributions for each option from the last session of Condition 3</td>
<td>65</td>
</tr>
<tr>
<td>14. Log-survivor functions from the last session of Condition 4</td>
<td>68</td>
</tr>
<tr>
<td>15. Relative frequency distributions for visit length from the last session of Condition 4</td>
<td>70</td>
</tr>
<tr>
<td>16. Relative IRT distributions for each option from the last session of Condition 4</td>
<td>71</td>
</tr>
<tr>
<td>17. Inclusive log-survivor functions for each condition</td>
<td>73</td>
</tr>
<tr>
<td>18. Log-survivor functions including only changeover IRTs for each condition</td>
<td>78</td>
</tr>
<tr>
<td>19. The proportion of each kind of IRT that was reinforced across conditions</td>
<td>81</td>
</tr>
</tbody>
</table>
INTRODUCTION

Historically, response strength has been an important concept in behavior analysis (e.g., Hull, 1943; Nevin & Grace, 2000; Skinner, 1938). When a reinforcer is delivered contingent upon a response, the reinforcement is said to “strengthen” the behavior. In fact, as Herrnstein (1970) notes, “reinforce” means “strengthen.” Thorndike’s Law of Effect, the first formal description of a change in behavior as a result of its consequences, describes the strengthening effect of reinforcement as the stamping in of responses that produce “satisfaction” (Thorndike, 1911). Although Thorndike’s initial account has since been reformulated to be more eloquent and specific, it could be argued that the entire field of operant research rests upon the qualitative law of effect. The qualitative law of effect is simply the idea that behavior is a function of its consequences, and the goal of behavior analysis is to determine the variables of which behavior is a function. To say that a response is strengthened implies that a change in some property of the behavior has taken place. Although this may involve the emergence of a “new” behavior, behavior continues to change with reinforcement long after its full form has developed.

A current, and longstanding, issue is what measure of behavior should be interpreted as reflecting response strength. When considering possible methods for measuring the strength of a response, it is important to remember that the notion was developed to characterize the change in a response as a function of its consequences. Therefore, response strength implies a quantitative relation between the measure of response strength and the parameters of reinforcement (e.g., its rate, amount, delay) that are thought to affect it. For example, a higher rate of reinforcement should result in a response that, everything else being equal, is stronger. In the search for an effective measure of response strength, it seems reasonable to expect an orderly relation between the measure of response strength and the variables that affect it (Herrnstein, 1970).
Response Strength as Response Rate

One of the most commonly used measures of response strength was proposed by B. F. Skinner (e.g., 1938; 1950; and 1953). He interpreted a change in the strength of a response as a change in its probability, and he developed a methodology for measuring that change. Skinner had become disenchanted with traditional methodology for studying the changes in behavior described as learning. Researchers were most commonly using discrete-trial maze research in which each animal experienced a maze over many trials, and the change in their latency to reach the goal box, or a reduction in the number of errors before reaching the goal box, was the dependent variable. A change in the latency to reach the goal box, or a change in the number of errors made could be interpreted as a reflection of learning, and when the performance of animals was averaged together, researchers could make observations about the changes in behavior when an animal “learned” the maze. However, for Skinner, learning was not separate from performance. To say that an animal had learned something was simply to say that there had been a certain change in its behavior. He also took issue with latency or number of errors as dependent variables, because he asserted they were not the best descriptions of behavior, or of changes in behavior. A change in latency or a change in the number of errors did not reflect the notion of a change in the “probability” of behavior very well. Skinner (1950) noted that in a single discrete trial in a maze, for example, the behavior occurring at the time the experimenter begins the trial will affect the latency to finish the trial. Furthermore, it is unlikely that a decrease in the number of errors across trials directly reflects the learning history of either the “correct” or the “incorrect” response. Rather, it describes the number of instances of which an incorrect response was stronger than a correct response (Skinner, 1950).
Instead, Skinner invented and instituted the free-operant preparation still prevalent in much of today’s research (e.g., Skinner, 1938, 1956). Subjects are placed in an operant chamber in which they can make an arbitrary response (i.e., lever press, key peck) and earn food, and they are “free” to make this response at any time. The free-operant preparation minimizes experimenter intervention as an extraneous variable, and allows researchers to test as many animals at one time as boxes are available (Skinner, 1950). As different parameters of reinforcement are manipulated, the change in the rate of the behavior is measured. Skinner thought that as a response was strengthened, its probability would increase, and the change would be reflected in its rate of occurrence (e.g., Skinner, 1938, 1950, 1953). Skinner asserted that response rate “appears to be the only datum that varies significantly and in the expected direction under conditions which are relevant to the ‘learning process’” (Skinner 1950, p. 198). Skinner’s conceptualization influenced behavior analysis in such a way that response rate became the primary dependent variable within the field (e.g., see Honig, 1966; Honig & Staddon, 1977).

However, it seems that rate of responding as a pure measure of response strength has certain limitations (e.g., Nevin & Grace, 2000). Reinforcement may not simply strengthen the response upon which it was explicitly contingent (Morse, 1966). Indeed, responses that are followed by reinforcement will be more likely to occur again; they will increase in probability. However, in a free-operant preparation, isolation of the unit of behavior that is strengthened is not always straightforward. Each instance of a response carries with it many values of different properties of the response which may or may not be relevant to the contingencies of reinforcement. No two responses will ever be identical with respect to all of their properties. Also, responding is rarely reinforced continuously. Both in the natural environment and in the
laboratory, reinforcement is more commonly delivered intermittently. A reinforcer then, does not and cannot increase the probability of (i.e., strengthen) a particular response that has already occurred, but instead increases the probability of a class of responses, called an operant, that meets the criterion for reinforcement. Because no two responses are identical and not every response is reinforced, it is inevitable that specific properties of a response will be reinforced with a higher probability than others. Those properties of behavior will be strengthened and occur at a higher probability than the others (e.g., Morse, 1966). For example, in a variable-interval (VI) schedule of reinforcement, the first response following reinforcement that occurs after a given period of time has elapsed is reinforced. The lengths of the intervals will average to some experimenter-defined value (Ferster & Skinner, 1957). These types of schedules differentially reinforce longer interresponse times or IRTs (Morse, 1966). Because the interval is elapsing irrespective of behavior, the longer an organism pauses between responses, the higher the probability that the interval will have elapsed during the pause and the next response will produce reinforcement. As a result, responses following longer IRTs are more likely to be reinforced and strengthened than responses following shorter IRTs, and longer IRTs will therefore be more likely to occur (Morse, 1966). As responses following longer IRTs are more likely to occur than responses following shorter IRTs, a moderate rate of responding develops (Ferster & Skinner, 1957). An IRT of any length can meet the requirement for reinforcement on a VI schedule, but because certain IRTs are more likely to meet the criterion, and presumably, be strengthened, what is selectively strengthened may actually be a response following a class of IRTs. The class of IRTs might not be reflected in absolute response rate in the same way that strengthening effects are reflected in other schedules (Nevin & Grace, 2000). It appears that in this case, the operant, or unit of behavior, that is strengthened is not a lever press, but a lever
press following an IRT of some approximate length (or a response following a collection of other activities that occur during that IRT). The unit strengthened may be a function of the contingencies of reinforcement. Different schedules of reinforcement may strengthen different units of behavior, and the free-operant preparation may make it difficult to identify that unit. Researchers can only measure a response as it is recorded which makes it difficult to make a judgment about response strength by comparing two response rates that were generated by different schedules.

An alternative method to recording each arbitrary response without regard for the unit being strengthened might be to isolate the behavioral unit. Being able to record the change in the probability of a unit as that unit is strengthened would allow response strength to be a viable and useful notion. Also, in this way it might be possible to compare the probability or change in probability of two units of behavior that are not the same. The challenge then becomes isolating the unit. Schick (1971) reviewed Skinner’s writing on the subject and determined that Skinner’s view (1953) is that reinforcement actually strengthens multiple classes of responses of which the reinforced response is a member, not just the response class containing the property upon which reinforcement was contingent. Because reinforcement probably strengthens multiple units of behavior, it can be difficult to discern the unit strengthened most often (see Catania, 1974).

Response Strength as Choice

Some researchers (de Villiers & Herrnstein, 1976; Herrnstein, 1970) have argued that relative rate of responding may be a better measure of the strength of a response. A measure of relative response rate is made possible in experimental situations in which there is more than one experimenter-defined response. When an organism emits one response instead of another, the behavior might be characterized as “making a choice,” and these arrangements are used in
laboratories to examine variables affecting choice. In the natural environment, organisms often have several options concurrently available. An individual may engage in one behavior for some time before switching to another behavior and may be engaged in that behavior for some time before switching back to the first behavior (or to a third behavior). Presumably, each of these behaviors is reinforced (and/or punished) according to some schedule. In the laboratory, concurrent schedules of reinforcement mimic these natural situations. Variables that affect choice are manipulated, and the pattern of behavior has been shown to be a function of these variables (Catania, 1963; Catania, 1966; Chung & Herrnstein, 1967; Davison & McCarthy, 1988; de Villiers, 1977; Herrnstein, 1961; Herrnstein, 1970; McDowell, 1988). As the relative rate of responding on one option changes, the response is interpreted to have changed in relative “strength” (Herrnstein, 1970).

In a typical concurrent schedule arrangement, there are two operanda present on which the organism can respond, and each response is controlled by its own independent schedule of reinforcement. The two schedules of reinforcement could both operate on the same operandum, but each schedule still must arrange reinforcement for its own operant. The operants may differ on some property of the behavior (i.e. force, topography) (Catania, 1966), and/or may each operate in the presence of their own discriminative stimuli (Findley, 1958). In all cases, the organism is “free” to switch back and forth between the two responses. Although many different schedules of reinforcement have been studied concurrently, VI schedules are by far the most extensively researched because of the pattern of behavior emitted under these schedules and because of the experimenter’s ability to control reinforcement rate on these schedules. Variable-interval schedules produce consistent, moderate rates of behavior (Ferster & Skinner, 1957). If both schedules in a concurrent schedule are VIs, because the schedules operate independently,
while an organism is engaged in one response, the other schedule’s interval is elapsing, and the probability that one response on the other option will produce reinforcement is increasing. In concurrent ratio schedules, no such relation exists. As a result, concurrent ratio schedules tend to produce exclusive responding, whereas concurrent VI schedules produce alternation between the two responses (Catania, 1966). This pattern of behavior allows experimenters to study variables affecting response and time allocation.

Relative response rate in choice experiments as a measure of response strength is evidenced by its orderly quantitative relation to parameters of reinforcement (e.g., Herrnstein, 1970). As noted earlier, if strength is a useful concept for operant behavior, any measure of response strength should have a close relation to the variables thought to affect it. Relative response rate was first shown to be systematically related to the rate of reinforcement by Herrnstein (1961) in a simple, but monumental experiment. Herrnstein used concurrent VI, VI schedules of reinforcement to investigate the effect of changing relative rates of reinforcement on the relative rate of responding. Herrnstein examined the response rates of three pigeons exposed to standard concurrent VI, VI schedules in which the two responses were pecking a left key and pecking a right key. Overall rate of reinforcement was held constant at one reinforcer delivery on an average of every 1.5 min. The values of the VI schedules in effect on the two options were manipulated, and Herrnstein exposed the pigeons to each set of VI, VI values during daily sessions until responding stabilized. The concurrent schedules experienced by the pigeons were (left, right): VI 3 min, VI 3 min; VI 1.5 min, extinction; VI 2.25 min, VI 4.5 min; VI 1.8 min, VI 9 min; VI 4.5 min, VI 2.25 min; and VI 9 min, VI 1.8 min. Under steady state conditions, Herrnstein found that the proportion of responding allocated to either option approximated the proportion of reinforcements obtained from that option. The relation between
relative response rate and relative reinforcement rate can be expressed via the matching-law equation:

$$\frac{R_1}{R_1 + R_2} = \frac{r_1}{r_1 + r_2},$$

(1)

in which $R$ is the rate of responding, and $r$ is the rate of reinforcement obtained for responding, on option 1 or 2. Note that Equation 1 uses obtained, as opposed to programmed, rates of reinforcement because behavior is considered to be a function of what the organism experiences. Herrnstein interpreted his results to mean that as he manipulated the rate of reinforcement for each response, he had changed the strength of those responses, which was reflected in the relative rate of responding (see Herrnstein, 1970). As discussed earlier, it seems reasonable to expect that an effective measure of response strength will have an orderly quantitative relation to the parameters of reinforcement. It does not appear that the absolute response rate of responding on single schedules of reinforcement always reflects its relation with the parameters of reinforcement as it should if it is a good measure of response strength (e.g., Catania, 1963).

However, the matching law describes a very specific quantitative relation between reinforcement rate and relative rate of responding. Perhaps, if relative rate of responding obtained from choice experiments is more sensitive to the parameters of reinforcement than absolute rate of responding, it might be a better measure of response strength and thus, might reveal specific quantitative relations between reinforcement parameters and response strength more effectively.

In experimental situations such as those described above (i.e., in which there are two schedules of reinforcement operating concurrently for different responses), there actually may be four operants controlled by the experimental contingencies (see Catania, 1966). The first two operants are those programmed for reinforcement by the experimenter, but the other two are by-products of the programmed contingencies. The responses of switching from each schedule to
the other may be their own classes of responses, and may be adventitiously reinforced (Herrnstein, 1961). MacDonall has argued (1999, 2000, 2003, 2009) that in a concurrent arrangement, when an organism is responding on one option, there are two schedules of reinforcement operating: one sets up reinforcement for staying engaged on that option and the other arranges reinforcement for switching away from the option. The same is true when the organism is engaged on the other option, and there is some evidence to suggest that it is the synthesis of these four operants that produce concurrent performance. Because concurrent VI, VI schedules make it likely that reinforcement will become available for switching behaviors while an organism is engaged on one option, the unit of behavior that is strengthened may be a response to one option followed by a response to the other option. Again, the contingencies of reinforcement have made it difficult to isolate a pure operant that is a function of its consequences. In an effort to reduce the likelihood of the switching operant, many researchers, including Herrnstein (1961), have used a changeover delay (COD) which specifies a length of time that must elapse before a given response can produce reinforcement following a switch to that response. Without a COD, concurrent VI schedules produce frequent switching and, thus, responding on the two schedules does not appear to be simply a function of independently operating schedules of reinforcement. Shull and Pliskoff (1967) demonstrated that short CODs appear to produce independence in the schedules of reinforcement, but that long CODs punish switching, and responding occurs almost exclusively on the schedule with the higher rate of reinforcement.

If choice, or relative response rate, reflects the strength of a response, then it should also be sensitive to parameters of reinforcement other than rate. Although rate of reinforcement is undoubtedly the most extensively studied variable, it has also been shown that a matching
relation exists between amount of reinforcement and response rates on concurrent schedules (Catania, 1963). Pigeons were exposed to a concurrent schedule in which the rates of reinforcement for responding on the two keys were held constant at VI 2 min, VI 2 min. The duration access to food for responding on each of the two keys was manipulated. The durations studied were (left, right): 4.5 s, 4.5 s; 6 s, 3 s; and 3 s, 6 s. The rate of responding on each option was shown to increase with the duration of food presentations. Interestingly, within the same experiment, Catania failed to find such a relation under single schedules, indicating again that absolute rate of responding may not be sensitive to changes in the parameters of reinforcement and, therefore, may not be the best measure of response strength. Thus, like those with reinforcement rate, data with reinforcement amount suggest that choice arrangements may provide a more effective methodology for examining effects of variables thought to modulate response strength. Equation 1 can be modified to reflect reinforcement amount as the controlling variable:

\[ \frac{R_1}{R_1 + R_2} = \frac{m_1}{m_1 + m_2}, \]

in which R is the rate of responding, and m is the amount (magnitude) of reinforcement delivered for responding, on option 1 or 2.

Chung and Herrnstein (1967) showed that immediacy of reinforcement (the reciprocal of the delay to reinforcement) is a third parameter that produces a matching relation with relative response rates. Six pigeons were exposed to concurrent schedules in which the delay to reinforcement associated with pecking one key was held constant either at either 8 s or 16 s, while the delay for pecking the other key ranged from 1 to 30 s across experimental phases. All birds experienced a dark chamber following the peck producing reinforcement and the delivery
of food. The relative response rates were shown to approximate the relative immediacy of the reinforcer. This relation can be expressed via the equation:

\[
\frac{R_1}{R_1 + R_2} = \frac{i_1}{i_1 + i_2},
\]

in which \( R \) is the rate of responding, and \( i \) is the immediacy of reinforcement (the reciprocal of the delay to reinforcement), for Option 1 or 2.

