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Assessing the Generality of a Bout Analysis in the Description of Operant Behavior

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ASSESSING THE GENERALITY OF A BOUT ANALYSIS IN THE DESCRIPTION OF OPERANT BEHAVIOR

by

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A dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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Operant psychologists typically use response rate as a primary measure of behavior. Although response rate has proven a useful dependent measure resulting in the identification of many important behavioral regularities, many researchers have argued that the measure has significant limitations. Primarily, response rate treats all responses in the measured response class as functionally equivalent and distributed uniformly across time. This conceptualization of behavior is useful as long as all responses are affected similarly by different experimental manipulations. Research has shown, however, that certain manipulations differentially affect responses with relatively short or long inter-response times. This has led to a new conceptualization of responding in terms of periods of engagement and disengagement, or response *bouts*. In this approach, responses are characterized as either initiating bouts of responding (i.e., responses with relatively long inter-response times), or comprising bouts of responding (i.e., responses with relatively short inter-response times). Initiation responses are thought to be affected by motivational or reinforcement variables, whereas within-bout responses are thought to be affected by variables affecting the capability to respond. Most studies investigating the bout nature of responding have used rats responding for food pellets. Few studies have explored the generality of approach with other reinforcers or species. Thus, Experiment 1 attempted to
assess the generality of a response-bout conceptualization of behavior by investigating rat lever pressing for milk reinforcers across manipulations shown in prior studies to differentially affect within-bout and bout-initiation responses. Experiment 2 sought to extend the generality of the bout analysis to human button and footswitch pressing for hypothetical monetary reinforcers. Data were analyzed with log-survivor functions, which have previously been used to assess the two-state nature of responding. Only results from some of the manipulations in Experiment 1 provided compelling support for the two-state conceptualization of responding. Therefore, the generality of the bout conceptualization of responding appears limited. The bout analysis has been posited as a possible method for elucidating behavioral mechanisms of drug action. The potential utility of the bout analysis for investigating drug effects is discussed in light of the present findings. Other limitations of the bout analysis are also discussed.
ACKNOWLEDGMENTS

While a product of my personal research, this document serves as the culmination of years of joint scholarship and close relationships with countless individuals who played integral parts in shaping my behavior both as a scientist and as a person. My achievements are a function of heeding the sound advice that each individual provided. An attempt at properly acknowledging all who assisted in this journey is beyond the space allotted for this section. As such, I would like to provide a general thank you to all the undergraduate research minions, fellow graduate students and lab members (especially my sister-in-lab, Dr. Steve Stilling, for your assistance in my absence), colleagues (special thanks to Dr. Lavinia Tan for restraining my mad-scientist hypothesizing), friends, and family who provided guidance and support while on this journey. Additional, specific acknowledgments are warranted:

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J. Adam Bennett
TABLE OF CONTENTS

ACKNOWLEDGMENTS ........................................................................................................ ii

LIST OF TABLES .................................................................................................................. ix

LIST OF FIGURES ................................................................................................................ x

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

Assessing the Generality of Log-survivor Analyses in the Description of Behavior: Extensions in Animal and Human Operant Behavior ..................... 1

Analyses of Changes in Within-session Response Rates ............................................. 2

IRT Analyses .......................................................................................................................... 4

Molecular Analyses of Behavior and Behavioral Pharmacology .................... 6

A Two-mode Conceptualization of Response Rate and Response Bout Analysis ........................................................................................................ 7

Simulations to assess the validity of bout analysis ............................................. 10

Data from rats ..................................................................................................................... 15

Quantitative estimates from survivor functions .............................................. 19

Generalizability of bout-analyses: Response topography and species .............. 21

Refractory model ................................................................................................................. 30

Survivor Functions: Utility in Elucidating Behavioral Mechanisms of Drug Action ............................................................................................................. 34

Quantitative models and behavioral mechanisms of drug action .................... 34
Table of Contents—Continued

Matching law and behavioral mechanisms of drug action ............... 36
Problems with Herrnstein’s matching analysis............................... 36
Bout analysis and behavioral pharmacology .................................. 37
Purpose....................................................................................... 38
EXPERIMENT 1 ........................................................................... 40
Method ....................................................................................... 40
Subjects and Apparatus.................................................................. 40
Behavioral Procedure..................................................................... 41
Stability Criteria............................................................................ 42
Data Analysis................................................................................ 43
Results ......................................................................................... 44
Terminal Schedules....................................................................... 44
  Overall response rates............................................................... 44
  Survivor functions ................................................................. 46
  Bout-estimate calculations...................................................... 51
Tandem Schedules........................................................................ 52
  Overall response rates............................................................... 52
  Response-rate effects of tandem schedules.............................. 54
  Survivor functions ................................................................. 54
  Bout-estimate calculations...................................................... 56
  Effects of tandem schedules on survivor functions.................. 61
### Table of Contents—Continued

Effects of tandem schedules on bout-estimate calculations ............ 64

Single Schedules............................................................................. 65

Overall response rates................................................................... 65

Survivor functions ........................................................................ 65

Bout-estimate calculations............................................................ 66

Experiment 1 Discussion ................................................................ 72

Multiple Schedules ........................................................................ 72

Tandem Schedules ......................................................................... 76

Single Schedules............................................................................ 79

Response Rates Across Conditions................................................. 80

Summary ......................................................................................... 83

EXPERIMENT 2 ................................................................................. 85

Method ............................................................................................ 86

Subjects ......................................................................................... 86

Apparatus ....................................................................................... 86

Procedure ....................................................................................... 87

Data Analysis ................................................................................... 89

Results ............................................................................................ 90

Button-press Group ....................................................................... 90

Overall response rates .................................................................. 90

Survivor functions ......................................................................... 91
Table of Contents—Continued

Bout estimate calculations ................................................................. 94

Footswitch-responding Group .............................................................. 95

Overall response rates ........................................................................ 95

Survivor functions .............................................................................. 96

Bout estimate calculations ................................................................. 98

Experiment 2 Discussion ...................................................................... 103

Survivor Analysis ................................................................................ 103

Button-press responding ..................................................................... 103

Footswitch responding ....................................................................... 104

Comparisons Between Button-press and Footswitch Responding ......... 105

Response Rates .................................................................................. 107

Summary ............................................................................................. 114

DISCUSSION ....................................................................................... 116

Limitations of the Present Research and Future Directions .................. 117

Limitations of Log-survivor Analysis of Responding ............................ 119

IRT sample size considerations ............................................................ 119

Schedule and rate considerations ........................................................ 121

Other Methods for Analyzing Responding as Two-state in Nature ......... 124

Behavioral Mechanisms of Drug Action .............................................. 125

Possibility of a One-state Model .......................................................... 127

Utility of the Bout Conceptualization of Responding .............................. 128
# Table of Contents—Continued

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conclusion</td>
<td>129</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>131</td>
</tr>
<tr>
<td>APPENDICES</td>
<td>139</td>
</tr>
<tr>
<td>A. Post-experiment Questionnaire and Debriefing Form</td>
<td>139</td>
</tr>
<tr>
<td>B. Generation of Simulated IRTs Based Upon Response-bout Parameters</td>
<td>142</td>
</tr>
<tr>
<td>C. Figure Copyright Permissions</td>
<td>144</td>
</tr>
<tr>
<td>D. Western Michigan University Institutional Animal Care and Use Committee and Human Subjects Institutional Review Board Approvals</td>
<td>157</td>
</tr>
</tbody>
</table>
LIST OF TABLES

1. Sequence and Number of Sessions per Condition (in Parentheses) for Each Rat ........................................................................................................................................................................... 43

2. Response Rates (in Responses per Minute) for all Rats During Each Component for all Conditions (Mult Condition, Tand Condition, and Single RI 30-s Schedule) ........................................................................................................................................................................... 46

3. Obtained Values of $r^2$ and Sum of Squared Residuals (SS) From Double Exponential Equations fit to Single-session and Three-session Survivor Functions ........................................................................................................................................................................... 51

4. Obtained Parameter Estimates From the Fitted Double Exponential for all Rats, Components, and Sessions ........................................................................................................... 53

5. Obtained Values of $r^2$ and Sum of Squared Residuals (SS) for all Rats and Components During the Tand and Single RI Conditions ........................................................................................................... 59

6. Obtained Values of $r^2$ and Sum of Squared Residuals (SS) for all Human Button Pressing for Hypothetical Monetary Reinforcers ........................................................................................................... 96

7. Obtained Parameter Estimates From the Fitted Double Exponential for all Humans Engaging in Button Pressing ........................................................................................................... 97

8. Obtained Values of $r^2$ and Sum of Squared Residuals (SS) for all Human Footswitch Responding for Hypothetical Monetary Reinforcers ........................................... 101

9. Obtained Parameter Estimates From the Fitted Double Exponential for all Humans Engaging in Footswitch Responding ........................................................................................................... 102
LIST OF FIGURES


3. Sample log-survivor function. Proportion of IRTs greater than some time (t) is plotted as a function of time. The point (a) represents an initial steep drop, which is indicative of within-bout responding (shorter IRTs), while (b) represents a more gradual decline indicative of bout-initiations............................ 11


List of Figures—Continued


8. Representative log-survivor plot (replotted from Figure 4) with a double-exponential fit. Parameter estimates are from Equation1: \( \tau(t) = (1 - p) e^{wt} + pe^{bt} \). Parameter \( w \) provides an estimate of the rate of within-bout responding (in responses per second), \( b \) represents the rate of bout-initiations (in responses per second), and the inverse of the \( y \)-intercept \( (p) \) provides an estimate of the average number of responses per bout...................... 22


List of Figures—Continued

11. Response rates (in responses per minute) for all rats during the multiple RI 15-s RI 60-s schedule. Response rates during RI 15-s schedules are represented by black bars and response rates during RI 60-s schedules are represented by grey bars. Error bars show standard deviations. ........................................... 45

12. Survivor functions of the last stable session of the Mult condition for all rats. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Solid and dashed lines indicate responding during RI 15 s and RI 60 s, respectively. ............................................................................. 49

13. Survivor functions for all rats collapsed across the last 3 stable sessions of the Mult condition. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Solid and dashed lines indicate responding during RI 15 s and RI 60 s, respectively. Fitted functions represent the best-fitting double-exponential. ........................................................................................................ 50

14. Estimated within-bout and bout-initiation response rates (in responses per second; left y-axis) and average number of responses per bout (right y-axis) obtained from double-exponential fits for the RI 15-s and RI 60-s components of the Mult condition for all rats, save S1 and S2 (see text). Axes are individually scaled. ........................................................................................................ 55

15. Response rates (in responses per minute) for all rats during the Tand condition. Rates of responding during RI 15 s schedules are represented by black bars and rates of responding during RI 60 s schedules are represented by grey bars. Error bars indicate standard deviations ......................................................... 56

16. Response rates (in responses per minute) for all rats on the multiple (No-Tandem) and multiple plus tandem (Tandem) schedules. The upper panel represents rates of responding during RI 15-s schedules and the lower panel represents rates of responding during RI 60-s schedules. Error bars indicate standard deviations ........................................................................................................ 57

17. Survivor functions for all rats collapsed across the last 3 stable sessions of the Tand condition. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Solid and dashed lines indicate responding during RI 15 s and RI 60 s, respectively. Fitted functions represent the best-fitting double-exponential ........................................................................................................ 58
List of Figures—Continued