Relative response rate is further evidenced as a measure of response strength by its generality. The matching law has been generalized to many species. For example, Poling (1978) extended the matching law to rats for the continuous response of standing on one side of the chamber or another using negative reinforcement (timeout from shock). Matthews and Temple (1979) found matching in cows for pressing a nose plate. The matching law has been extended to humans as well. Conger and Killeen (1974) studied the proportion of time spent talking to one of two confederates and found that the subjects matched talking time to the proportion of verbal reinforcements obtained from each confederate in a human conversation. An optimal measure of response strength should be universal, and the matching law’s generality supports relative response rate as an effective measure of response strength by demonstrating its relation to parameters of reinforcement across species.

Despite its generality, the matching law sometimes fails to account for all of the variance in relative response rates (de Villiers, 1977). Often, the deviations from matching are systematic and explained via variables such as reinforcement history. Deviations from matching are of three basic types: undermatching, overmatching, and bias. Undermatching occurs when responding is less sensitive to the parameters in effect than would be predicted by the matching law. Overmatching occurs when responding is more sensitive to the variables than would be predicted by the matching law, and bias occurs when more responding occurs on one option than
the matching law would predict regardless of the parameters in effect. To characterize these data, Baum (1974) developed the generalized matching law. The generalized matching law is a logarithmic equation adapted from Herrnstein’s (1970) matching equation that produces a linear function in which the values of two free parameters are used to characterize systematic variance unexplained by the reinforcement parameters in effect:

$$\log \left( \frac{B_1}{B_2} \right) = \log k + a \log \left( \frac{r_1}{r_2} \right),$$

in which $B$ is the rate of responding and $r$ is the rate of reinforcement for responding on option 1 or 2, $a$ is a measure of sensitivity of the ratio of responses to the ratio of reinforcement, and $\log k$ is a measure of bias. The value of $a$ is the slope of the function expressed by the equation. Conceptually, a value of $a$ greater than 1 indicates overmatching, and a value of $a$ less than 1 indicates undermatching. A value of $\log k$ different than zero indicates a bias for one option or the other and graphically is the y-intercept of the function (Baum, 1974).

The matching relation between the parameters of reinforcement and relative rate of responding could be obtained in two ways: an organism could respond at equal rates throughout the session with the proportion of time spent responding on one option matching its relative reinforcement rate, amount, or immediacy; or, an organism could allocate approximately equal time to the two options, but respond more quickly on the option with the richer of the two reinforcement rates, amounts, or immediacies. Studies which have measured the proportion of time allocated to one of two options (Baum & Rachlin, 1969; Brownstein & Pliskoff, 1968) have found that relative time allocated to one option also is predicted by the relative proportion of reinforcements obtained from that option and can be used as a dependent variable when studying continuous responses, such as standing in a particular location (Poling, 1978).
Because relative time allocation can be measured both when the response is continuous and when it is discrete, it has been suggested that relative time allocation may be a more effective measure of choice (e.g., Baum & Rachlin, 1969). Indeed, it appears that choice as measured by time allocation may show a more orderly quantitative relation to the parameters of reinforcement than relative rate of responding does. It has been shown that when measuring relative rate of responding, the sensitivity to rate of reinforcement ($a$ in the generalized matching law) typically is around 0.8 (e.g., see Baum, 1974). In contrast, with time allocation, sensitivity often is around 1.0 (e.g., Baum & Rachlin, 1969), indicating that changes in the parameters of reinforcement are reflected approximately equally in changes in relative time allocation. Because of its generality, and because it appears to show a more orderly relation to the parameters of reinforcement than does response rate, some researchers (e.g., Baum & Rachlin) have argued that time allocation may be a more fundamental measure of choice and, thus, of relative response strength.

However, a measure of relative rate of responding or relative time allocation requires experimental situations in which there are two experimenter-defined responses. It seems that for it to be a practical measure of response strength, Equation 1 should be modified to describe situations in which there is only one experimenter-defined option for responding. In 1970, Herrnstein adapted Equation 1 to single-alternative situations. He considered that an organism is always behaving and, thus, conceptualized all behavior as choice. When an organism is in a situation in which there is only one target response, according to Herrnstein, the organism is still in a choice situation. One option is to perform the target response, and the other option is to do one of the infinite other possible responses in that situation. All of the other options present presumably are controlled by their own schedules of reinforcement, and the responses “exist in
some strength” within the repertoire of the individual. A simple change in Equation 1 allows for Herrnstein to consider this situation:

\[ \frac{R}{R + R_e} = \frac{r}{r + r_e}, \]  

(5)

in which R is the rate of responding, and r is the rate of reinforcement for the target response. The parameter \( R_e \) is conceptualized as the rate of responding for all other behaviors present in that situation, expressed in the same units as R, and \( r_e \) is conceptualized as the rate of reinforcement for those behaviors, expressed in the same units as r. Let \( R + R_e \) (the sum of all possible responses in that situation) equal a constant, \( k \); using algebra, a new equation is produced:

\[ R = \frac{kr}{r + r_e}. \]  

(6)

Interestingly, the equation has now become an equation for absolute rate of responding instead of relative rate. The equation, commonly referred to as Herrnstein’s single-alternative hyperbola, describes a hyperbolic function in which \( k \) is the value of the asymptote and \( r_e \) is the rate of reinforcement at which the function reaches half of that asymptote. Conceptually, \( k \) is the maximum rate of responding on the target option, and \( r_e \) is the summed rates of reinforcement for all of the extraneous responses in that situation (Herrnstein, 1970).

The single-alternative hyperbola predicts that changes in the rate of responding on some target option can be produced by manipulating either of two variables. If relative response rate is an optimal measure of response strength as evidenced by Equation 1, and Herrnstein’s conceptualization of all behavior as choice is valid, absolute response rate and therefore response strength should be sensitive to changes in \( r \) and \( r_e \). The equation predicts that higher rates of reinforcement for the target option, or \( r \), will produce higher rates of responding on the target option. Decreasing the rate of reinforcement for extraneous behavior, or \( r_e \), should also produce
an increase in the target behavior (see McDowell, 1988). In experiments involving a single target option in which the rate of reinforcement for responding on that option, or \( r \), was manipulated, the corresponding response rates generally fit the function predicted by Herrnstein (e.g., Herrnstein, 1970, McDowell, 1988). Research has also shown that response rates can be controlled by manipulating reinforcement rates for responses other than the target option (\( r_e \)) (e.g., Ayllon & Roberts, 1974; McDowell, 1981). Allyon and Roberts demonstrated the applicability of Equation 6 to a clinical setting. In an effort to decrease disruptive behavior, in this case the target response, a contingency was arranged in which points were provided for correct responses on a reading test, an alternative behavior. Increasing reinforcement for a response other than disruptive behavior, or \( r_e \) in Equation 6, will presumably raise the strength (i.e., rate) of the alternative response. When \( r_e \) was increased, rate of responding on the target option (rate of disruptive behavior) decreased (Allyon & Roberts, 1974), as predicted by Equation 5. These results provide evidence for single-alternative situations to be conceptualized as choice situations, and illustrate the generality of Herrnstein’s formulation in applied settings.

The matching law and the single-alternative hyperbola are predicted by the notion of response strength as reflected in relative response rate. Herrnstein’s pigeons (1961) did not have to match the proportion of their responses on one option to the proportion of reinforcements obtained from that option to obtain all of the available reinforcers. All reinforcements could have been obtained by equal time and responses allocated to the two schedules as long as there was frequent enough alternation between the schedules to earn all of the available reinforcers. Herrnstein conceptualized the strength of an operant response as the relative response rate, which appears to have a direct quantitative relation to relative reinforcement rate. For Herrnstein, every reinforcer delivery increases the probability of, or strengthens, the response upon which it was
contingent (Herrnstein, 1970). A response reinforced twice as often (or twice as immediately, or with twice the amount) should be twice as probable and, hence, twice as “strong.”

Although it appears that the concurrent arrangement may provide for a useful comparison of the strength of two operants, the arrangement is not immune to the issue of identifying a unit. Without a COD, the matching relation between relative reinforcements received and relative responding is not obtained (Herrnstein, 1961). In a pure, concurrent arrangement, the unit that is strengthened may not simply be a response to one option or the other, but it may be a response to one option following a response to the other option. The strengthening of the switching operant results in such frequent alternation between the two options that the distribution of responses has been shown to generally approximate 50-50 regardless of the distribution of obtained reinforcements (Herrnstein, 1961). Adding the COD may prevent the adventitious reinforcement of the switching operant. Ideally, the COD would allow for the strengthened unit to be a response (i.e. keypeck, lever press) to the option that produced the reinforcement. If this were the case, then the strength of two responses could be compared because the units being strengthened by reinforcement would be the same. Of course, this is only true if both options reinforce responding according to comparable schedules (e.g., VI schedules). For the reasons discussed above, different units would be produced if one of the options reinforced responding according to a VI schedule of reinforcement while the other reinforced responding according to some other schedule, such as a fixed-ratio (FR) schedule of reinforcement. There is, then, reason to search for a measure of response strength other than absolute or relative response rate.

**Response Strength as Resistance to Change**

Some researchers (Bell, 1999; Nevin & Grace, 2000; Smith, 1974) have suggested that response rates generated by reinforcement schedules do not reflect the strength of responding,
and instead, are a measure of “performance.” According to behavioral-momentum theory (Nevin & Grace, 2000), response rate is a function of the response-reinforcer relation present within a the three-term contingency. For Nevin and Grace, then, response rate under VI schedules seem to reflect what Morse (1966) called a “shaping effect” (e.g., an outcome of differential reinforcement of certain classes of IRTs). Alternatively, according to behavioral-momentum theory, the “strength” of the response is a function of the relation between the discriminative stimulus present and the parameters of reinforcement. According to this theory, operant contingencies (response-reinforcer relations) do not contribute to the strength of a response; rather, response strength is said to be a result of the Pavlovian contingencies (stimulus-stimulus pairings). Behavioral-momentum theory is named for its metaphor in which a response is likened to an object moving through space. The strength of the response can be interpreted as its behavioral mass. The rate of responding is interpreted to be the object’s velocity. For example, a cannonball and a feather moving through space with the same velocity require different forces to be stopped. The force required to stop the cannonball or the feather is a function of their momentum and their mass. In this analogy, the mass of the two objects is likened to the strength of two ongoing behaviors, which may or may not have different response rates (velocities). When a force (disruptor) is applied to the ongoing behavior, the degree to which the behavior “resists” the force can allow for its momentum and, thus, its mass (strength) to be estimated. The strength of responding cannot be observed until the behavior is challenged, and then the response’s resistance to change can be interpreted as a reflection of response strength.

Studies examining resistance to change as a measure of response strength typically use multiple schedules. In a multiple schedule, two schedules of reinforcement alternate, and each schedule is associated with its own discriminative stimulus (Ferster & Skinner, 1957).
Performance is established before a disruptor (i.e., extinction, prefeeding) is introduced. In the presence of the disruption, the schedule that maintains a higher proportion of its baseline level of responding is said to have greater resistance to change and is interpreted to have greater strength (Nevin & Grace, 2000). Using proportion of baseline as the dependent variable circumvents the problem of differing original response rates that are said to reflect the performance of the response produced by differential reinforcement (Nevin & Grace, 2000). Because schedules of reinforcement produce patterns of responding that are a product of the contingencies defined by the experimenter, and do not reflect the strengthening effects of reinforcement alone, comparing the absolute reduction from baseline responding for two different schedules of reinforcement may not be appropriate. However, when comparing the proportion of baseline responding, one response’s resistance to change can be meaningfully compared to another’s.

Interestingly, Nevin and Grace (2000) agree with Herrnstein (1970) that choice appears to be meaningfully related to response strength. Choice and resistance to change appear to covary with the parameters of reinforcement providing evidence that they may both successfully measure the effects of reinforcement (Nevin, 1979). As discussed in terms of the matching law, options with higher rates of reinforcement, higher magnitudes of reinforcement and shorter delays to reinforcement are more “preferred” than their alternatives. However, Nevin and Grace (2000) acknowledge the problems discussed above with rate and argue that when different schedules of reinforcement are compared, choice is confounded. One way of circumventing the problem is to use concurrent-chains schedules to assess preference (Nevin, 1979). In a concurrent-chains schedule (Autor, 1969), on each choice cycle, the subject is presented with two options. These are called the initial links and each one controls access to a second schedule of reinforcement (its terminal link). On any given cycle, only one initial link is preset to allow
access to its terminal link. However, nothing signals which link will produce access to its terminal link. Usually, equal VI schedules are used in the initial links, with the reinforcer being access to the terminal link. The terminal links provide the independent variable of interest. The two terminal-link schedules are usually different in some way (e.g., schedule type, rate of reinforcement, amount of reinforcement, delay to reinforcement). Because each initial link option is only active half of the time, subjects must sample both options, and response rates during the initial links can be compared to determine preference for the terminal link schedules. Very different schedules of reinforcement, in which entirely different units of behavior are strengthened, can be used in the terminal links. Generally, comparing response rates under these schedules to determine strength would be difficult, but as long as equal schedules of reinforcement are used for the initial links, response allocation can still be compared there. Nevin and Grace (2000) describe evidence that preference assessed using concurrent-chains schedules appears to be a function of the parameters of reinforcement in the same way as is resistance to change (Grace & Nevin, 1997). This kind of evidence supports the notion that the two measures are both reflections of the strengthening effect of reinforcement.

Response Strength, Units, and Rate as a Composite Measure

As discussed earlier, if the notion of strength is to be a useful one, then it is necessary to identify the unit being strengthened, especially if comparisons are to be made between different responses or response patterns. The unit should change in probability in an orderly way with the parameters of reinforcement. Rate of responding also carries with it some difficulties because the unit being strengthened often is unclear. Perhaps, one of the difficulties is that the rate of responding may not be a unitary measure, but is instead a composite one (Shull, Gaynor, & Grimes, 2001). Although the pattern of responding on VI schedules of reinforcement is typically
thought to be consistent with little pausing (Ferster & Skinner, 1958), when examining the
temporal patterns of individual operant responses made on these schedules, it appears that
responding is actually organized into bouts of rapid responding in between which there are
periods of no responding (Blough, 1963; Gilbert, 1958). The bouts of responding consist of
several consecutive responses emitted with short IRTs separated by very long IRTs (no
responding). It is possible that these bouts of responding reflect periods of engagement in the
target response between which the organism is actually disengaged from the response (Gilbert,
1958; Pear & Rector, 1979; Shull et al., 2001). If an organism is always behaving (Herrnstein,
1970), then these periods of disengagement in the target response may represent times in which
the organism is actually engaged in other, unmeasured, responses (Pear & Rector, 1979). In
Herrstein’s (1970) formulation, these unmeasured responses would be reinforced at rates which
sum to $r_e$ (Equation 6). A traditional measure of response rate does not capture the
engagement/disengagement pattern of responding, and it may be that response rate actually
represents a composite measure of responding (engagement and disengagement) instead of a
unitary one (Shull et al., 2001). If this is true, then it may not be valid to consider each instance
of the response as equal. Responses that initiate a bout of responding may be functionally
different than those within a bout. The two classes might have their own probabilities of
occurrence and be affected differently and independently by variables in the environment (i.e.,
are fundamentally different units). A change in the environment may make it more likely that
the organism will engage in bouts of behavior (i.e., increase the class of responses that are bout-
initiations) or it may change characteristics of the bout once the organism is engaged in
responding (e.g., within bout response rate, or bout length). The historical method of analysis
(responses/time) would fail to capture the differential effects on the two classes (Shull et al.,
Theoretically, it is possible that two variables changed in the environment might result in approximately equal changes in overall response rate, and the two variables may be interpreted to have the same effect on behavior. However, if each variable affected only one class of responses, or affected each class differentially, then the variables will have changed behavior in very different ways.