18. Estimated within-bout and bout-initiation response rates (in responses per second; left y-axis) and average number of responses per bout (right y-axis) obtained from double-exponential fits for the RI 15-s and RI 60-s schedules during the Tand condition. Axes are individually scaled. .................................................. 60

19. Survivor functions from data collapsed across the last 3 stable sessions of the Mult and Tand RI 15-s components for all rats, save S1 and S2 (see text). Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Solid and dashed lines indicate responding during the no-tandem and tandem conditions, respectively. Fitted functions represent the best-fitting double-exponential. ................................................................. 62

20. Survivor functions from data collapsed across the last 3 stable sessions of the Mult and Tand RI 60-s components for all rats. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Solid and dashed lines indicate responding during the no-tandem and tandem conditions, respectively. Fitted functions represent the best-fitting double-exponential. ......................... 63

21. Estimated within-bout and bout-initiation rates (in responses per second; left y-axis) and the average number of responses per bout (right y-axis) obtained from double-exponential fits for the RI 15 s no-tandem (Mult) and tandem (Tand) schedule for all rats, save S1 and S2 (see text). Axes are individually scaled. .................................................................................................................. 64

22. Estimated within-bout and bout-initiation rates (in responses per second; left y-axis) and the average number of responses per bout (right y-axis) obtained from double-exponential fits for the RI 60 s no-tandem (Mult) and tandem (Tand) schedules. Axes are individually scaled. ................................................................................. 67

23. Response rates (in responses per minute) for rats during the Single RI (RI 30-s) condition, re-plotted with response rates from the Mult condition (from Figure 11). Error bars indicate standard deviations. ................................................. 68

24. Survivor functions for all rats in the Single RI 30 s condition. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Fitted functions represent the best-fitting double-exponential. ............................................................................. 69
List of Figures—Continued

25. Survivor functions for all rats collapsed across the last three stable sessions for all schedule values in Experiment 1. Log proportion of IRTs $> t$ are plotted as a function of time ($t – s$: time in seconds). Solid, dotted, and dashed lines represent the RI 15 s, RI 30 s, and RI 60 s component, respectively. Fitted functions represent the best-fitting double-exponential. 70

26. Estimated within-bout and bout-initiation response rates (in responses per second; left y-axis) and average number of responses per bout (right y-axis) from double-exponential fits for all rats during the single RI 30-s schedule, and during the RI 15-s and RI 60-s components of the multiple schedule (replotted from Figure 4). Graphs for S1 and S2 show only data from RI 30 s and RI 60 s (see text). Axes are individually scaled. 71

27. Response rates (in responses per minute) for all participants during the multiple RI 60 s RI 120 s RI 240 s schedule. Response rates during RI 60 s schedules are represented by black bars, rates during RI 120 s schedules are represented by light grey bars, and rates during RI 240 s schedules are represented by dark grey bars. 91

28. Final session survivor functions for all participants in Button-press group. Log proportion of IRTs $> t$ are plotted as a function of time ($t – s$: time in seconds). Closed circles represent the RI 60 s component, open circles represent the RI 120 s component, and closed triangles represent the RI 240 s component. 92

29. Log survivor functions for all human button pressing during the final completed session with the refractory period subtracted from IRTs. Log proportion of IRTs $> t$ are plotted as a function of time ($t – s$: time in seconds). Closed circles represent RI 60 s, open circles represent RI 120 s, and closed triangles represent RI 240 s. Fitted functions represent the best-fitting double-exponential. 93

30. Response rates (in responses per minute) for all participants during the RI 60 s RI 120 s RI 240 s multiple schedule. Response rates during RI 60 s schedules are represented by black bars, rates during RI 120 s schedules are represented by light grey bars, and rates during RI 240 s schedules are represented by dark grey bars. 98
31. Log survivor functions for all human footswitch responding during the final completed session without the refractory period subtracted from IRTs. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Closed circles represent RI 60 s, open circles represent RI 120 s, and closed triangles represent RI 240 s. Fitted functions represent the best-fitting double-exponential. ................................................................. 99

32. Log survivor functions for all human footswitch responding during the final completed session with the refractory period subtracted from IRTs. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Closed circles represent RI 60 s, open circles represent RI 120 s, and closed triangles represent RI 240 s. Fitted functions represent the best-fitting double-exponential. ........................................................................ 100

33. Log survivor functions constructed from human button pressing data during a multiple RI 20-s RI 60-s schedule and a multiple RI 20-s + laptop RI 60-s + laptop schedule (see text description). Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). The top frame represents responding maintained on an RI 20-s schedule (solid line) and its corresponding RI 20-s + laptop schedule (dashed line). The bottom frame represents responding maintained on an RI 60-s schedule (solid line) and its corresponding RI 60-s + laptop schedule (dashed line)................................. 113

34. Parameter estimates for p (predicted value = 0.75) as a function of IRT sample size. Plots were constructed from simulations of IRT distributions and parameter estimates were obtained by fitting double-exponential functions to data from these simulations. Each x indicates the estimate for p from a single simulation. ................................................................. 121

35. Hypothetical single exponentials for within-bout response distributions (dot-dashed lines) and bout-initiation distributions (dashed lines) and the combined double-exponential function (solid lines; obtained from the sum of the two single exponentials) for differing within-to-between-bout response ratios. Parameter values used to construct these functions are located in the bottom right corner of each figure. Figures represent (from right to left and top to bottom): 8:1, 4:1, 3:1, and 2:1 ratios. ........................................ 122
List of Figures—Continued

36. Parameter estimates for $p$ (predicted value = 0.75) as a function of $w:b$ ratio. Plots were constructed from simulations of IRT distributions using the parameters from Figure X and parameter estimates were obtained by fitting double-exponential functions to data from these simulations. Each x indicates the estimate for $p$ from a single simulation. .................................................. 124
INTRODUCTION

Assessing the Generality of Log-survivor Analyses in the Description of Behavior: Extensions in Animal and Human Operant Behavior

The use of response rate as a primary measure of operant behavior has resulted in the identification of many important functional relationships (see Baum, 2003). Overall rate of responding, however, is a molar analysis: counts of responses across extended time periods are collapsed into a single measure. All responses within the measured response class are thus treated as if they were functionally equivalent. Measures of overall response rate may, therefore, obscure patterns of responding that are observable at a more molecular level. There are no set standards for appropriate levels of analysis. It may therefore be valuable to analyze behavior at more molecular as well as molar levels. Many researchers have insisted that molecular analyses can reveal patterns important to our understanding of behavior (e.g., Felton & Lyton, 1966; Mechner, 1992; Schneider, 1969). For example, Mechner (1992) noted:

Molecular information often provides the key to understanding and explaining molar phenomena… Examples can also be seen in other sciences: Our understanding of the properties of substances, such as hardness, viscosity, adhesion, lubricity, color, etc., is based on information about molecular and atomic structure. Similarly, our understanding of genetics is based heavily on information about genes and the structure of the DNA molecule. It is likely that molecular information about operants will similarly shed light on the molar behavioral phenomena that interest us. (p. 17)

Researchers who have argued that operant responding should be analyzed at a more molecular level have offered various alternatives to overall response rate, including
analyses of local, within-session response rates (see McSweeney, 1992), and inter-
response time (IRT) distributions (see Richards, Sabol, & Seiden, 1993). Discoveries
from these two types of local analyses are discussed below.

**Analyses of Changes in Within-session Response Rates**

One early example of how molecular analyses of responding can provide insights
into behavioral processes comes from Skinner’s analysis of fixed-interval (FI) schedule
of reinforcement (Skinner, 1938). Under FI schedules, the first response emitted after a
fixed period of time produces reinforcement. By analyzing cumulative records, Skinner
discovered that with continued exposure to this schedule, a temporal discrimination
seemingly develops, and responding begins after the start of the interval, i.e., response
pattern becomes “scalloped” in nature. Some researchers have described this as an
acceleration of responding across an interval (see Keller & Schoenfeld, 1950), while
others have described it as a more discreet “break and run” patterning (see Cumming &
Schoenfeld, 1958). This pattern, however, is only observable if individual responses are
graphed across time. If researchers only measured overall rate of responding on the fixed-
interval schedule, the temporal patterning of responding produced by the schedule would
be obscured.

Similarly, Ferster and Skinner (1957) found that on fixed-ratio (FR) schedules, in
which reinforcers are delivered following a constant number of responses, overall
response rate decreased as a function of increasing ratio requirement. However, in a
seminal study, Felton and Lyon (1966) assessed the effects of increasing fixed-ratio (FR)
requirements not only on overall response rate, but also on the length of the post-
reinforcement pause (the inter-response time between the last reinforced response and the
next response of a new ratio). They found increases in the post-reinforcement pause as FR value increased, but found only slight and inconsistent decreases in response rates when the pauses were excluded from analysis (i.e., run rates). These results suggested that decreases in response rate observed when ratio requirements were increased could be attributed nearly entirely to changes in the postreinforcement pause. Powell (1968) observed similar results.

McSweeney, Hatfield, and Allen (1990) investigated other interesting within-session changes in responding. McSweeney et al. exposed 10 rats to a multiple variable-interval (VI) 60 s VI 60 s schedule in a series of experiments. Experiment 1 provided food reinforcers or lever pressing, whereas Experiment 2 provided milk reinforcers for key poke responding. The schedules (i.e., multiple VI 60 s VI 60 s) provided a constant averaged programmed rate of reinforcement throughout experimental sessions. Despite this constant rate of programmed reinforcement and stable conditions within and across sessions, a bitonic function was observed when response rate was plotted as a function of time within the session. That is, there were large increases in response rates earlier in the session, and subsequent decreases in rates of responding later in the session. More specifically, response rates increased to approximately three times their initially observed value and then gradually decreased to just above the value observed at the beginning of the session. Additional investigations (e.g., McSweeney, Roll, & Weatherly, 1994) and reviews (McSweeney, Hinson, & Cannon, 1996; McSweeney & Roll, 1993) have shown similar results. Together, these results and those from many other studies suggest that an overreliance on response rate as our primary unit of measure may sometimes mask important details in responding.
IRT Analyses

Detailed analyses of IRTs can also help generate new theoretical interpretations of behavior-environment relations. For instance, Blough (1963) discovered regularities in pigeons’ keypecking by carefully analyzing IRTs. Blough exposed 12 White Carneau pigeons to a variety of schedules (e.g., VI schedules of varying length, extinction, FR 25, and FR 30) in order to assess the utility of a new technique to study IRT distributions. Obtained IRTs for each schedule were plotted as a function of time within the session. These plots revealed that across sessions there were regular patterns to the length of IRTs. Specifically, IRTs tended to cluster or band at specific values. These repeating bands tended to occur around 0.35 s, 0.7 s, and 1.2 s. Interestingly, the longer IRT clusters were approximately multiples of the lowest band of IRTs (0.35 s), suggesting that secondary bands may have been the result of missed pecks. That is, if a pigeon emitted two responses with IRTs of 0.35 s but the first was not recorded, then the second IRT would be recorded at 0.7 s. Similarly, the IRT band occurring at 1.2 could be construed as two missed pecks followed by a single key peck. These detailed response patterns suggest that overall response rate (which includes time during which “missed” responses are emitted) may be a function of the topographical control of responding. As such, Blough (1966) suggested that many emitted responses are not entirely independent of previous responses and that careful training may eliminate some of these off-key responses.