In order to tease apart the hypothesized class of responses, it may be beneficial to analyze changes in bout-initiation and within-bout responding separately. Unfortunately, it is difficult to classify any individual response as a bout-initiation or within-bout response. Figure 1 is a diagram taken from Shull et al. (2001; see Figure 1) and demonstrates the difficulty. While there are clear groups of responses between which it seems there are periods of disengagement, it is difficult to determine how many bouts, if any, compose these groups of responses. For example, section “a” could be simply one bout of responding, but some IRTs within the bout appear longer than others and it is difficult to determine if they represent short periods of disengagement or simply slightly longer-than-usual IRTs within a bout. That is, it is difficult to determine whether the responses following these different IRTs represent different classes or simply variation within a single class. Some researchers have used an IRT-cutoff method in which a time is chosen by the experimenter, and all responses occurring after IRTs longer than the cutoff are classified as bout-initiations while all IRTs shorter than the cutoff are deemed within-bout responses (Mellgren & Elsmore, 1991). However, it is likely that if there are two classes of responses, their IRT distributions will overlap, perhaps considerably. If that were the case, then any IRT cutoff chosen will likely misclassify responses from each operant class.

In a two-part paper, Shull and colleagues (Shull et al., 2001) proposed a two-state model of operant responding shown in Figure 2 (Shull et al., Figure 2). Suppose an animal is
Figure 2. Model of operant responding. At left an animal is disengaged from the target response and presumably engaged in some other, unmeasured response. There is a constant probability, \( p(V) \), of initiating a bout of responding. Once the animal initiates a bout of responding, it emits within-bout responses at a constant probability, \( p(R) \). Every within-bout response carries with it the probability that it will end the bout, \( p(D) \), and allow the animal to enter disengagement, or that it will not, \( 1-p(D) \). Reprinted with permission from Shull, R. L., Gaynor, S. T., & Grimes, J. A. (2001). Response rate viewed as engagement bouts: Effects of relative reinforcement and schedule type. *Journal of the Experimental Analysis of Behavior, 75*, 249. Copyright 2001 by the Society for the Experimental Analysis of Behavior, Inc.
disengaged from the target response. There may be a constant probability of emitting a bout-initiation response (i.e., initiating a “visit”), \( p(V) \). An increase in \( p(V) \) indicates an increase in the likelihood of engaging in bouts of behavior, but not the rate of responding once the organism was engaged or the length of the bouts of responding. Once the animal has entered a bout of responding, within-bout responses are emitted at a constant probability, \( p(R) \); \( p(R) \) determines the emitted rate of responding when the organism is engaged in a bout. Each response carries with it a probability of ending the bout and initiating a period of disengagement from the target response, \( p(D) \); thus, the probability of continuing the bout is \( 1-p(D) \). The length of the bouts of responding would be determined by \( p(D) \). To examine a pattern of responding that might be produced by the model, Shull et al. generated two different computer simulations in which two components (perhaps VI schedules) alternated within a multiple schedule. Both computer simulations held the probability of emitting a within-bout response, \( p(R) \), constant across components, while one simulation manipulated between components the probability of emitting a bout-initiation, \( p(V) \), and the other simulation manipulated the probability that each response would end a visit, \( p(D) \).

Shull et al. (2001) plotted the results of these simulations using log-survivor functions shown in Figure 3 (see Shull et al. Figure 3). In a log-survivor function, the proportion of IRTs greater than a given time \( t \) is plotted on a log scale as a function of \( t \). The log-survivor functions of a distribution of IRTs in which the probability of responding is constant will plot as a linear function in which the slope is a function of the probability of responding. The higher the probability of responding is, the steeper the slope will be. If the probability of responding decreases as time passes since the last response, the function will be decreasing, but concave up. Alternatively, if the probability of responding increases as time elapses since the last response,
Figure 3. The log-survivor functions produced by Shull et al.'s (2001) simulations. The logarithmic proportion of interresponse times longer than \( t \). The two functions in the first simulation (left) were produced using simulations with the same probability of responding during a bout, \( p(R) \), and the same probability that each response would end a bout, \( p(D) \). They differ in their probability of emitting a response when in a period of "disengagement," \( p(V) \). The two functions in the second simulation (right) are produced by simulations in which the probability of emitting a bout-initiation, \( p(V) \), and the probability of responding during a bout, \( p(R) \), were held constant. The probability that each within-bout response would end the bout, \( p(D) \), however, was manipulated. Reprinted with permission from Shull, R. L., Gaynor, S. T., & Grimes, J. A. (2001). Response rate viewed as engagement bouts: Effects of relative reinforcement and schedule type. *Journal of the Experimental Analysis of Behavior, 75*, 251. Copyright 2001 by the Society for the Experimental Analysis of Behavior, Inc.
the function will be decreasing, but concave down. As shown in Figure 3 the functions generated by Shull et al.’s (2001) simulations were “broken stick” in appearance, with the two linear “limbs” of each function having their own distinct slopes. The two-limb appearance indicates that there may be two different probabilities of responding operating: one at shorter IRTs and the other at longer IRTs. The initial, shorter, steeper limbs could be conceptualized as within-bout responding as their IRTs are those that are short. The second, longer and shallower limbs represent longer IRTs, and are conceptualized as bout-initiations. Because the y-axis is logarithmic, the slope of the first limb indicates within-visit response rate, whereas the slope of the second limb can be considered the bout-initiation rate. If the break of the function is shifted to the y-axis, the y-intercept of the break is the proportion of responses that are bout initiations. Because the functions had two reasonably linear limbs with different slopes, Shull et al. (2001) suggested that overall response rate was a composite measure of two different classes of responses: responses occurring following short IRTs occurring at one probability and responses following long IRTs occurring at a different probability. For these simulations, this was necessarily true, because the experimenters programmed the simulations to emit responding in this way. However, the simulations provided examples against which actual obtained IRT distributions could be compared.

As noted above, Shull et al. (2001) ran two separate simulations. When each component of the two simulations was plotted using this method, the functions produced by the two different simulations differed in two key ways. The first simulation, shown in left panel of Figure 3, in which the probability of initiating a visit was manipulated, produced similar initial limbs, but distinct second limbs. The second limbs had different slopes, indicating different rates of emitting bout-initiations. The second simulation, shown in the right panel of Figure 3, in which
the probability of disengagement following each response was manipulated, produced initial limbs with similar slopes but different lengths. Therefore, the second limbs have different y-intercepts (proportion of responses that are bout-initiations). The slopes of the second limbs (bout-initiation rates) were equal. Another interesting feature of the two simulations is that the change in overall response rates between the two components is approximately equal for both simulations, illustrating the possibility that the change between components would be regarded as the same using the standard dependent variable of overall response rate. However, the pattern of responding clearly is changed differently across the two simulations. Again, these simulations do not show that actual responding necessarily is organized in the way Shull et al. (2001) hypothesize, but instead they show the functions that would develop if responding were to be organized according to their model. The functions can now serve as comparisons for log-survivor functions produced by real responding.

In Part 2 of their study, Shull et al. (2001) used the log-survivor analysis to characterize the IRTs produced under VI schedules of reinforcement. Would the broken-stick structure emerge in the responding of live organisms? If so, this would suggest that overall response rate might be a composite measure of different classes of responses. The notion that response rate is a composite measure also raises the possibility that different classes of IRTs might be affected differentially by different classes of manipulations. Thus, Shull et al. examined effects of a) reinforcement rate, b) reinforcement amount, c) the percentage of reinforcement contingent on responding, and d) adding a tandem variable-ratio (VR) requirement to the VI. Seven rats nose-poked pigeon keys for food reinforcement under multiple VI, VI schedules. Under all conditions, log-survivor analyses revealed a broken-stick appearance very similar to those obtained from the computer simulations. The first three variables appeared to have little effect
on the length of a visit (the y-intercept of the second limb) or the within-visit response rate (the slope of the first limb), but affected the visit-initiation rate, indicated by the differing slopes of the second limbs of each function. As the reinforcement rate, reinforcement amount, and percentage of reinforcement that was response dependent were increased, the slope of the second limb became steeper. These results suggest that the first three variables increased the probability of emitting a bout-initiation response, but did not affect the length of a bout or the within-bout response rate once the animals were engaged. In contrast, when a tandem VR requirement was added, the length of the initial limb increased, indicating that a lower proportion of responses were visit initiations and that the average visit length was longer than without the added VR. Thus, the data from part 2 of Shull and colleagues’ study indicated that responding under VI schedules of reinforcement may indeed be a composition of two classes of responses, and that the probability of emitting one of these classes of responses can be changed independent of the probability of emitting the other class of responses giving more evidence for the two-state model of responding.

The first three variables manipulated by Shull et al. (2001), rate of reinforcement, amount of reinforcement, and the percentage of reinforcement contingent on responding, are variables that often have been conceptualized as affecting the strength of a response (e.g., de Villiers & Herrnstein, 1977; Herrnstein, 1970; Morse, 1966). Theoretically, these strengthening effects would not change the particular behavioral unit generated by a particular reinforcement contingency. That is, these three variables increase the probability of the particular unit selected. Indeed, as noted previously, an effective measure of response strength would be expected to show a quantitative relation to changes in these variables. Shull et al.’s results suggest that, at least under VI schedules, the strengthening effects of reinforcement may be reflected in one of
the two classes of responses revealed by the log-survivor analysis: those responses that initiate bouts of responses during periods of disengagement. The stronger the response (i.e., the higher the rate or magnitude of reinforcement, or the higher the percentage of reinforcement that is response dependent), the higher the probability of initiating a bout of responding was. In contrast, the effects of the last variable, in which a tandem VR requirement was added to a VI schedule of reinforcement, were of a different sort; these effects appeared to reflect a change in the behavioral unit strengthened by reinforcement. Once the interval had elapsed, a consecutive number of responses had to be emitted. In fact, as long as the interval had elapsed, the more quickly the responses were emitted, the more quickly reinforcement was obtained. Overall rate of responding increased when the tandem VR was added although the rate of reinforcement remained unchanged. Instead of causing an increase in response rate as a result of an increase in the strength of the response, adding a tandem VR might have changed the unit of behavior that was strengthened. Instead of a class of IRTs (as has been hypothesized as the behavioral unit in a VI schedule of reinforcement), what may have been strengthened under this contingency is a number of consecutive responses emitted quickly. It is also possible though that the differential reinforcement of long IRTs has simply been destroyed. When looking at the log-survivor analysis of IRTs following the addition of a tandem VR, the rate of bout-initiations (i.e., the probability of emitting a response that initiates a bout) did not change, but the first limb of the log-survivor function became longer. The first limb of the function increased in length because, presumably, each bout of responding contained more responses. This increase in the number of responses within each bout may have reflected a shift in the behavioral unit. If this was true, then changes in the behavioral unit may be reflected in the initial limb of the log-survivor analysis of IRTs.
Further evidence that the log-survivor analysis might be an effective method for characterizing the strength of responding under VI schedules of reinforcement was provided by Shull, Gaynor, and Grimes (2002). In this study, log-survivor analyses were used to examine resistance to change under multiple VI schedules. As discussed above, a response’s resistance to change has been suggested as a measure of response strength because of its relation to variables that are thought to affect response strength. When faced with a disruptor (e.g., extinction) the response that maintains a higher proportion of baseline is considered to show more resistance to change, and is interpreted to be stronger (Nevin & Grace, 2000). A common finding is that there is more resistance to change in the presence of the stimuli associated with the higher rate of reinforcement, regardless of whether or not the additional reinforcement was response dependent. This is true even though baseline response rates appear to be related to the rate of response-dependent food presentations only (e.g., Burgess & Wearden, 1986; Rachlin & Baum, 1972). Shull et al. (2002) considered the possibility that while two components with the same response-dependent reinforcement rates and different overall food-presentation rates produce similar overall baseline response rates, the rate of bout-initiations or the rate of within-bout responding may be different between the components. Further, it may be that bout-initiation rate and within-bout responding are affected differently during disruption (extinction); that is, one of these measures might show differential resistance to change. If bout-initiation responses are the class of responses that best reflect response strength, it might be expected that they would be the class of responding to slow orderly decreases during extinction (as extinction is thought to be a weakening of behavior and the opposite of the strengthening that takes place when a response is reinforced).
Two squads of rats each experienced two conditions. In one condition, nose poking was reinforced on a MULT VI 1-min (rich) VI 4-min (lean) schedule. In the second condition, nose poking was reinforced on a MULT VI 4-min VI 4 min, but in one of the components (the rich component) a VT 1.33-min schedule of food presentation was conjointly arranged. Following the production of stable performance, both components were switched to extinction. In the first condition (MULT VI 1-min, VI 4-min), higher baseline response rates in the rich component were a result of a higher bout-initiation rate; the within-bout responding was approximately the same for the two components (these results replicated those found in Shull et al., 2001). However, in the second condition (MULT VI 4 min, conjoint VI 4 min VT 1.33 min), the log-survivor functions did not differ across the components, showing that any differences found later in the resistance to change tests were not the result of differences in baseline rates of within-visit or bout-initiations responses. As expected, overall response rates in both components declined during extinction, and responding that had been reinforced under a lean schedule declined faster than responding that had been reinforced under a rich schedule, regardless of whether or not the additional reinforcers were response-dependent. During extinction, responses per bout remained relatively consistent, decreasing only slightly, while the decrease in overall response rate appeared to be mainly the result of a decrease in bout-initiation rate. The bout-initiation rate decreased much more quickly in the lean reinforcement schedule than in the rich reinforcement schedule, providing evidence that bout-initiation rate may be the best measure of resistance to change. Showing that bout-initiations is the class of responses changed when a behavior is disrupted suggests that bout-initiations are the class of responses reflecting the strengthening of reinforcement under VI schedules.
In summary, Shull and his colleagues (2001, 2002) have provided evidence that operant responding does indeed appear to be organized into periods of engagement and disengagement. It also appears that there may be two, functionally different classes of responses: those that initiate a bout of responding and those within a bout. The most persuasive evidence for the two-mode model is that different variables appear to affect the classes of responding independently. Reinforcement rate, reinforcement amount, and percent of reinforcement that is response dependent appear to increase the likelihood of emitting a bout-initiation response. Because an increase in strength is generally interpreted to mean an increase in the probability of responding and these three variables are thought to affect response strength, there is evidence that when responding under VI schedules is strengthened, the class of responses that increases in probability is the class of bout-initiation responses. Alternatively, adding a tandem VR to the VI schedule would be expected to change the behavioral unit as well as the overall response rate while having little effect on the strength of the response. Data reported by Shull and colleagues (2001, 2002) indicate that, at least in this case, a change in the behavioral unit is reflected in changes to the length of the bout. It may be that characteristics of the behavioral unit are reflected in the characteristics of the bout of responding. Finally, when reinforcement for responding is discontinued, it appears that bout initiations, rather than within-bout responses, are the primary component of differential responding to change. Extinction appears to be a weakening of responding, so just as bout-initiations were the class of responses to be strengthened with reinforcement, they are the class of responses to be weakened when it is discontinued.

Thus far, the log-survivor analysis has proven to be useful when examining nose-poking in rats. Unfortunately, attempts to generalize the log-survivor analysis to pigeons have been
unsuccessful (Bennett, Hughes, & Pitts, 2007; Bowers, Hill, & Palya, 2008; Podlesnik et al., 2006). For example, Bennett et al. examined key-pecking in pigeons under a multiple random-interval (RI) 1-min, RI 4-min schedule using the log-survivor analysis. They were unable to obtain the broken-stick appearance Shull and colleagues obtained with rats (Shull et al., 2001, 2002). Instead, the log-survivor functions produced by the birds were decreasing, concave up. The higher reinforcement rate did produce a steeper slope, but there were not two distinct limbs. These results indicate that keypecking by pigeons may not be organized into periods of engagement and disengagement and, thus, this analysis of IRTs may lack generality. It seems that if Shull et al.’s (2001) model of responding is meaningful, then the two classes of responding should be reflected in two distinct limbs regardless of the subject’s species or the response.