A detailed IRT analyses by Schneider (1969) suggested a new interpretation of patterning on fixed-interval (FI) schedules. As noted above, fixed-interval schedules have been shown to produce a scalloped pattern when response rates are represented
graphically on cumulative records. This has commonly been described as an acceleration of response rate across the interval (see also Dews, 1962; Ferster & Skinner, 1957; Keller & Schoenfeld, 1950; Skinner, 1953). Investigating this issue, Schneider (1969) conducted a detailed analysis of pigeons’ keypecking for grain on FI schedules of reinforcement by analyzing cumulative records. According to Schneider, responding did not appear to gradually increase in rate as the organism neared food reinforcement. Rather, it appeared as a two-state process: (1) an initial low (or zero) rate of responding following reinforcement from a previous interval, and (2) a high and constant rate of responding. Instead of a gradual shift in behavior from a low to high rate, responding tended to abruptly shift from near-zero responding to higher rates, suggesting that the FI scallop was an artifact of averaging across intervals. Similarly, Branch and Gollub (1974) conducted a detailed analysis of pigeon keypeck responding under FI schedules of food reinforcement. Again, it was concluded that pigeons’ keypecking did not produce a scalloped patterning. Rather, responding occurred at either high or low rates. Averaging rates across intervals masked the bimodal nature of FI responding.

Gentry, Weiss, and Laties (1983) conducted a detailed analysis of pigeons’ keypecking maintained on FI 5- and FI 15-min schedules of reinforcement. Like Schneider (1969), Gentry et al., found that FI schedule responding did not show evidence of the scalloped pattern that is typically observed on FI schedules when individual IRTs were recorded and analyzed. Indeed, the scalloped pattern could be accounted for by a few long IRTs occurring early in the interval interspersed with many short IRTs. Rather than an acceleration across time, which would be expected with a scalloped patterning, they showed that longer IRTs did not gradually shift towards shorter IRTs within the
interval. Interestingly, Gentry et al. also did not observe just two states of responding, but three states: (1) an initial pause which immediately follows reinforcement, (2) long IRTs interspersed with bursts of responding (short IRTs), and (3) short IRTs occurring at a steady rate.

**Molecular Analyses of Behavior and Behavioral Pharmacology**

Studies of the behavioral effects of drugs also have suggested that reliance on overall rate of responding may obscure important drug effects that are apparent at more molecular levels. For example, Weiss and Gott (1972) found that response rate might mask multiple response topographies, each of which may be affected differentially by drug manipulations. They assessed pigeon FR 30 performance under varying doses of d-amphetamine, pentobarbital, and imipramine. Each drug’s effect on individual IRTs was assessed according to their ordinal position across the ratio. Interestingly, drug effects on IRTs were dependent upon where that IRT occurred within the ratio. Amphetamine and imipramine both served to increase mean IRT length, whereas pentobarbital tended to decrease the mean IRT length. This effect, however, was most evident in the post-reinforcement IRT and the second through fifth IRTs, but tended to dissipate with successive IRTs. Additionally, Weiss and Gott also observed responding occurring in clusters of three distinct response types: (1) a rapid opening and closing of the beak while in contact with the key, (2) keypecking, and (3) harmonics which are IRTs containing a missed peck terminated by an actual keypeck. This analysis was similar to Blough’s (1963) analysis, as well as other studies investigating the recurrent bands of IRTs in pigeons (e.g., Bennett, Pitts, & Hughes, 2007; Bowers, Hill, & Palya, 2008; Palya, 1992). Amphetamine and imipramine had varying effects depending upon the topography of the
response: administration of these drugs tended to eliminate the initial grouping of IRTs, what Weiss and Gott termed *nibbles*, while shifting the distributions of true pecking behavior and harmonics to the right. Though these different topographies of behavior are normally collapsed together to produce an overall measure of responding (i.e., response rate), these data indicate that this method of analysis masks important details about the behavioral effects of a drug, and illustrates the value of detailed response analyses in the classification of drug effects.

In another example, Ziriax, Snyder, Newland, and Weiss (1993) assessed the effects of several doses of d-amphetamine on monkey lever pressing on concurrent stochastic reinforcement of waiting (SRW) schedules maintained by access to fruit juice reinforcers. SRW schedules are essentially VI schedules programmed to maintain a constant rate of reinforcement regardless of response rate. The authors found that d-amphetamine dose-dependently decreased response rate and switching rate. More detailed analyses revealed, however, that drug effects were confined to only a subset of IRTs. Specifically, d-amphetamine tended to lengthen shorter IRTs. Thus, orderly changes in the microstructure of behavior were found to produce changes in overall rates of responding.

A Two-mode Conceptualization of Response Rate and Response Bout Analysis

Careful analysis of the structure of behavior, specifically the patterning of IRTs, has also led to the view that operant responding may generally be characterized as two-state in nature. One of the first researchers to propose that behavior may be conceptualized as two-state in nature was Gilbert (1958), who suggested that responding
could be characterized by its *perseveration*, or the period of time in which an organism emits a specific behavior. According to this view, an organism emits two separate responses: (1) a response that *initiates* a period of perseveration, and (2) a response that *comprises* a period of perseveration. This dichotomization of responding has been used by other researchers to argue that overall rate of responding is masking important variations in responding at more molecular levels (see Conover, Fulton, & Shizgal, 2001; Mechner, 1992; Shull, Gaynor, & Grimes, 2001).

Following Gilbert’s (1958) line of reasoning, Shull et al. (2001) conceptualized response rate as encompassing two distinct response classes: (1) periods of engagement similar to periods of perseveration that alter with (2) periods of disengagement, or the period of time between the last response in a period of perseveration and the first response initiating another perseverance period. These two types of responding combine to produce what Shull et al. called a *bout-like* patterning. That is, responses occur in bouts or visits consisting of clusters of responses with very short IRTs with periods of non-responding, or responses separated by longer IRTs, between these bouts.

Bout response patterning can be easily illustrated with the simple event record of rat nose poking shown in Figure 1 (Shull et al., 2001). Each vertical tick on this event record represents a single nose poke occurring across a 40 s time period. According to this event record, nose poking clusters into what might be considered periods of engagement (i.e., instances in which many ticks are present), that alter with periods of disengagement (i.e., instances in which time passes and no ticks are present).
Although the rationale for analyzing operant responding in terms of response bouts can be illustrated easily through use of this event record, one problem with bout analyses is that it is difficult to determine whether a response represents an initiation of a bout or a response within a bout. Note the cluster of responses labeled a in Figure 1. Depending upon the criteria set by an individual observer, one might consider the cluster of responding to be either a single bout of responding or two separate bouts of responding, if the longest IRT is indeed considered long enough to represent a disengagement. As this example illustrates, using visual inspection to group responses into bouts can be very subjective. Difficulties arise, also, when attempting to dichotomize responding into these two component parts via slightly more objective methods (e.g., by defining an IRT cutoff between the two response types). Selecting a quantitative IRT cutoff time is still a subjective endeavor and it is likely that selected cutoff times, depending on response distributions, would vary across individuals within a species.
across operants, and/or across procedural manipulations. Thus, a more objective method of separating initiations from responses within a bout is needed.

**Simulations to assess the validity of bout analysis.** To address the problem of how to distinguish within-bout from bout-initiation responses, Shull et al. (2001) programmed a computer to simulate an organism responding in a bout-like pattern. Figure 2 represents the model used by Shull et al. in their simulations. In this model, an organism may begin in a period of disengagement and alternate between this and a period of engagement, represented within the hyphenated rectangle. The probability of initiating a visit is \( p(V) \) and the probability of engaging in a response within a visit is \( p(R) \). Once in an engagement bout, the organism may disengage from the visit \([p(D)]\) or continue the visit \([1 – p(D)]\). In these simulations, Shull et al. manipulated two variables: (1) the probability of initiating a visit, \( p(V) \), and (2) the probability of disengagement, \( p(D) \), and then plotted the resulting IRTs in log-survivor functions which plot the log proportion of IRTs longer than time \( (t) \) as a function of time \( (t) \) on a linear scale.

These simulations produced log-survivor plots that were characterized by a distinct broken-stick function (see Figure 3). In these plots, it was evident that behavior could be characterized in terms of a two-state process: (1) an initial steep drop (responses with very short IRTs, see point \( a \)), which abruptly ends and gives way to (2) a more shallow and gradual decline (responses with relatively longer IRTs, see point \( b \)). Data from these simulations revealed that the broken-stick pattern was indicative of what Shull et al. hypothesized to be two distinct components of response rate. Their functions therefore provided a clear picture of the pattern that would be produced if responding was indeed consistent with the two-mode conception of response rate described above.

Figure 3. Sample log-survivor function. Proportion of IRTs greater than some time \( t \) is plotted as a function of time. The point (a) represents an initial steep drop, which is indicative of within-bout responding (shorter IRTs), while (b) represents a more gradual decline indicative of bout-initiations.
Figures 4 and 5 show the results of Shull et al.’s (2001) simulations. As can be seen in each of these figures, similar changes in response rate (from 20 to 50 responses per minute) could be produced via different means. Figure 4 represents data from simulations in which the probability of a visit, \( p(V) \), was varied (8.9 vs. 22.2 visits per minute), while the probability of disengagement, \( p(D) \), was held constant (approximately 2.85 responses per visit). Thus, changes in response rate were attributable to the changes in the number of visits per minute. Because the drop in the initial limb was similar across the two functions, Shull et al. considered changes in slope of the secondary limb to be indicative of changes in the visit-initiation rate. Figure 5 represents data from simulations in which the probability of disengagement, \( p(D) \), from the target response was varied (2.9 vs. 8.0 responses per visit), while the probability of a visit, \( p(V) \), was held constant (approximately 8.85 visits per minute). Thus, any difference in response rate was attributable to changes in the number of responses per visit (or how long the animal continues to engage in the target behavior once in a period of engagement). The slopes of the secondary limbs (what was considered a function of visit-initiation rate in Figure 4) were similar, confirming that these portions of the function were indeed representative of visit-initiation rate. However, differences were present in the initial limbs of the survivor function. When the number of responses per visit was high (i.e., longer visits), the initial drop was considerably steeper than when the number of responses per visit was low (i.e., shorter visits). Thus, changes in the initial limb of the survivor function represent changes in the number of responses per visit.
Sim 1 - Different visit rates

Elapsed time ($t$ s)

Proportion of response times $> t$

$y = 0.35e^{-0.15t}$

$y = 0.36e^{-0.37t}$

Figure 4. Log-survivor function produced by computer simulations. Proportion of IRTs greater than some time ($t$) is plotted as a function of time. This plot shows the effects of altering the number of visits (bouts) per minute. Reprinted from “Response rate viewed as engagement bouts: effects of relative reinforcement and schedule type,” R.L. Shull, S.T. Gaynor, J.A. Grimes, 2001, *Journal of the Experimental Analysis of Behavior*, 75(3), 251. Copyright [2001] by Society for the Experimental Analysis of Behavior. Reprinted with permission.
Sim 2 - Different responses per visit