One possible reason for the failure to obtain broken-stick functions in pigeons (Bennett et al., 2007) lies in the rate of reinforcement for extraneous responses. It may be that pigeons experience a very low \( r_e \) compared to rats, and at the investigated range of reinforcement rates, all of the responding is on the target option with no periods of disengagement (i.e., all responses are within-bout responses). Or possibly, each period of disengagement is so short that the two classes of responses have IRT distributions that almost completely overlap. In both of these cases, the log-survivor analysis would not produce a broken-stick appearance. In Herrnstein’s (1970) single-alternative hyperbola, this would mean all responding is close to \( k \), the asymptote of the function. In Shull et al. (2001)’s model, this would mean either that each response is a bout-initiation or that all were within-bout responses. There is reasonable evidence for this interpretation of the data. Shull (2005) examined 18 data sets from 17 previously published studies in which rats or pigeons had been exposed to several different VI schedules of
reinforcement (either singly across experimental phases, or within the context of a multiple schedule). The results of his analysis indicated that at the range of reinforcement rates typically investigated, rats were much more sensitive to changes in reinforcement rate than were pigeons. Each subject’s data was fit to Equation 6, and values of $k$ and $r_e$ were obtained for each animal. There were obvious differences between species. He found that for rats and pigeons, while the maximum response rate, $k$, was approximately equal, the values of $r_e$ were much lower for the pigeons than for the rats. Shull found that studies using pigeons as subjects typically examine rates of reinforcement too high to see changes in response rates as a result of a manipulation in reinforcement rate. Almost no studies with pigeons investigate reinforcement rates for the target option that were below the derived value of $r_e$; because $r_e$ is the rate of reinforcement at which response rates have reached half their maximum value ($k$), it would not be possible to see response rate increases of more than double the lowest obtained rate. Shull’s analysis suggests that studying lower rates of reinforcement for the target response, below about 10/hr, would decrease response rates to levels at which disengagements might emerge. That is, as the rate of reinforcement for the target option is decreased, the rate of reinforcement for engaging in alternative behavior (while not directly manipulated) would become relatively larger, and the organisms would begin to allocate more of their behavior to those other options, producing periods of disengagement.

Directly increasing the rate of alternative reinforcement, $r_e$, also might decrease relative value of engaging in the target response and, therefore, might produce periods of disengagement. One possible method for accomplishing this would be to use concurrent schedules of reinforcement. In concurrent schedules, each option is its own operant maintained by its own schedule of reinforcement. Each option provides an alternative source of reinforcement, or $r_e$ for
the other option. Because the reinforcement rate for each option is programmed by the experimenter, each can be arranged to provide an alternative source of reinforcement for the other to produce periods of disengagement. A second option may provide a sufficiently high rate of reinforcement for alternative responses and decrease responding below the maximum \( (k) \).

Presumably, periods of disengagement would be produced during which the organism would be engaged on the other option. It would be possible to examine IRTs on one option using a log-survivor analysis while considering time responding on the other option simply as an IRT from the first (i.e., a disengagement). The time spent engaged on the target response might then appear bout like, and consist of relatively short IRTs interspersed with long IRTs during which time the pigeon was engaged on the other option. The two distributions of IRTs should be fairly different with little overlap, which would produce a broken-stick appearance in the log-survivor analysis. If periods of disengagement from the target option produced from this arrangement consist primarily of periods in which the subject is responding on the other option, then each changeover to the target option will be a bout-initiation, and each response on the target option following a changeover will be a within-bout response. In addition to analyzing the IRTs on the target option, a log-survivor analysis of the dwell times on the second option would provide a measure of the rate of bout-initiation to the first option. A dwell time on the second option is a period of disengagement from the first option ending in a bout-initiation. If the dwell time analysis were to match the second limb of the IRT analysis, it would provide evidence that the periods of disengagement in this arrangement consist primarily of periods in which the subject was actually engaged on the other experimenter-defined response. There is some evidence to suggest that the log-survivor analysis of dwell times would yield a reasonably linear function.

For example, Gallistel, Mark, King, and Latham (2001) showed that analyzing the dwell times of
rats’ lever pressing maintained by brain stimulation on concurrent VI, VI schedules of reinforcement did result in relatively linear functions. If the concurrent arrangement produces the broken-stick appearance in the IRT log-survivor analysis, it would be the first successful attempt to generalize Shull’s analysis to pigeons, and it would strengthen the case that the log-survivor analysis is a valid, and general, method for distinguishing between two classes of responses that would otherwise be treated equally.

There has been one previous attempt to characterize the responding of pigeons under concurrent schedules using log-survivor plots. Davison (2004) re-analyzed data from three previously published studies that used concurrent schedules with pigeons (Davison & Baum, 2003; Landon, Davison, & Elliffe, 2002, 2003). Interestingly, the functions typically did not show the broken-stick appearance (they were similar to those reported by Bennett et al., 2007). However, it should be noted that the data analyzed by Davison were obtained from responding in an unstable environment. That is, he used data from situations in which the rates of reinforcement for the two options varied several times within each session. Furthermore, while each within-session change in reinforcement rate was signaled, the specific reinforcement rates in effect were not. That is, responding adapted within each condition. Finally, Davidson did not consider responding on one option as disengagement from the other option. He only analyzed the IRTs while the organism was engaged one option or the other. If responding on one option is not considered as time disengaged from the other option, the arrangement is the same as using a single-schedule of reinforcement. Thus, it is unclear whether or not a broken stick structure would have emerged had Davison considered time responding on a given option as disengagement from the other option.
The Present Experiment

The present experiment attempted to produce periods of disengagement from the target response in pigeons using concurrent VI, VI schedules of reinforcement by providing an alternative response that presumably holds a much higher rate of reinforcement than is typically experienced for extraneous responding under single schedule of reinforcement (e.g., Shull, 2005). It was predicted that if Shull’s interpretation is correct, and the present experiment was able to produce periods of disengagement, then the log-survivor functions would have a broken-stick appearance. One VI schedule was held constant while the rate of reinforcement for responding on the other option was manipulated. Conceptually, the aim was to raise the rate of reinforcement for engaging in behavior other than the target response, \( r_e \), and then examine behavior as the rate of reinforcement for the target response was manipulated. It was predicted that if the broken-stick appearance was obtained, as the rate of reinforcement for responding on the target option was manipulated, changes in the slope of the second limb should have been observed, while the slope and length of the first limb should remain relatively constant. However, it was also predicted that even if the broken-stick appearance was not obtained, changes in the slope of the function would still be observed as the rate of reinforcement was manipulated.

The second purpose of the experiment was to obtain data that might help address the issue of response strength as reflected in the rate of bout-initiations. As the rate of reinforcement for the target option was manipulated, if the rate of bout-initiations is a useful measure of response strength, the rate of bout-initiations would be predicted to change with it. A good measure of response strength should vary with the parameters of reinforcement thought to affect it. Also, it has been hypothesized that the number of responses within a bout is affected by the
behavioral unit shaped by the contingencies of reinforcement. If that is the case, the length of the initial limb might not have been predicted to change as a function of rate of reinforcement because, presumably, the contingencies governing that unit would not have changed. However, research with concurrent schedules has suggested that as the rate of reinforcement for responding on one option is increased, the rate of changing over from that option decreases (Shull & Pliskoff, 1967). In a log-survivor analysis, these results would predict that the length of the bouts would increase. Therefore, the present study examined changes of within-bout characteristics (e.g., rate, length) as reinforcement rate was changed. The concurrent VI, VI arrangement combines the previous research suggesting bout-initiations are the class of responses reflecting strength with the notion of response strength as choice. Manipulating the rate of reinforcement for the target option would be predicted to affect the relative strength of the fixed response. It was hypothesized that the rate of bout-initiations on the fixed response would change with each condition although its parameters of reinforcement were not directly manipulated.

METHOD

Subjects

Four Racing-Homer pigeons were used as subjects. Birds 182, 19, and 805 were experimentally naïve, and Bird 293 had previous experience responding under RI schedules of food presentation. They were housed in a temperature and humidity controlled colony room on a 12-hour light/dark cycle (Lights on 07:00). Experimental sessions took place 7 days a week during the light part of the cycle. The pigeons were maintained at 85% of their free-feeding weight via post-session feeding of Purina Pigeon Checkers.
Apparatus

Four identical Med-Associates ENV-007 operant chambers were used. The interior dimensions of the chambers were 30.5 cm L x 24.1 cm W x 29.2 cm H. The front wall contained three 2.5 cm in diameter response keys spaced 8 cm apart (center to center). The two side keys were 3.0 cm from their center to the adjacent wall. Each key was 21.5 cm from the floor, and could be illuminated white, red, or green. The keys required between .18-.38 N of force to register a response, but within each chamber the required force between keys was within .05 N. Each response produced a click from a relay that was audible from inside the chamber. A 1.5 cm in diameter house light that illuminated the chamber was centered on the rear wall 1.5 cm from the ceiling. There was a 6.5 cm X 5.5 cm opening centered on the front wall 12.8 cm from the center key, through which mixed grain could be delivered via a hopper. Each chamber was enclosed in a sound-attenuating cubicle, and an exhaust fan operated during all experimental sessions. White noise was broadcast within the experimental room during all sessions to help mask any extraneous sounds. The chambers were operated and data were recorded using a Microsoft Windows-based computer using Med Associates 4.0 (Georgia, VT) software and interface equipment that operates at a 0.01 s resolution.

Procedure

Preliminary Training

The three experimentally naïve birds experienced two sessions of adaptation and one session of hopper training before keypeck training began. Hopper training consisted of multiple presentations of milo with each presentation lasting until the bird ate from the hopper. For these naïve birds, pecking the center key was shaped via reinforcement of successive approximations. During hopper training and shaping, the middle keylight was lit white and the house light was
illuminated. During food presentations the house light and key lights were darkened and the hopper was illuminated. Following shaping, the birds experienced daily sessions during which an RI 5-s schedule of grain presentation was in effect. Access to grain was 3.5 s long. The bird with previous experience was placed directly on this RI 5-s procedure.

Concurrent Schedule

Birds were then shifted to a standard concurrent schedule of reinforcement in which both the left and right keys were illuminated white. The house light was on during all sessions except when reinforcement was delivered at which time the house light and the keylights were dark. Pecking each key produced a 3.5-s delivery of milo according to its own Fleshler-Hoffman (1962) VI schedule of reinforcement (i.e., independent concurrent scheduling). Intervals were randomly selected without replacement until all intervals had been selected at which point the computer again randomly selected from the complete list of intervals. One set of concurrent VI, VI schedules was in effect for the entire session. Because this experiment attempted to approximate a single-alternative situation in which there presumably is no penalty for switching, no COD was used. Sessions were ended either when a specified number of total reinforcers had been delivered or by a time limit, whichever occurred first. The time limits were set considerably longer than the time normally required to collect all of the scheduled reinforcers, and thus, sessions almost always ended via the number of reinforcers delivered. Table 1 provides the number of reinforcers and time limits for each condition. During the first three conditions, each VI schedule was comprised of 12 intervals, and the reinforcer limit was 48 so that, typically, the complete set of intervals had been experienced for both keys one or more times (keeping reinforcement rate close to the programmed contingencies). For the fourth condition (VI 3-min, VI 27-min), it was necessary to increase the number of reinforcers that terminated the
Table 1

*Concurrent VI, VI Conditions*

<table>
<thead>
<tr>
<th>Bird</th>
<th>Left</th>
<th>Right</th>
<th>Sessions</th>
<th># Reinforcers</th>
<th>Time Limit (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>182</td>
<td>3 min</td>
<td>3 min</td>
<td>69</td>
<td>48</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>9 min</td>
<td>3 min</td>
<td>46</td>
<td>48</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>1 min</td>
<td>3 min</td>
<td>36</td>
<td>48</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>27 min</td>
<td>3 min</td>
<td>75</td>
<td>90</td>
<td>270</td>
</tr>
<tr>
<td>19</td>
<td>3 min</td>
<td>3 min</td>
<td>69</td>
<td>48</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>3 min</td>
<td>9 min</td>
<td>20</td>
<td>48</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>3 min</td>
<td>1 min</td>
<td>62</td>
<td>48</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>3 min</td>
<td>27 min</td>
<td>33</td>
<td>90</td>
<td>270</td>
</tr>
<tr>
<td>293</td>
<td>3 min</td>
<td>3 min</td>
<td>17</td>
<td>48</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>3 min</td>
<td>9 min</td>
<td>75</td>
<td>48</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>3 min</td>
<td>1 min</td>
<td>55</td>
<td>48</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>3 min</td>
<td>27 min</td>
<td>28</td>
<td>90</td>
<td>270</td>
</tr>
<tr>
<td>805</td>
<td>1 min</td>
<td>1 min</td>
<td>59</td>
<td>48</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>3 min</td>
<td>1 min</td>
<td>36</td>
<td>48</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>20 s</td>
<td>1 min</td>
<td>58</td>
<td>48</td>
<td>60</td>
</tr>
</tbody>
</table>
session (from 48 to 90) and decrease the number of intervals that comprised each VI schedule (from 12 to 9) so that typical sessions ended when the complete set of intervals from both VI schedules had been experienced one or more times.

The VI schedule assigned to one option was held constant throughout conditions (the “fixed” option), while the schedule assigned to the other option changed for each condition (the “variable” option). Two birds experienced the right key as the variable option (Birds 182 and 805), and the other two birds experienced the left key as the variable option (Birds 19 and 293). In an effort to minimize bias, all birds experienced equal rates of reinforcement on the two keys as the first condition. Table 1 summarizes the conditions experienced for each bird. Conditions are presented in the order in which they were experienced. The number of reinforcers and the time limit that prompted the session’s end are also presented.

The parameters experienced by Bird 805 were different than those experienced by the other birds. This bird had very low response rates, and responding was not maintained at reinforcement rates lower than those used. While the parameters were different for this bird, the ratio of reinforcements obtained from the two keys across conditions remained the same as for the other birds. Because of this bird’s low response rates and the lean overall rate of reinforcement in the fourth condition, Bird 805 only experienced the first three conditions.

The data were collected each day, and the VI schedules were not changed until responding in a given condition had stabilized or until the bird had experienced 75 sessions in a given condition, whichever occurred first. Stability was determined using overall response rates (left and right responses summed and divided by session time) and the proportion of pecks on the left and right options. A bird’s performance was considered stable when the difference between
the average overall response rates from the past 3 sessions and the average overall response rates from the 3 previous sessions did not differ by more than ten percent from average of all 6 previous sessions. The proportion of responding on the key that had the majority of responding allocated to it was also required to meet this criterion. Finally, plots of the average number of responses per visit made to the left and right options were inspected visually for stability. Once all of these conditions were met, a bird advanced to the next condition.

Data Analysis

Each session, data were collected in several ways. The number of responses made on each option and the number of reinforcers earned for responding on each option were recorded. The total session time (excluding reinforcement time) also was recorded. Within-visit IRTs were grouped into 0.1s bins for the left and the right options. A within-visit IRT was defined as the time from a response on one option to another response on that option provided no responses occurred on the other option during that time. Changeover IRTs (CO-IRTs) were also grouped into 0.1-s bins for the left and the right options. A CO-IRT to one option was defined as the time between the initiation of a visit to the other option (i.e., a disengagement) and the first response to the first option (i.e., an IRT ending in a changeover). Finally, every event in the session (i.e., left keypeck, right keypeck, reinforcer presentation for responding on the left, reinforcer presentation for responding on the right) was time stamped so that any analysis not predetermined could be performed later.

The average log ratio of responses (left/right) from the last six sessions of each condition was plotted as a function of the average log ratio of obtained reinforcements (left/right) from the last six sessions of each condition. A linear-regression function was fit to the data, and sensitivity and bias were calculated using the generalized matching law (Baum, 1974) presented in Equation
4. For each session, the proportion of responses on each option that were visit initiations was calculated by summing the number of initiations and dividing it by the sum of the number of initiations and the number of within-visit responses for that option. The average visit length on each option was calculated by taking the inverse of the proportion of responses that were visit initiations for that option. Relative visit length distributions and the proportion of each type of IRT that was reinforced were calculated from the time-stamped data.

An important analysis for this experiment was the log-survivor analysis of IRTs. This analysis examines the probability of a response as a function of the IRT by graphing the logarithmic proportion of IRTs longer than t (s). Log-survivor functions were calculated from the binned within-visit and initiation IRTs. An “all-IRT” function for one option included typical within-visit IRTs as well as initiation IRTs from that option. From 0 to 1 s bins were .2 s, but thereafter bins were 1s long. Because of the concurrent arrangement, it was possible to create log-survivor functions from only those responses that were visit initiations. Relative frequency distributions of IRTs divided into within-visit and changeover IRTs also were created in the same way from the binned within-visit and visit-initiation IRTs.

There was reason to suspect that some pecks to the keys used here may have occasionally produced key bounces which were recorded as additional responses; the degree to which these key bounces occurred appeared to vary substantially from box to box and even from key to key. Therefore, all responses that ended IRTs of \( \leq 0.03 \) s were filtered out of the data. This criterion was used for several reasons. Extensive testing of the boxes produced key bounces with IRTs of 0.03 s or less. Also, a literature search showed that there has been a precedent for using a .03-s filter as a safeguard against key bounces in the past (e.g., Blough, 1963; Palya, 1992).
RESULTS

Figure 4 shows the log ratio of responses on the left/right options as a function of the log ratio of reinforcements obtained for responses on the left/right options for each bird. Data are averages of the last six sessions in each condition. Also included are best fit functions for each bird’s data and estimates of sensitivity to changes in reinforcement ($a$) and of key bias ($k$) derived from Equation 4 (Baum, 1974), along with the percentage of variance accounted for. The ratio of responses on the left/right showed orderly increases as the ratio of reinforcements for responses on the left/right increased. Bird 182 had a sensitivity value that was slightly greater than 1, indicating overmatching (i.e., a larger change in the ratio of responding than would be expected based on changes in the ratio of reinforcements). Birds 19, 293, and 805 had values of sensitivity less than 1, indicating undermatching (i.e., a smaller change in the ratio of responding than would be expected based on the change in ratio of reinforcements). All four birds showed some bias. The $k$ value for Bird 182 was less than 0 indicating a bias for the right option, and the $k$ values for Birds 19, 293, and 805 were greater than 0 indicating a bias for the left option. The fits account for a substantial proportion of the variance in the data. With the exception of Bird 293 (0.88), $r^2$ values were above .95.

Figure 5 shows log-survivor functions from the last session of Condition 1 (equal VI schedules) for each bird and each option. Data are presented in rows by bird. The left column of graphs shows data from the fixed option, or the option for which the rate of reinforcement did not change across conditions. The right column of graphs shows data from the variable option. Although rates of reinforcement on the two options were equal in Condition 1, graphs in the right column show data from the option for which the rate of reinforcement varied across Conditions 2, 3, and 4. The solid function in each graph includes all of the IRTs for that option (“all-IRT”
Figure 4. Log response ratios as a function of log reinforcement ratios for each bird. Data are averages of the last six sessions of each condition. The data for each bird are shown with the best fit function found using linear regression, and values of sensitivity ($a$) and bias ($k$) were derived using Equation 4. Values of $a$, $k$, and $r^2$ are presented for each bird.
Figure 5. Log-survivor functions from the last session of Condition 1. Graphs in the left column are from the option for which the rate of reinforcement remained constant across conditions. Graphs in the right column are from the option for which the rate of reinforcement varied across Conditions 2, 3, and 4. The solid functions include within-visit IRTs as well as those IRTs during which time the animal was engaged on the other option (IRTs ending in a changeover). The dashed functions include only those IRTs ending in a changeover. The range of x-axis values is different across birds to allow comparisons of the two different functions for each bird.
functions). Thus, these functions include both within-visit IRTs and IRTs that ended in a changeover response and initiated a visit on that option (during which time the animal was engaged on the other option). The dashed functions include only the initiation or changeover IRTs ("CO-IRT" functions). In general, the all-IRT functions do not have a broken-stick appearance. That is, they do not have a short, steep initial limb followed by a sharp break and a longer, shallower limb. For a couple of the birds, there is some hint of an initial limb (Bird 182: fixed; Bird 19: fixed; Bird 293: variable), but not enough to characterize the function as having a broken-stick appearance. The all-IRT functions are reasonably linear, indicating a fairly constant probability of responding. Within each graph, the all-IRT and CO-IRT functions have similar slopes, and the all-IRT function is to the left of the CO-IRT function, although they are generally very close to, and sometimes lie almost on top of, one another. These features indicate that almost all responses were changeovers. For the most part, the slopes of the all-IRT functions are similar across the two options for each bird, indicating that the probability of making a response was the same on each option. A notable exception to this occurred with Bird 182. The all-IRT function for Bird 182 on the fixed option is steeper than the one from the variable option. This comparison is complicated, however, because the all-IRT function on the fixed option for Bird 182 is not linear. The all-IRT function from the variable option for Bird 805 also appears steeper at short IRTs than the all-IRT function from the fixed option. Again though, it may not be a valid comparison because for this bird, the all-IRT function from the variable option is not linear.

There are some differences across birds and between keys with regard to the all-IRT functions shown in Figure 5, especially at very short IRTs. In some instances (Bird 182: variable; Bird 19: variable; Bird 805: fixed and variable), the all-IRT functions are flat with a y-value of 1 at very short IRTs, indicating that there were no IRTs (within-visit or changeover) at these short
values. In other instances (Bird 182: fixed; Bird 19: fixed; Bird 293: variable), the all-IRT functions have a relatively steep slope at these short IRTs, which is then followed by a flattening in the function. In these cases, the CO-IRT function does not have this same change in slope at short IRTs, indicating that these shorter IRTs producing the change in slope shown in the all-IRT functions were produced by within-visit responses. The flattening of the all-IRT function after the initial, steep limb indicates that there were no within-visit IRTs in those bins, but that there were no changeover IRTs either. When an initial, steep slope in the function occurs at short IRTs, it appears on the side for which the bird had a bias. As shown in Figure 4, Birds 182 and 293 had a bias for the right option, and it was on the right option that some behavior developed which caused the difference in slope at short IRTs (Bird 182: fixed; Bird 293: variable). The same was true for Bird 19 on the left option (Bird 19: fixed). As mentioned above, there are a couple of instances in which the all-IRT functions are not linear (Bird182: fixed; Bird 805: variable). In these instances, the CO-IRT functions mirror the changes in slope of the all-IRT functions indicating that there was not a constant probability of initiating a visit on that option.

The similarities between the all-IRT and CO-IRT functions shown in Figure 5 indicate that there were very few within-visit IRTs; indeed, most visits consisted of only one response. The relative visit-length distributions for Condition 1 that correspond to the data in Figure 5 are presented in Figure 6 for each option. Solid and gray bars show the proportion of visits of each length on the fixed and variable options, respectively. Visits longer than 15 responses are grouped into the last bin. Visit lengths were short; few visits were longer than five responses. In many cases (Bird 182: variable; Bird 19: fixed and variable; Bird 293: fixed; Bird 805: fixed), the largest proportion of visits consisted of only one response. Interestingly, cases in which a substantial proportion of visits were two or more responses appeared to be correlated with the
Figure 6. Relative frequency distributions for visit length from the last session of Condition 1. Shown are the proportions of visits on each option that are each length. All visits of 15 responses or longer are included in the last bin. Black bars represent the visit length distribution for the fixed option, and gray bars represent the visit length distribution for the variable option.
emergence of an initial, sharp drop in the all-IRT functions presented in Figure 5. For example, the functions for Birds 182 (fixed), 19 (fixed), and 293 (variable) show an initial, steep limb on the option that had a higher proportion of visits longer than 1 response. The exception to this generalization for Condition 1 is that for Bird 805, the highest proportion of responses per visit to the variable option was 2. However, the all-IRT function on the variable option for Bird 805 is flat at very short IRTs.

Figure 7 shows relative frequency distributions of IRTs from the last session of Condition 1 for within-visit and changeover responses. Each graph shows the proportion of all IRTs that fall into each 0.2-s bin further divided as either within visit or changeover IRTs. It is important to note here that each bar represents the proportion of all IRTs that is of a given type (within-visit or changeovers) and length, and not the proportion of a given type that is each length. All IRTs 5 s or longer are grouped into the last bin. If a broken-stick appearance in the log-survivor function were present, then the distribution of IRTs for within-visit responses would be to the left of the distribution of IRTs for changeover responses. If the two distributions overlap slightly, the break in the function will be more curved. The more the two distributions overlap, the less distinct the two limbs will be until the two distributions overlap completely at which point there would only be one limb in the log-survivor functions. In a single-alternative situation, it would be impossible to detect the presence of two distributions if they were completely overlapping. However, the present experiment allows for the categorization of within-visit and changeover IRTs. Interestingly, in some cases (Bird 182: fixed; Bird 19: variable), the within-visit and changeover IRT distributions appear to be a part of a single, unimodal, distribution. In these cases and others (Bird 805: fixed and variable), the two distributions overlap substantially, making a broken-stick appearance in the log-survivor function unlikely. In other
Figure 7. Relative IRT distributions for each option from the last session of Condition 1. Shown are the proportion of all IRTs in each 0.2-s bin, further divided into within-visit and changeover IRTs. All IRTs 5 s or longer are grouped in the last bin. Black bars represent within-visit IRTs and gray bars represent changeover IRTs. For example, the first set of bars represent the proportion of all IRTs that are within-visit and fall between 0.03 s and 0.2 s (black bars) and the proportion of all IRTs that are changeovers and fall between 0.03 and 0.2 s (gray bars). Data are from the last session of Condition 1.
instances (Bird 19: fixed; Bird 293: fixed), the within-visit distribution appears to be separate from, and to the left of, the changeover distribution. These graphs may provide some information regarding the source of the development (or lack of development) of an initial limb representing within-visit IRTs in the all-IRT functions presented in Figure 5. For example, for Bird 805 on the variable option, visits were typically longer than 1 response, which would increase the likelihood of an initial limb developing in the all-IRT function. However, the within-visit and changeover IRT distributions overlap substantially, making the development of an initial limb less likely.

Figure 7 also illustrates the source of the flattening in the all-IRT function following the initial limb for Bird 182 on the fixed option (Figure 5). There were many within-visit IRTs less than 0.2 s, creating the first, initial limb, but there were almost no IRTs between 0.2 s and 1 s. This produces the flattening in the all-IRT function. This is likely the result of the difference between the typical time for a within-visit IRT and the minimum required time for a changeover response. For a bird to complete a changeover IRT, enough time must elapse for the bird to peck the other option and come back to peck the first option. Thus, although within-visit IRTs longer than 0.2 s rarely occurred, changeover IRTs shorter than 1 s never occurred.

For Bird 293, the within-visit IRT distribution appears to the left of the changeover IRT distribution for both keys. While this is necessary for the broken-stick appearance to occur, it must not be sufficient because the all-IRT functions for this bird are reasonably linear. There is a small initial limb on the variable option, but not the fixed option. Although about half of the visits to the fixed option consisted of only a changeover response, there were some within-visit responses present (Figure 6), and their IRTs generally were shorter than the changeover IRTs (Figure 7). The all-IRT function for Bird 293 on the fixed option is linear, and the CO-IRT function is flat at short IRTs and linear after about 0.5 s. This indicates that on the fixed option
for this bird, although many within-visit IRTs were shorter than any changeover IRTs, there was a relatively constant probability of making a response regardless of what type of response it was. For Bird 293 on the variable key, about 70% of visits were at least two responses. Many of these within-visit IRTs were shorter than the changeover IRTs, and a small, initial limb emerged.

Figure 8 shows the all-IRT and CO-IRT log-survivor functions from the last session of Condition 2. Graphs in the left column are from the fixed option (here the rich option) and those on the right are from the variable option (here the lean option). When comparing the functions across the two options, the all-IRT functions from the fixed options have a steeper slope than the all-IRT functions from the variable option (i.e., the probability of responding was higher on the richer option). Additionally, the CO-IRT functions are steeper for the rich option than for the lean option, indicating that there was a higher likelihood of initiating a visit to the rich option. For all birds, except Bird 293, the all-IRT and CO-IRT functions for both options are very similar, especially at longer (>1-s) IRTs. The all-IRT functions are linear at longer (>1-s) IRTs for all of the birds except for Bird 805. Note that, for Bird 805, overall response rates in this condition had become quite low (sometimes < 8 resp/min), and there were probably periods of disengagement from both options during which the bird was engaged in unmeasured behavior. For three of the birds (Birds 182, 19, and 293), there is a difference between the all-IRT functions for the fixed and variable options at short (<1-s) IRTs. For Birds 182 and 19, a small, initial limb followed by a flattening of the function is present on the fixed option. This initial limb is absent in the CO-IRT function, indicating that the small, initial limb represents within-visit responses. For these birds, the all-IRT function for the lean option is flat at short IRTs and linear starting around 0.5 s. The all-IRT and CO-IRT functions lie on top of each other in these cases, indicating that almost all of the responses were changeovers, very few responses occurred.
Figure 8. Log-survivor functions from the last session of Condition 2. All characteristics of these graphs are as described in Figure 5.
at IRTs shorter than 0.5 s, and there was a constant probability of changing over to the lean option. Bird 293’s all-IRT function on the variable option has a classic broken-stick appearance. There is a steep initial limb followed by a break, and a shallower second limb, indicating that the probability of making a response at short IRTs was constant and high and the probability of making a response at long IRTs was also constant, but lower. The CO-IRT function has the same slope as the all-IRT function at IRTs that are longer than the x value of the break in the all-IRT function. The CO-IRT function is flat until then indicating that the steep initial limb in the all-IRT function represents only within-visit IRTs. However, the log-survivor functions for the fixed option look different than those for the variable option for Bird 293, especially at short IRTs. At longer IRTs, the slope of the all-IRT function is similar to that of the CO-IRT function, although the all-IRT function is decreasing at short IRTs, and the CO-IRT function is flat with a y-value of 1 at short IRTs. This indicates that there were within-visit IRTs shorter than any changeover IRTs. However, in contrast to the all-IRT function from the variable option, the slope of the all-IRT function for the fixed option has the same slope at short IRTs as it does at long IRTs indicating that, on the fixed option, although within-visit IRTs were generally shorter than changeover IRTs, the probability of making a response was the same regardless of the IRT. Unlike those for the other birds, the all-IRT and CO-IRT functions for Bird 805 are curved. Nevertheless, the all-IRT and the CO-IRT functions are very similar. Together these two features (curved functions that lie on top of one another) indicate that most visits consisted of only a changeover response and there was not a constant probability of changing over. Also, the initial slopes for both the all-IRT and the CO-only functions (IRTs < 5 s) are steeper for the fixed (richer) option than the variable (leaner) option, indicating that there was a higher probability of making these short IRTs on the richer option.
Figures 9 and 10 show the relative visit-length distributions and the relative IRT distributions from the last session of Condition 2 that correspond to the log-survivor functions in Figure 8. Figure 9 shows that, for all of the birds, visits to the fixed (rich) option were longer than visits to the variable (lean) option. However, for Birds 19 and 805, the largest proportion of visits to the rich option still consisted of only one response. For all of the birds except Bird 293, the largest proportion of visits to the variable (lean) option consisted of only one response. Because most (> 75%) of the visits to the lean option were only one response, the all-IRT log-survivor functions for these birds (Bird 182; Bird 19; Bird 805) essentially lie on top of, or very near to, the CO-IRT functions (Figure 8). For Bird 293, the largest proportion of visits to the variable option consisted of two responses (Figure 9), and there were substantial proportions of 3-, 4-, and 5-response visits. Thus, for this bird, a broken-stick appearance developed in the all-IRT function (Figure 8). The visit length distributions for the fixed option look very similar for Birds 182 and 293. However, the all-IRT function on the fixed option for Bird 182 has a distinct initial limb, while that for Bird 293 does not (Figure 8). These patterns are analyzed in Figure 10. The within-visit and changeover distributions overlap for all of the birds on the fixed option. However, over 40% of Bird 182’s responses to the fixed option were within-visit and fell into the first bin (< .2 s), which created the steep initial limb shown in the all-IRT function in Figure 8. For Birds 182, 293, and 805, the relative within-visit and changeover IRT distributions for the fixed option appear to be part of one, coherent distribution. For Bird 19, the modes of the within-visit and changeover IRT distributions are separate, but the two distributions still overlap substantially. On the variable option, the distribution of within-visit IRTs is to the left of that for CO IRTs for Birds 182, 19, and 293, but it appears there were too few within-visit IRTs for Birds 182 and 19 for a broken-stick appearance to develop. Figures 9 and 10 illustrate the
Figure 9. Relative frequency distributions for visit length from the last session of Condition 2. Characteristics of these graphs are as described in Figure 6.
Figure 10. Relative IRT distributions for each option from the last session of Condition 2. All characteristics of these graphs are as described in Figure 7.
properties of responding underlying the broken-stick appearance that developed for Bird 293 on the variable option. Close to 90% of visits contained at least two responses (Figure 9), and most within-visit responses were short (< .4 s), with the distribution of within-visit IRTs falling substantially to the left of the distribution of changeover IRTs. Changeover IRTs were all longer than 1s, but were widely distributed thereafter. Under these conditions, a clear broken-stick appearance emerged for Bird 293 on the variable option (Figure 8).