Proportion of response times $> t$

$y = 0.35e^{-0.15t}$

$y = 0.12e^{-0.15t}$

Elapsed time ($t$ s)

Figure 5. Log-survivor function produced by computer simulations. Proportion of IRTs greater than some time ($t$) is plotted as a function of time. This plot shows the effects of altering the number of responses per visit (bout). Reprinted from “Response rate viewed as engagement bouts: effects of relative reinforcement and schedule type,” R.L. Shull, S.T. Gaynor, J.A. Grimes, 2001, *Journal of the Experimental Analysis of Behavior*, 75(3), 251. Copyright [2001] by Society for the Experimental Analysis of Behavior. Reprinted with permission.
In summary, the initial limb of the functions was representative of within-bout responses (i.e., those with shorter IRTs), whereas the secondary limb was representative of bout-initiations (i.e., those responses with longer IRTs). In Shull et al.’s (2001) simulations, when the probability of a visit was altered, only the secondary limb of the survivor function was affected, and when the probability of a disengagement (the time spent within a bout) was manipulated, only the \( y \)-intercept of the secondary limbs (and thus, how far down the initial limb dropped) was altered. These changes in the qualitative nature of these survivor functions were produced even though response rates were similar. This similarity in overall response rates highlights one of the concerns of using overall response rate as a primary measure of behavior: that very different molecular response patterns may yield similar overall response rates. Changes in rate may be evident, but may occur for drastically different reasons.

**Data from rats.** To further explore the utility of the bout analyses, Shull et al. (2001) trained rats to emit nose pokes for food pellets on a series of VI schedules. Log survivor plots were created from obtained IRTs. If rat nose poking occurs in a bout-like pattern similar to that produced by Shull’s simulations, the log-survivor functions should look very similar to those produced by their computer counterparts. This was the case, as survivor plots from all rats showed clear broken-stick functions.

Following confirmation that rat nose poking occurred in a bout-like pattern as indicated by clear broken-stick log-survivor functions, Shull et al.(2001) manipulated the reinforcer schedule, amount, and probability to determine how these variables affected the bout pattern. Specifically, these manipulations included: (a) altering the rate of programmed reinforcement (VI1 vs. VI4 schedules), (b) altering the magnitude of
reinforcement (1 vs. 4 pellets), (c) altering the percentage of reinforcers which were contingent upon responding (25% vs. 100%), and (d) adding a tandem VR requirement to the end of a VI schedule of reinforcement. Figure 6 shows these data. Shull et al. found that these manipulations altered either the slope of the secondary limb or the steepness of the initial limb of the survivor function. Manipulations which altered reinforcer properties (i.e., rate, amount, and percentage of reinforcers contingent upon responding, the top three rows of Figure 6) tended to alter the slope of the secondary limb (bout-initiations) of the function but had little effect on the steepness of the initial limb, whereas manipulations which altered what the organism had to do to obtain reinforcement (i.e., addition of a tandem VR requirement – the bottom row of Figure 6) altered the steepness of the initial limb (bout length), but left the secondary limb relatively unchanged.

Given the results discussed above, Shull et al.’s (2001) study therefore found those manipulations that altered reinforcer properties produced their changes on response rate by altering the rate of bout initiations. That is, when the rate or quality of reinforcement (or the percent contingent) was increased, increases in response rate were produced as a result of an increased number of bouts per minute. However, these manipulations did not change the number of responses emitted once rats were engaged in a bout. Similarly, manipulations that altered what the organism had to do to obtain reinforcement (i.e., the addition of a tandem VR requirement) produced their changes on response rate by altering the number of responses emitted once the rat was in a period of engagement, while bout-initiation rate was not changed. Specifically, the addition of the tandem requirement increased the overall rate of responding by increasing the number of
responses emitted per visit. Similar results were observed in further investigations (see Brackney, Chrung, Neisewander, & Sanabria, 2011; Shull, Grimes, & Bennett, 2004).

**Figure 6.** Log-survivor functions of rat nose poking. Proportion of IRTs greater than some time (t) is plotted as a function of time. These plots reveal the results of reinforcer and tandem manipulations on survivor functions. Each column represents a single rat and rows are representative of different manipulations (rate of reinforcement, amount of reinforcement, percent of reinforcers contingent upon the target response, and addition of a tandem requirement). Reprinted from “Response rate viewed as engagement bouts: effects of relative reinforcement and schedule type,” R.L. Shull, S.T. Gaynor, J.A. Grimes, 2001, *Journal of the Experimental Analysis of Behavior*, 75(3), 258. Copyright [2001] by Society for the Experimental Analysis of Behavior. Reprinted with permission.
In a subsequent study, Shull and Grimes (2003) assessed the extent to which rat lever pressing for pellets on VI schedules could be described as two-state in nature and observed similar results. Log-survivor functions showed similar patterning: an initial limb with a steep drop followed by a secondary limb with a more gradual decline, again suggesting that responding may be a two-state process. Similar to Shull et al. (2001), changes in bout initiations were primarily responsible for changes in overall rate of response when rate of reinforcement was manipulated, and changes in bout length were primarily responsible for changes in overall rate of responding when VI schedules were changed to VI + VT tandem schedules of reinforcement. Figure 7 (Shull & Grimes, 2003), however, depicts an important distinction between these lever press functions and those derived from rat nose poking (e.g., Shull et al., 2001). Note that for the rat nose poke data (see Figure 6), the transition from the first to secondary limb tended to be abrupt, resulting in a discrete <180 degree angle. However, for the rat lever press data, the transition between these two limbs tended to be more gradual and curved (Figure 7). Henceforth, the qualitatively different nature of these two types of functions shall be referred to as broken-stick and bent-stick, respectively.