Figure 11 shows the log-survivor functions for Condition 3, in which the fixed option (left column) was the leaner schedule and the variable option (right column) was the richer schedule. The functions for the variable option are steeper than those for the fixed option, indicating that there was a higher probability of responding on the rich option. In general, the functions are relatively linear, indicating a constant probability of responding (the notable exceptions to this are Bird 805’s functions for the variable option). For Birds 19 and 805, the all-IRT functions from the fixed option are nearly identical to the CO-IRT functions, indicating that almost all of the responses on the fixed option were changeovers. For Birds 182 (fixed) and 293 (fixed), there is a very small initial limb in the all-IRT function indicating that when there were within-visit responses, the IRTs were very short. For Birds 182, 19, and 293, the all-IRT functions for the variable option are slightly steeper at short IRTs than the CO-IRT functions. The CO-IRT functions are flat at these short IRTs (< 1 s), indicating that there were some within-visit IRTs that were shorter than any changeover IRTs.

Figures 12 and 13 show the relative visit-length distributions and the relative IRT distributions for Condition 3 that correspond to Figure 11. Figure 12 shows that all birds typically made more than one response when visiting the variable (rich) option (gray bars). For Birds 182, 19, and 805, at least 60% of visits to the fixed (lean) option (black bars) consisted of
Figure 11. Log-survivor functions from the last session of Condition 3. Characteristics are as described in Figure 5.
Figure 12. Relative frequency distributions for visit length from the last session of Condition 3. Characteristics of these graphs are as described in Figure 6.
Figure 13. Relative IRT distributions for each option from the last session of Condition 3. Characteristics of these graphs are as described in Figure 7.
only one response. For Bird 19, over 90% of visits to the fixed option consisted of only one response, meaning almost all responses on this option were changeovers and, thus, a broken-stick was unlikely to have developed. Bird 293 had longer visits to the fixed (lean) option than the other birds (the mode was 2). The all-IRT functions for Birds 182 and 293 on the fixed option show a steep (albeit short) initial limb (solid functions of Figure 11). Figure 12 shows that, for these birds, although many visits to the fixed option consisted of only one response, there was still a considerable number of two and three-response visits. These may have produced the steep initial limb shown in Figure 11. Figure 13 shows that, indeed, a large proportion of the within-visit IRTs on the fixed option for Birds 182 and 293 were between 0 and 0.2 s which was shorter and separated from almost all of the other responses. These responses produce the small, initial limb present in the all-IRT functions for these birds. Interestingly, Bird 293 had a larger proportion of visits to the rich option that were longer than one response than Bird 182 did. However, the initial limb on the fixed option for Bird 182 is longer than the one for Bird 293. This indicates that some of the within-visit IRTs produced by Bird 293 on the fixed option were substantially longer than others and included in the second limb. Indeed, Figure 13 confirms this; many within-visit IRTs fall into the first 0.2-s bin, but there are no IRTs of any kind between 0.2 s and 0.4 s.

Figure 13 shows that, for Birds 182, 19, and 805, while there were plenty of within-visit responses on the variable (rich) option, the within-visit IRT distribution overlaps completely with the changeover distribution, and, thus, there is an absence of a broken-stick in the all-IRT log-survivor functions (Figure 11). At IRTs shorter than 0.5 s for Birds 182, 19, and 293, there was a substantial proportion of within-visit IRTs shorter than all changeover IRTs, causing the all-IRT functions (Figure 11) to be steeper at short IRTs than the CO-IRT functions. For Bird
293, the within-visit and changeover IRT distributions overlap only slightly, and there were many within-visit IRTs longer than 0.5 s but shorter than any changeover IRTs. However, the all-IRT function is still linear after 0.5 s, indicating that after 0.5 s the probability of making a response was constant, even though those responses that occurred at short IRTs were more likely to be within-visit responses and those IRTs that occurred at long IRTs were more likely to be changeover IRTs. Bird 805 had too much overlap of the within-visit and changeover distributions on both options to see a broken-stick in the all-IRT functions.

Figure 14 shows the log-survivor functions from the last session of Condition 4. Condition 4 arranged the most extreme difference in rate of reinforcement between the two options and, thus, might be expected to encourage substantial visit lengths to the rich, fixed option. (Recall that Bird 805’s overall response rates were very low and, thus, this bird was not exposed to Condition 4.) For all birds, the all-IRT functions from the variable option have very shallow slopes, indicating that there was a very low probability of responding on the variable, lean option. For Bird 19, the all-IRT and CO-IRT functions lie right on top of each other, indicating that most of the IRTs are changeovers. However, for Birds 182 and 293 on the variable option, there is a steeper slope at short IRTs than the slope at longer IRTs in the all-IRT function. The all-IRT function could be considered to have a broken-stick appearance (although the initial limb is not as long or steep as the one for Bird 293 in Condition 2 on the variable option). Also, in both of these cases, the CO-IRT function lies flat with y-values of 1 until the point on the x-axis where the all-IRT function breaks. After the break in the all-IRT functions, the CO-IRT functions have the same slope as the second limb of the all-IRT function. These results indicate that within-visit IRTs occurred at short IRTs with a relatively higher and constant probability and that changeover IRTs occurred at longer IRTs with a relatively lower, but still
Figure 14. Log-survivor functions from the last session in Condition 4. Characteristics of these graphs are as described in Figure 5.
constant, probability. For both Birds 19 and 293 on the fixed option, the all-IRT and CO-IRT functions are very similar to each other, indicating that there was a similar probability of making a changeover response as there was of making a response in general to the fixed option. If visits to the lean option for these birds were very short, changeover IRTs on the fixed option would also be very short. It is likely that the distributions of within-visit and changeover IRTs overlap substantially, but that within-visit and changeover responses were emitted with the same probability. In contrast to Birds 19 and 293, for Bird 182, the CO-IRT function on the fixed option had a very different slope than the all-IRT function. Because what differs between the all-IRT and CO-IRT functions is the addition of within-visit IRTs to the all-IRT function, within-visit IRTs must be the source of the steeper slope in the all-IRT function. The difference in slope may indicate that the within-visit and changeover IRT distributions overlapped substantially, but that within-visit and changeover IRTs were emitted with different probabilities.

Figures 15 and 16 show the relative visit length distributions and relative IRT distributions from the last session of Condition 4 that correspond to Figure 14. Figure 15 shows that for Birds 182 and 19, over 75% of the visits to the variable (lean) option consisted of only the changeover response. For Bird 182, over half of the visits to the fixed (rich) option were 15 responses or longer. This indicates that changeover IRTs to the lean option for this bird must be very long, and it is likely that the distribution of changeover IRTs is far to the right of the within-visit IRT distribution. This may have contributed to the development of a broken-stick appearance in the all-IRT function on the variable option for Bird 182. For Bird 293, visits to the fixed (rich) option were typically longer than visits to the variable (lean) option, with visits to the fixed option never being just one response. Interestingly for this bird, visits to the variable option typically consisted of more than one response. Because visits to the rich option were also usually
**Figure 15.** Relative frequency distributions for visit length from the last session of Condition 4. Characteristics of these graphs are as described in Figure 6.
Figure 16. Relative IRT distributions for each option from the last session of Condition 4. Characteristics of these graphs are as described in Figure 7.
long, it is likely that changeover IRTs for the variable option were long, and this may have contributed to the development of a broken-stick in the all-IRT function for the variable option.

Figure 16 shows that for Birds 182 and 19, the changeover-IRT distribution on the fixed option is completely imbedded in the within-visit IRT distribution making the development of a broken-stick in the all-IRT function for the fixed option unlikely. For Bird 293, visits to the lean option did consistently consist of more than one response (Figure 15), and Figure 16 shows that as a result, changeover IRTs were generally longer than within-visit IRTs. However, the distributions still overlap substantially, and it appears the probability of making a response on the fixed option was relatively constant after 0.5 s regardless of what type (within-visit or changeover) of response it was. Figure 16 shows that the within-visit and changeover IRT distributions for the variable option were separate with within-visit IRTs almost always being shorter than changeover IRTs for all birds. For Birds 182 and 293, a substantial proportion of responses on the lean option were still within-visit responses causing a broken-stick appearance to develop in the all-IRT function. However, for Bird 19, too few responses to the variable option were within-visit and the all-IRT function was linear (Figure 14).

Figure 17 shows inclusive log-survivor functions (all-IRT functions in above figures) for each condition on the same graph for each option. The functions presented are the same as those presented separately above by condition, but this presentation allows for direct comparisons across conditions. For the fixed option, each function represents IRTs from a different condition for which the programmed rate of reinforcement was always the same (VI 3 min for 182, 19 and 293; VI 1 for 805). For the variable option, within each graph, different functions represent conditions from which the rate of reinforcement was manipulated. Within each bird, the same type of line is used to represent the same condition across the two keys (i.e., the dotted function
Figure 17. Inclusive log-survivor functions for each condition. Data are from the last session of each condition. Graphs in the left column are from the fixed option for which the rate of reinforcement did not vary across conditions. Graphs in the right column are from the variable option for which the rate of reinforcement is different for each condition. Functions are matched by condition across the two options. The condition is presented in the legend within the variable graph.
in the fixed option graph is from the same condition as the dotted function in the variable option graph for that bird). Across birds, the same lines are used to represent the same ratios of reinforcement. Dotted lines, solid lines, dashed lines, and dashed/dotted lines represent the conditions for which the programmed ratio of reinforcements (fixed: variable) were 3:1, 1:1, 1:3, and 9:1, respectively. The rates of reinforcement corresponding to dotted, solid, dashed, and dashed/dotted lines were VI 3 min, VI 9 min; VI 3 min, VI 3 min; VI 3 min, VI 1 min; and VI 3 min, VI 27 min, respectively for Birds 182, 19, and 293 and VI 1 min, VI 3 min; VI 1 min, VI 1 min; VI 1 min, VI 20 s, respectively for Bird 805. Across conditions, the functions show orderly changes with the changes in reinforcement rate. Interestingly, orderly changes are observed in the log-survivor functions on both the variable option, for which the rate of reinforcement was manipulated directly, and the fixed option, for which the rate of reinforcement was manipulated only relatively. As the rate of reinforcement for the variable option was increased, the slope of the function for that option becomes steeper, indicating that there was a higher probability of making a response. As the rate of reinforcement on the variable option increased, the slope of the function on the fixed option becomes shallower, as might be expected considering that the rate of reinforcement on fixed option was relatively lean. Note that changes in the functions for the variable option appear to be more orderly across conditions than those for the fixed option, as might be expected because the rate of reinforcement was changed only relatively for the fixed option. For example, for Bird 293, the function from the fixed option in the VI 3-min, VI 1-min condition is steeper than the functions from the VI 3-min, VI 3-min and the VI 3-min, VI 9 min conditions, even though the VI 3-min, VI 1-min condition should have been the relatively leanest condition. Also, for Bird 805 on the fixed option, the log-survivor functions do not appear in the order that might be expected given the relative rates of reinforcement. For IRTs between 1 s and
9 s, the probability of making a response to the fixed option was higher in the VI 1-min, VI 20-s condition than in the VI 1-min, VI 1-min condition even though the relative rate of reinforcement for responding on the fixed option was lower in the VI 1-min, VI 20-s condition. Also, the dashed function representing the VI 1-min, VI 3-min condition crosses the other two functions at later IRTs indicating a lower probability of responding compared to the other conditions at long IRTs, even though the VI 1-min, VI 3-min condition was the one in which reinforcement rate for the fixed option was relatively the richest. In general, the slopes of the functions on the fixed option within a single graph do not change as much across conditions as the slopes of the functions on the variable side within a single graph indicating that behavior allocated to the variable option was more sensitive to these changes in rate of reinforcement.

Figure 17 illustrates that at short IRTs, for the most part, there is very little change in the functions across conditions as the rate of reinforcement was manipulated for responding on the variable option. Any small, initial limbs present show very little change in length or slope as rate of reinforcement is changed. For Bird 182 on the fixed option, changes in the length of the initial limb are present, but they are slight. The initial limb present in the dotted function from the VI 3-min, VI 1-min condition does appear shorter than the initial limbs present in all of the other functions in that graph, indicating that if a bout pattern of behavior was present, the bouts were shortest in that condition. This might be expected because the rate of reinforcement was relatively the lowest in that condition. However, if there are any other differences in the initial limbs between the other conditions for Bird 182 on the fixed option, they are too small to discern. For Bird 19 on the fixed option, changes in the slope of the initial limb are present, but again, these changes are very small. Both the dashed/dotted, and the dashed-only functions representing the VI 3-min, VI 27-min and the VI 3-min, VI 9-min conditions, respectively, have
initial limbs with steeper slopes than the solid and dotted lines representing the VI 3-min, VI 3-min and the VI 3-min, VI 1-min conditions; this indicates that the probability of emitting a within-visit response at these short IRTs was higher in VI 3-min, VI 27-min and the VI 3-min, VI 9-min conditions than in the other two. This might be expected because these two conditions provide higher relative rates of reinforcement for responding on the fixed option than do the other two conditions. One instance in which there were large changes at short IRTs across conditions was for Bird 293 on the variable option. The VI 3-min, VI 9-min condition yielded a much longer initial limb than did the other conditions. This exception is interesting, because it might be expected that as the rate of reinforcement on the variable option is decreased, any initial limb present would become shorter or shallower, but this change is in the opposite direction.

Figure 18 shows the CO-IRT log-survivor functions across conditions. These functions are the same as those presented in the condition by condition graphs above. They are organized in the same way as the all-IRT log-survivor functions were in Figure 17. With the exception of the functions from Bird 805, the functions are reasonably linear indicating that there was a constant probability of emitting a changeover response. The functions from both the fixed and the variable options show orderly changes with changes in the rate of reinforcement to the variable option. As in Figure 17, the functions from the variable option show more sensitivity to these changes than the functions from the fixed option (i.e., the changes in slope from condition to condition are greater for the variable option). On the fixed option, the slopes of the functions are generally similar, as would be expected given that changes in the rate of reinforcement occurred only relatively. Also, for Bird 19 on the fixed option, the function from the VI 3-min, VI 27-min condition is steeper at some IRTs than the function from the VI 3-min, VI 9-min condition which would not be expected because the VI 3-min, VI 27-min condition should have
Figure 18. Log-survivor functions including only changeover IRTs for each condition. Data are from the last session of each condition. Graphs in the left column are from the fixed option for which the rate of reinforcement did not vary across conditions. Graphs in the right column are from the variable option for which the rate of reinforcement varied across conditions. Functions are matched by condition across the two options. The condition is presented in the legend within the variable graph.
been relatively more rich than the VI 3-min, VI 9-min condition. Also, for Bird 182 on the fixed option, the function from the VI 3-min, VI 27-min condition is shallower than both the function from the VI 3-min, VI 9-min condition and the function from the VI 3-min, VI 3-min condition. Additionally, the slopes of the log-survivor functions for Bird 805 on the fixed option are not in the order that would be expected given the condition, with the function representing the VI 1-min, VI 3-min condition crossing the other two functions. These deviations from what would be expected given the changes is relative reinforcement rate across conditions illustrate that changeover IRTs on the fixed option were not as sensitive to changes in rate of reinforcement as changeover IRTs on the variable option.

Figure 19 shows the proportion of each IRT type that was reinforced across conditions for each bird. Data are averages of the last six sessions of each condition. Within each condition, the left two bars represent within-visit and changeover IRTs from the fixed option, and the right two bars represent within-visit and changeover IRTs from the variable option. VI values for each condition are presented on the x-axis. Data may be interpreted as the likelihood that a given type of emitted IRT would be reinforced. As would be expected, the proportion of IRTs that was reinforced is low. Bird 805 had the highest overall proportion of responses reinforced, probably because the programmed reinforcement rates were higher for this bird and response rates were lower for this bird than for any of the other birds. In general, Figure 19 shows that in any given condition, the probability of an emitted IRT meeting the criterion for reinforcement was higher for the option that had the higher programmed rate of reinforcement. For all birds in all conditions except Bird 805 on the fixed option in Conditions 1 and 2, changeovers were reinforced with a higher probability than within-visit responses to the same option. This might be expected given the contingencies of a VI schedule. Because the interval is elapsing irrespective
Figure 19. The proportion of each kind of IRT that was reinforced across conditions. Data are averages of the last six sessions of each condition. The left two bars in each condition cluster represent within-visit and changeover IRTs from the fixed option. The right two bars in each condition cluster represent within-visit and changeover IRTs from the variable option. Y-axes are scaled for each bird to allow for comparison across IRT types.
of behavior, the longer an organism pauses between responses, the more likely it is that the next response will be reinforced. Therefore, VI schedules differentially reinforce longer IRTs, and changeover IRTs are likely to be longer than within-visit IRTs. Interestingly, for Bird 805 on the fixed option, within-visit responses had a higher likelihood of reinforcement than changeover responses in Conditions 1 and 2. This bird had very low response rates, and the distribution of within-visit IRTs consistently overlapped substantially with the distribution of changeover IRTs. The log-survivor functions for Bird 805 on the fixed option (Figure 17) also showed the least orderly relation to the changes in reinforcement rate made to the variable option.

DISCUSSION

Across the range of reinforcement rates tested in the present study, a broken-stick appearance was not present in the all-IRT log-survivor functions in most cases. Log-survivor functions generally were linear, indicating a constant probability of responding. This was true for both the fixed option, for which the rate of reinforcement changed only relatively, and the variable option, for which the rate of reinforcement was manipulated directly across conditions. The only instances in which the all-IRT function might be classified as having a broken-stick appearance resembling that found by Shull et al. (2001) were with Bird 293 on the variable (lean) option in the VI 3-min, VI 9-min condition and the VI 3-min, VI 27-min condition, and with Bird 182 on the variable (lean) option in the VI 3-min, VI 27-min condition. There were a few instances in which the log-survivor functions had a small, steep, initial limb (Bird 182, all conditions, fixed; Bird 19, Conditions 1, 2, and 4, fixed; Bird 293, Condition 3, Bird 293, Conditions 1 and 3, variable). These functions, however, still did not have the classic broken-stick appearance. The initial limb was very short, did not contain all of the within-visit IRTs, and was usually followed by a plateau in the function. Relative IRT distributions indicated that there
were many within-visit IRTs that were longer than the break in the function following this initial limb and, therefore, these IRTs were included in the second limb.

When this small, initial limb was present, relative IRT distributions revealed that a substantial proportion of within-visit responses fell into the first (<.2-s) IRT bin, causing the initial drop in the log-survivor function. Often, these IRTs were substantially shorter than all other IRTs, including other within-visit IRTs. It seems unlikely that these IRTs were produced in the same way as other within-visit IRTs. Past research (Gott, 1969; Palya, 1992; Weiss & Gott, 1972) has shown that pigeons sometimes emit responses, called “nibbles,” that have much shorter IRTs, and which perhaps are topographically different, than typical keypecks. It may be that the high frequency of within-visit IRTs shorter than 0.2 s in the present experiment was produced by nibbles. It is also possible, however, that these IRTs were not the behavior of the birds at all. As stated above, there was reason to suspect that a single keypeck sometimes caused more than one response to be recorded (i.e., there may have been key bounces). Although all of the data presented here had IRTs of 0.03 s or less removed, it is still possible that the birds pecked with some topography that produced key bounces longer than 0.03 s, which contributed to the high proportion of IRTs less than 0.2 s, and, in turn, created the short, initial limb in some of the functions.

When rate of reinforcement was equal between the two options, visit lengths were very short (the mode of the visit length distribution was usually 1). When the rate of reinforcement was manipulated on the variable option, visit lengths on the richer option lengthened, while visit lengths on the leaner option generally remained short. Relative IRT distributions revealed that, when the rate of reinforcement was relatively rich, although there was a substantial proportion of within-visit responses, CO IRTs generally were short and their IRT distribution frequently
overlapped substantially with the within-visit IRT distribution. The two distributions must be separate if a broken-stick appearance is to develop. When the rate of reinforcement was lean, the distribution of CO IRTs generally was shifted to the right of the distribution of within-visit IRTs, but visits usually were short and, thus, there were too few within-visit IRTs for a broken-stick to develop. When the rate of reinforcement between the two keys was equal (Condition 1), the distributions sometimes overlapped (e.g., Bird 182, fixed; Bird 805, fixed and variable; Bird 19, variable) and sometimes were separate (e.g., Bird 293, fixed).

Across conditions, many characteristics of behavior showed sensitivity to changes in rate of reinforcement. The slopes of the log-survivor functions showed an orderly relation to direct and relative changes in rate of reinforcement. As the rate of reinforcement was increased, directly or indirectly, the log-survivor functions became steeper, indicating a higher probability of responding on the rich option. As might be expected, the slopes of the log-survivor functions were more sensitive to direct rather than by relative-only changes in reinforcement rate, indicating that the probability of making a response was more influenced by direct changes in rate of reinforcement than changes to rate of reinforcement made only relatively. The visit-length distributions also were sensitive to changes in rate of reinforcement. When the rate of reinforcement between the two keys was equal, visit lengths were short (the mode usually was 1), but when the rate of reinforcement between the two keys was unequal, visits were longer on the richer option. The visit-length distribution on the rich option tended to be more variable than that for the lean option. On the leaner option, birds typically made only one response per visit. The only exception to this generalization was for Bird 293 on the lean option in Conditions 2, 3, and 4, when the mode of the visit distribution was 2. The relative IRT distributions also were sensitive to changes in rate of reinforcement made to the variable option.
Interestingly, the two types of IRT distributions (within-visit and CO) did not appear to be affected by changes in rate of reinforcement equally. It is somewhat difficult to make comparisons about the within-visit distributions because when the rate of reinforcement was relatively lean, visit lengths were almost always one (Bird 182, Condition 2, variable; Bird 19, Conditions 2 and 4, variable; Bird 19, Condition 3, variable). However, when comparing the very few within-visit IRTs that were emitted, the placement of the distribution on the x-axis did not change across conditions (Bird 182, Condition 3, fixed; Bird 182, Conditions 2 and 4, variable; Bird 19, Conditions 2 and 4, variable; Bird 293, Condition 2, variable). That is, the distribution of within-visit IRTs did not show an orderly relation to rate of reinforcement. The proportion of responses that were within-visit increased when the rate of reinforcement was rich, but the length of the IRTs was relatively insensitive to changes in rate of reinforcement. The placement of the CO-IRT distribution, however, did change across conditions. When the rate of reinforcement between the two keys was equal, the mode of the CO-IRT distribution was usually around 1 s. When the rate of reinforcement between the two keys was unequal, the mode of the CO-IRT distribution on the rich option was usually still around 1 s, probably because 1 s was roughly the minimum time required to make a changeover response. However, when the rate of reinforcement was relatively lean, the distribution of CO IRTs shifted to the right on the x-axis. This was most obvious in the fourth condition when the ratio of the rates of reinforcement between the two keys was 9:1. For all birds, a substantial proportion of IRTs on the lean option were changeover IRTs that were 5 s or longer (over 50% for Bird 182, 30% for Bird 19, and 20% for Bird 293).
The Pigeon Problem

This experiment was designed to test the hypothesis that past attempts to obtain a broken-stick appearance in log-survivor analyses for pigeons’ keypecking failed because the rate of reinforcement for engaging in behavior other than the target behavior typically is very low for pigeons relative to the rate of reinforcement for engaging in the target behavior and, therefore, pigeons do not disengage from the target response often (e.g., Shull, 2005). This hypothesis would predict that a broken-stick appearance would be most likely to develop when the rate of reinforcement was relatively lean compared to the rate of reinforcement for engaging in alternative behaviors. The present experiment attempted to imitate a single-alternative situation in which the rate of reinforcement for engaging in behavior other than the target behavior was as high as or higher than the rate of reinforcement for engaging in the target behavior. The results of this experiment do not support that hypothesis. The concurrent arrangement did not reliably produce a broken stick. This suggests that substantial reinforcement for engaging in alternative behavior is not sufficient for a bout pattern to emerge for the target behavior.

One alternative to the above hypothesis is that keypecking, or the behavior of pigeons in general, somehow is inherently different than the behavior of rats. However, this is not the only conclusion regarding the present results. The present arrangement was still very different from the single-alternative situation in which the broken-stick appearance has previously been obtained (Shull et al, 2001; 2002). First, in single-alternative situations, any alternative behavior in which an organism engages during their disengagement from the target response is likely to be topographically different than the target behavior, whereas the alternative behavior in which pigeons engaged in the present study was topographically very similar to the target behavior. The two behaviors were reinforced according to independent schedules of reinforcement, so
functionally they should be different behaviors, but it is possible that it is important for the two behaviors to be topographically distinct. However, previous research with pigeons in single-alternative situations has not yielded a broken-stick in log-survivor analyses, and presumably any alternative behavior in these situations is topographically different than the target response (Bennett et al., 2007; Podlesnik et al., 2006). So, if it is important for the emergence of a broken stick that alternative behaviors are topographically different, it must not be the only necessary condition. Second, in a single-alternative situation, the reinforcement obtained for engaging in alternative behavior is qualitatively different from the reinforcement for engaging in the target behavior. The consequence for engaging in the target behavior is a primary reinforcer delivered by the experimenter (e.g., food presentation), but the reinforcers for engaging in alternative behaviors could be many things (e.g., self stimulation from grooming, olfactory stimulation). In the present experiment, however, the reinforcer for engaging in the target behavior was the same as the reinforcer for engaging in the alternative behavior (3.5-s access to food). Additionally, in the present experiment, both reinforcers were obtained from the same source. In a single-alternative situation, the reinforcers for engaging in competing behaviors presumably are obtained from different sources than the reinforcers for the target behavior. It is possible that one, or more, of these differences is key to obtaining the broken stick in the log-survivor functions.

Another reason that the present experiment may have failed to produce a broken stick in the all-IRT functions is that this experiment did not employ a COD to punish switching between schedules. A COD was not used because it was thought that in a single-alternative situation there is no penalty for switching back and forth between the target behavior and other behaviors, and that reinforcement sometimes is available from either source immediately after a switch. It may
be, however, that the use of a COD actually would have better mimicked a single-alternative situation. Although there are no programmed punishment contingencies associated with switching between behaviors, punishment contingencies could still be arranged naturally. When an organism disengages from the target behavior and engages in some unmeasured behavior, there may be some response cost associated with the time and effort required to switch. This may be particularly true when the target and alternative behaviors are very different topographically. It may be because of this punishment associated with switching between behaviors that organisms typically make more than one response when they engage in the target behavior and that behavior is organized into bouts.

The Broken-Stick Appearance: Necessary and Sufficient Conditions

Because this experiment was unsuccessful at creating a broken stick in the log-survivor functions, it seems important to consider the conditions that are necessary and sufficient for such a pattern to develop. First, if a broken stick is to develop, it is necessary that responding be organized into bouts. A bout pattern of behavior necessarily consists of at least two classes of IRTs, visit initiations and within-visit responses. Therefore, visits must contain at least two responses (i.e., on average, there must be at least one initiation and one within-bout response per visit). In the present experiment, when the rate of reinforcement between the two keys was equal in Condition 1, the mode of the visit length distribution usually was 1. In Conditions 2, 3, and 4, when the rate of reinforcement between the two keys was unequal, over 50% of the visits to the lean option consisted of only one response for all of the birds. A broken stick may not have developed because visits to the lean option were not long enough. The only exception to this was Bird 293’s function for the lean option in Conditions 2, 3, and 4. For this bird, the mode of the visit length distributions was 2, and a broken stick did indeed develop in Conditions 2 and 4.
Throughout conditions, visits to the rich option frequently consisted of more than one response. However, a broken stick did not develop. Thus, although an average visit length of at least two responses may be necessary, it clearly is not sufficient. The distributions of within-visit and CO IRTs also may be important. If a broken stick in which the first limb is representative of within-bout IRTs and the second limb is representative of bout-initiation IRTs is to develop, within-visit IRTs must be shorter than CO IRTs (i.e., within-visit and CO-IRT distributions must be separate). In this experiment, when the rates of reinforcement between the two options were unequal in Conditions 2, 3, and 4, the relative IRT distributions may be helpful in explaining the lack of a broken stick in the functions for the rich option. Generally, the IRT distributions were dominated by within-visit responses (i.e., the birds rarely left the rich option), and the within-visit IRT distribution tended to be variable and overlapped substantially with the CO-IRT distribution. Although some of the within-visit IRTs were shorter than any of the CO IRTs, many of the within-visit IRTs were just as long as, and some were even longer than, the CO IRTs. On the rich option, CO IRTs included time spent responding on the lean option. Because most visits to the lean option consisted of only one response, CO IRTs for the rich option were short, and the distribution for those IRTs was centered at short values on the x-axis and, thus, the all-IRT and CO-IRT distributions overlapped considerably.

Although an average visit length of two responses and separate distributions for within-visit and CO-IRTs are necessary conditions for a broken-stick appearance to develop under the conditions arranged here, they clearly are not sufficient. In addition to these two conditions, the probability of emitting a within-visit response must be higher than the probability of emitting a changeover. The slope of the log-survivor function between any two points indicates the probability of emitting a response at those IRTs. Therefore, if there is to be a steep limb of the
function at short IRTs, and a shallower limb of the function at long IRTs, the probability of emitting a response must be different at the two ranges of IRTs. In this experiment, there were instances in which the first two necessary conditions described above appear to have been met, but no broken stick developed. For example, Bird 293, on the fixed option in Conditions 1 and 3, had a substantial number of visits that were longer than 1 response, and the distribution of within-visit IRTs was to the left and touching the distribution of changeover IRTs; that is, there was very little overlap in the two distributions. The all-IRT function, however, was linear, indicating that the distributions of both types of IRTs fell on a single negative exponential, which suggests that they all were examples of responses emitted with a constant probability. These three conditions (average visit length of at least 2, within-visit IRTs shorter than changeover IRTs, and the two types of responses being emitted at constant, but different, probabilities) are all necessary for a broken stick to develop in the all-IRT log-survivor function, but whether they are sufficient is unclear. It seems that these conditions should be sufficient to engender a broken stick, but it is possible that there are other necessary conditions that the present analyses have not revealed.

In the present experiment, the only instance in which a classic broken stick in the all-IRT function developed was for Bird 293 on the variable (lean) option in Condition 2 (VI 9 min). The all-IRT functions for Bird 182 and Bird 293 on the variable (lean) option in Condition 4 also might be considered to have a broken stick (although it is less classic than the one produced by Bird 293). In all of these cases, the broken stick developed on the lean option, and there were a substantial proportion of visits to that option longer than 1 response. In general, it seems that if an organism visits each of two options for a substantial length of time, a broken-stick appearance is more likely to develop on the leaner of the two because the distribution of changeover IRTs is
likely to be farther to the right on the $x$-axis, and the placement of the distribution of within-visit IRTs generally remains to the left.

Effects of Reinforcement on Operant Behavior

Across conditions, the log-survivor functions (i.e., the probability of responding) were sensitive to changes in rate of reinforcement, both absolute and relative. The functions generally became steeper when the rate of reinforcement became richer (Figure 17). One relevant question is what characteristics of behavior produce the changes in the log-survivor functions, and thus, what characteristics of behavior are sensitive to changes in rate of reinforcement. The probability of initiating a visit, or $p(V)$ from Shull et al.’s (2001) model, clearly is sensitive to changes in rate of reinforcement. Figure 18 shows log-survivor functions for only those responses that were initiations; the slope of the function shows a very orderly relation to changes in rate of reinforcement. Additionally, the placement of the relative distribution of CO IRTs on the $x$-axis shifts across conditions. When the rate of reinforcement was lean, the distribution shifts to the right, indicating that CO IRTs were longer than in other, richer, conditions.

For those instances in which the functions contained a small, steep initial limb at short IRTs (Bird 182, Conditions 2, 3, and 4, fixed; Bird 19, Conditions 1, 2, and 4, fixed; Bird 19, Condition 3, variable; Bird 293, Conditions 1 and 3, variable), the slope of the initial limb was remarkably insensitive to changes in rate of reinforcement, suggesting that these within-visit responses (with shorter IRTs) were not as sensitive to changes in rate of reinforcement as were changeovers (with longer IRTs). Also, the placement of the relative distribution of within-visit IRTs on the $x$-axis was fairly insensitive to changes in rate of reinforcement, compared to the placement of the relative distribution of CO IRTs. These results indicate that, under the conditions arranged here, the probability of emitting a within-visit response when an organism is
engaged in the target behavior, or p(R) from Shull et al.’s (2001) model, was somewhat insensitive to changes in rate of reinforcement. This is consistent with Shull et al.’s findings. Although the probability of emitting a within-visit response was relatively insensitive to reinforcement rate, the relative IRT distributions indicate that the proportion of IRTs that were within-visit (i.e., the visit length) indeed was sensitive to changes in rate of reinforcement, both direct and indirect. This finding is in contrast to Shull et al.’s findings that bout length was not sensitive to changes in rate of reinforcement. The results of the present experiment, however, also show that when the rate of reinforcement for engaging in one behavior is manipulated, the probability of initiating alternative behavior also is affected (although less so than for the target behavior). If the probability of engaging in an alternative behavior is affected by changes in rate of reinforcement for the target behavior (as would be expected; see Herrnstein, 1970), then the probability that each target response will end a bout and produce a period of disengagement, or p(D) in Shull et al.’s model, necessarily would be affected. That is, bout length for the target behavior necessarily is changed as the probability of reinforcement for disengaging from that behavior is changed. Also, if changes in the probability of initiating a visit to an alternative behavior directly affect the length of emitted bouts of the target behavior, and the probability of initiating a visit to an alternative behavior is less affected by changes in rate of reinforcement than is the probability of initiating a visit to the target behavior, then the length of a bout would be less sensitive to changes in rate of reinforcement than would the probability of initiating a visit to the target behavior. This may be the reason Shull et al. (2001) showed that bout length was insensitive to changes in rate of reinforcement. It may be that it is sensitive to these changes, but less so than the probability of initiating a visit.
The Isolation of the Behavioral Unit

Log-survivor analyses of IRTs have been suggested as potentially useful for revealing the unit of behavior that is strengthened as parameters of reinforcement are manipulated (Shull et al., 2001). Shull and colleagues (2001; 2002) have suggested that initiating a bout of responding may be the class of behavior that is selectively strengthened as the parameters of reinforcement are manipulated. In the present experiment, the log-survivor analysis did not clearly reveal the bout as a unit of behavior, at least not in most cases. The relative IRT distributions, however, may be informative when attempting to discern the operant unit. The results of this experiment suggest that in this arrangement, when no broken stick was present, the emitted operant is either a keypeck or a keypeck following a certain class of IRTs. Any engagement in alternative behaviors is brief and takes place during these IRTs. When the log-survivor functions were linear, relative IRT distributions frequently resembled one, coherent IRT distribution consisting of both within-visit and changeover IRTs (Bird 182, Condition 2, fixed; Bird 182, Condition 3, variable; Bird 19, Condition 4, fixed; 19, Bird Condition 3, variable; Bird 293, Condition 2, fixed; Bird 805, Conditions 2 and 3, fixed; Bird 805, Condition 3, variable). Because there appeared to only be one coherent distribution, within-visit and changeover responses appear to be members of the same class of behavior. If the operant is a keypeck following a class of IRTs, the unimodal shape of the distribution illustrates the class of IRTs differentially reinforced by the programmed contingencies. The mode of the distribution may be the IRT reinforced, strengthened, and emitted most frequently. Other IRTs could and did meet the criterion for reinforcement, however. Those IRTs slightly shorter and slightly longer than the mode of the distribution may have been the next mostly likely IRTs to be reinforced, and therefore, they were the next most likely to be emitted. In this way, a unimodal distribution of IRTs may have developed.
representing the class of IRTs that was most likely to meet the criterion for reinforcement. It is important to point out, however, that because the IRT distributions were skewed, in most cases, it would be possible to remove the left half of the distribution, creating a negative exponential distribution, by increasing the size of the bins. This raises the possibility that the operant unit is simply a keypeck, with the probability of emission being constant in time. Evidence for this interpretation is the linear shape of the log-survivor functions, which generally indicate a constant probability of emitting a response.

When the rate of reinforcement is leaner, response strength should be lower, and the probability of emitting a keypeck should be lower. The results of the present experiment suggest that this may be the case. In instances in which the rate of reinforcement was lean and the log-survivor functions did not have a broken stick, the distribution of IRTs shifted to the right on the x-axis. It may be (and the results of the present study suggest this) that the birds allocated more time between each emitted keypeck to alternative behaviors. However, a keypeck or a keypeck following a class of IRTs cannot always be the emitted operant on VI schedules. There were instances in this experiment in which the rate of reinforcement was relatively lean, but log-survivor analyses suggested that the behavior of the birds was organized into bouts (Bird 283, Condition 2, variable; Bird 293, Conditions 2 and 4, variable). The behavior of the rats used in Shull et al.’s (2001; 2002) studies also appeared to be organized into bouts. Perhaps certain conditions punish, and therefore change, the operant. When the operant is a keypeck or a keypeck following a class of IRTs, it is likely that organisms are engaged in other behaviors during each IRT, and are therefore switching between behaviors frequently. When switching between behaviors is made more difficult (e.g., requires more time or effort), the frequent switching between behaviors that appears to be present with this operant would be punished. In
this case, the reinforced operant may become a bout of behavior, with its emission being a function of the parameters of reinforcement, and presumably, its strength. As discussed earlier, this type of punishment contingency may be present frequently in the natural environment and may be responsible for the bout pattern of behavior emitted by the rats in Shull et al.’s (2001; 2002) studies.

In the present study, there was no programmed punishment for switching between options. Switching required little time or effort, and for most of the birds, did not appear to be punished, which may be why a bout pattern of behavior failed to emerge in most cases. However, it may be that in some instances, the time and effort required in switching was sufficient to punish behavior, resulting in a broken-stick appearance. This appears to have been the case for Bird 293, for whom the mode of the visit-length distribution for the lean alternative was always two responses and whose log-survivor functions on the variable alternative had a broken-stick appearance in Conditions 2 and 4. It may also have been the case for Bird 182, whose ratio of responses on the left/right options most closely matches the ratio of reinforcements obtained for responding on the left/right options (Figure 4). Generally, a COD (a switching-punishment contingency) is necessary to prevent undermatching, and it may be that for this bird, a punishment contingency existed naturally, causing a broken-stick to develop on the lean alternative in Condition 4. When this punishment contingency exists, the present study suggests that a bout pattern of behavior only develops on the lean option. However, it may be that bouts of behavior are emitted with such a high probability on the rich option, that within-visit and changeover IRTs are not different enough to discern the bout pattern of behavior. Importantly, this theory is testable. If a punishment contingency creates a bout pattern of behavior, the insertion of a punishment contingency should create a broken stick in the log-
The functions produced by the log-survivor analysis in the present experiment did indeed show an orderly relation with rate of reinforcement. This suggests that they can be useful when considering response strength and when making comparisons about strength across different responses. In any condition of the present study in which the rates of reinforcement for responding on the two options were unequal, comparing the log-survivor functions from the two responses showed that the log-survivor function for the response with the richer rate of
reinforcement had a steeper slope indicating a higher probability of that response being emitted. Presumably, the steeper slope also indicates that the behavior that had the richer rate of reinforcement had more strength than the other behavior. These results indicate that within a single situation, the log-survivor analysis can be used to determine relative strength between two behaviors that are being emitted in alternation. Across conditions, rate of reinforcement was changed for both of the two measured behaviors, either directly or indirectly. When the log-survivor functions from one option (Figure 17) were compared across conditions, the slopes of the log-survivor functions corresponded with the relative or absolute changes in rate of reinforcement, indicating that the probability of a behavior, and presumably the strength of that behavior, was higher in conditions in which the rate of reinforcement was higher. These results show that across time, the log-survivor analysis can be used to determine changes in the strength of a single behavior. Finally, it seems logical that direct changes in rate of reinforcement should change the strength of behavior more than indirect changes in rate of reinforcement. In this experiment, for each bird, log-survivor analyses were conducted for two behaviors; for one of these behaviors (the variable option) the rate of reinforcement changed absolutely and relatively and for the other (the fixed option) it changed only relatively. The changes in slopes of the log-survivor functions were greater when the rate of reinforcement was changed directly than when it was changed only relatively. The results of the present study strongly suggest that the slopes of log-survivor functions are useful for making judgments about the strength of a behavior. Additionally, the log-survivor functions in the present study were usually linear, indicating a constantly probability of responding. Response strength is related to the probability of emitting a behavior, and so a measure of behavior that reflects that probability seems logically related to response strength.
However, the present study differs from Shull et al. (2001) in that it suggests that behavior may be organized into bouts only when some punishment contingency exists for switching between behaviors. The broken stick appearance was present in some instances, indicating this was the case; in these instances, it was the second limb of the log-survivor function that showed the orderly relation to rate of reinforcement. The log-survivor analysis was able to reveal the bout pattern of behavior in these cases, and allowed for the comparison of its probability of emission (i.e., its strength) to instances in which the operant unit was not a bout of behavior. A composite measure, such as rate, may not allow for a measure of the probability of emission of a bout of behavior in many cases. There may have been instances in which the operant unit was a bout of behavior, but the IRTs preceding within-bout and bout-initiation IRTs were not different enough to reveal a broken stick. If this is the case, the two classes of behavior were being emitted at the same probability, and that probability is revealed in the log-survivor analysis. If a bout pattern of behavior was present in some cases in which there was not a broken-stick, while the log-survivor analysis did not reveal a bout as the unit of behavior, it still allows for a measure of its probability of emission (a measure of its strength). In general, the log-survivor analysis’ orderly relation to rate of reinforcement and its ability to estimate a measure of probability of emitting a unit of behavior across different behavioral units makes it an effective measure of response strength to measures that do not always show an orderly relation to rate of reinforcement or do not allow for a measure of probability of emission when the unit is a not simply a response.

Future Directions and Limitations

Future directions should include investigation of the effects of a COD. As discussed earlier, a concurrent arrangement with a COD may be more similar to a single-alternative
situation in which there is a relatively lean rate of reinforcement for the target behavior. In fact, punishment contingencies, such as a COD may be the source of a bout pattern of behavior when it is present. Indeed, Kukubekova and McDowell (2008) have suggested that this type of contingency might be necessary for a reliable production of a bout pattern of behavior and, hence, broken-stick log-survivor functions. In one study, these researchers tested the behavior of a virtual organism using a computational model in which emitted behaviors are integers, each having a corresponding 10-digit binary sequence. The closer that two integers or binary sequences are to each other, the more similar the two behaviors will be. When considering a class of target behaviors as binary sequences that are very similar to each other, and a class of alternative behaviors as binary sequences that are very similar to each other but fairly different from the sequences of the target class, the number of digits in the target behavior that must be changed to create a behavior from the alternative class of behaviors is called the hamming distance. Conceptually, hamming distance is a measure of the difficulty required in switching from one behavior to another, and the authors liken it to a COD. The authors found that when the rate of reinforcement was very lean, log-survivor functions began to have a more broken-stick appearance, and they hypothesize that increasing the hamming distance between the target class of behaviors and alternative behaviors might increase the likelihood of seeing a broken-stick appearance on the target option when the rate of reinforcement was lean. In another study, Popa and McDowell (2010) showed that an increased hamming distance decreased the likelihood of changing between behaviors and increases the proportion of all behavior allocated to each option.

In the present experiment, particularly when rate of reinforcement was rich, the distributions of within-visit IRTs and CO IRTs may have overlapped too much for a broken stick
to develop. With the use of a COD, changeovers must have a minimum IRT. It is possible that the use of a COD would punish switching such that visits would frequently contain more than one response and when IRTs between visits were long (as would likely be the case on the lean alternative) a broken stick might develop. In the present experiment, with the absence of a COD, the birds in the present experiment frequently “fixed” on the rich option and only “sampled” the lean option (i.e., responded just once per visit) (e.g., Baum, Schwendiman, & Bell, 1999). These short (1 response) visits to the lean alternative took place during IRTs on rich option that were not longer than other IRTs on that option, preventing a bout pattern of behavior from developing for that option. The use of a COD would require that at least two responses be made per visit in order to obtain reinforcement.

Note, however, that the data in Figure 19 suggest that changeover responses were more likely to be reinforced because they tended to have longer IRTs. It is possible that this is the reason that when a bout pattern of behavior is present, the initiations of behavior are more likely to show an orderly relation to the parameters of reinforcement; they are the IRTs most likely to encounter the changes in the parameters. The use of a COD would take the probability of immediate reinforcement for a changeover response to 0. While reinforcement for the changeover responses could be delayed, it will always be a within-visit response that is immediately reinforced. As within-visit IRTs become more likely to encounter changes in rate of reinforcement, it is possible that within-visit IRT length also will show an orderly relation to rate of reinforcement. When rate of reinforcement is decreased, a longer class of IRTs also could be selected to precede within-visit responses. Although CO IRT length is likely to increase with the introduction of a COD, within-visit IRTs also may increase under some conditions. It is difficult to determine if the distributions will be any more separated than they were in the rich conditions.
of the present experiment, which is necessary for a broken-stick appearance to develop in the log-survivor functions.

It should be noted that the present study was limited in several ways. As discussed above, the study was an attempt to mimic a single-alternative situation in which the rate of reinforcement for engaging in alternative behaviors is relatively high. In a single-alternative situation, reinforcement for engaging in behavior other than the target behavior is qualitatively different and comes from a different source than the reinforcement for the target behavior. It may be that these differences in reinforcement between competing behaviors are important in obtaining a broken stick in the log-survivor function. The present study delivered the same food reinforcement from the same hopper for both measured behaviors. The use of different hoppers or even qualitatively different reinforcers may have increased the likelihood of obtaining the broken-stick appearance.

It also is worth mentioning the possibility that some of the data presented here include “responses” that were not produced by the behavior of the birds. It is difficult to determine whether the substantial proportion of within-visit IRTs between 0 and .2 s was the result of a topographically distinct response class (“nibbles”) or whether it is an artifact of the machinery used. If these within-visit responses represent a different class of behavior from within-visit and initiation responses, it may be a class of behavior specific to keypecking and to pigeons. However, because the origin of these responses is uncertain, no conclusions can be drawn from their production.

The data from the present study suggest that log-survivor functions will show a broken stick, reflecting a bout pattern of behavior, when a) visits have at least two responses, b) within-visit IRTs are shorter than initiation IRTs, and c) the probability of emitting a within-visit
response is higher than the probability of emitting a bout-initiation. It appears that these conditions are not usually met in a concurrent arrangement without a COD, and this may be because the behavioral unit in this arrangement is not a bout, but a keypeck following a class of IRTs. The use of a switching-punishment contingency may change the behavioral unit and produce these necessary conditions, giving rise to a broken stick. Whether the behavioral unit is a keypeck or a bout of keypecks, it is the emission of the unit that shows an orderly relation with rate of reinforcement, which presumably reflects the strength of that response; in one case, however, it is the emission of a keypeck and in the other, it is the emission of a bout of keypecks. In the present study, the log-survivor analysis was able to reveal a bout pattern of behavior in some cases. It is not possible to know if these are the only instances in which behavior was organized into bouts. However, the log-survivor analysis was always useful in making judgments about response strength, and it may be a more effective measure of the effects of reinforcement than more conventional measures of strength.
REFERENCES


Davison, M., Baum, W. M. (2003). Every reinforcer counts; reinforcer magnitude and local preference. *Journal of Experimental Analysis of Behavior, 80*, 95-129