Shull and Grimes (2003) argued that the less discreet transition between the two limbs was likely a function of differences in response topography. Specifically, they noted that the increased force required to press the lever, the distance the lever needed to travel, and the greater distance between the lever and pellet dispenser for lever pressing as opposed to nose pokes, could all have produced overlap in the two distributions of responding. For instance, it is possible that a greater force requirement would result in the organism emitting longer IRTs while responding within a bout. As such, the within-bout
portion of the survivor function would have a shallower slope (shown in an IRT distribution as a skew towards longer IRTs). This would produce a more gradual break in the survivor function as a result of more overlap in two IRT distributions.

![Graphs of IRT distributions for different rats](image)


**Quantitative estimates from survivor functions.** If clear broken-stick functions are obtained following a log-survivor analysis, it is relatively easy to obtain quantitative estimates of bout-initiation rate and the number of responses per bout. As the
secondary (initiation) limb is linear on a semi-log axis, it is represented by an exponential function:

\[ r(t) = pe^{bt} \] (1)

where \( r(t) \) represents the proportion of IRTs longer than some elapsed time \( t \). The term \( pe^{bt} \) provides estimates of bout-initiation responding, such that \( p \) represents the proportion of all responses that are classified as bout-initiations, and \( b \) represents the rate of bout-initiations (in responses per second). Lastly, \( e \) is the base of the natural logarithms. In order to obtain parameter estimates, a line must be fit to the secondary limb of the survivor function and be allowed to intersect the \( y \)-axis. This is most easily accomplished using linear regression. The point at which this fitted line intersects the \( y \)-axis represents the proportion of all emitted responses that are classified as initiations \((p)\). Because responses are either classified as either initiations or responses within a bout, the inverse of this proportion \((1/p)\) indicates the average number of responses per bout (e.g., if the proportion of responses classified as initiations was 0.5, the average number of responses per bout would be 2.0).

If log-survivor analyses do not generate clear broken-stick functions (e.g., if the two functions are connected by a curve instead of a straight angle), it may be difficult or impossible to determine the point at which these two distributions intersect using this method. In this situation, fitting a double-exponential equation to the data can help distinguish the two states (see Shull & Grimes, 2003). The double exponential equation is a 4-parameter equation, represented as:

\[ r(t) = (1 - p)e^{\omega t} + pe^{bt} \] (2)
where $r(t)$ represents the proportion of IRTs longer than some elapsed time $(t)$. The initial term following the equality sign $[(1 - p)e^{-wt}]$ provides estimates of within-bout responding, such that $1 - p$ represents the proportion within-bout responses, and $w$ provides an estimate of within-bout response rate (in responses per second). The second term of the equation following the equality sign $(pe^{-bt})$ provides estimates of bout-initiation responding, such that $p$ represents the proportion of responses that are classified as bout-initiations, and $b$ represents the rate of bout-initiations (in responses per second). Lastly, $e$ is the base of the natural logarithms. If this equation provides a good fit, parameter estimates may be obtained. Other than providing parameter estimates for functions which are not clearly broken-stick in nature, this double-exponential equation has an added benefit over the single-exponential, as it provides quantitative estimates of rate of within-bout responding. Figure 8 shows a double-exponential fit to the example survivor function from Figure 4. Parameter estimates are indicated in the figure.

**Generalizability of bout-analyses: Response topography and species.** While researchers (e.g., Gilbert, 1958; Mechner, 1992; Shull et al., 2001) have argued that overall response rate may obscure order at a more molecular level, whether certain molecular analyses reveal important order and not just “superfluous detail” (Fahmie & Hanley, 2008, p. 320) remains an empirical question. According to Fahmie and Hanley, for example, data should remain aggregated if division into smaller units results in unnecessary and uninformative detail. Thus, it is important to establish whether the analysis of responding into more molecular components (e.g., examination of individual IRTs, post-reinforcement pauses, etc.) produces orderly and predictable functional relationships. A survivor analysis seemingly provides a clear picture of how
two different components of response rate (i.e., bout-initiations and responses within a bout) may be responsible for changes in the overall rate of behavior. That an overall increase in rate of responding may be produced by changes in one or both of these components suggests that a more molecular analysis of behavior may determine which aspect of behavior underlies the response-rate change.

Figure 8. Representative log-survivor plot (replotted from Figure 4) with a double-exponential fit. Parameter estimates are from Equation 1: \( r(t) = (1 - p)e^{wt} + pe^{bt} \). Parameter \( w \) provides an estimate of the rate of within-bout responding (in responses per second), \( b \) represents the rate of bout-initiations (in responses per second), and the inverse of the \( y \)-intercept (\( p \)) provides an estimate of the average number of responses per bout.

An interesting use of the survivor analysis was conducted by Hill, Herbst, and Sanabria (2012) in which they investigated the differences in log-survivor plots and parameter estimates in three different strains of rats (SHR, WKY, and WIS). SHR (spontaneous hypersensitive rats) rats have been studied as an animal model of ADHD. In
order to assess the mechanism by which SHR rats emit higher rates of operant behavior (operant hyperactivity) than controls, Hill et al. plotted survivor functions for each type of rat (WKY and WIS served as controls) across a five-component multiple VI schedule. It would be expected that, if the increased rates of responding were primarily due to a heightened motor ability, changes in the initial limb of the function (or shortest emittable IRT) should be observed. On the other hand, if the increased rates of responding were a function of an increased sensitivity to reinforcement, changes in the secondary limb should be observed. Consistent with prior investigations of lever pressing in rats (e.g., Shull et al., 2001), all subjects, regardless of strain, produced functions which could be described as bent-stick in nature at some schedule values and changes in schedule values primarily produced changes in bout-initiation rate. However, performance from richer schedule values often produced functions that were nearly linear in nature and best described by a single exponential. Bout parameter estimates tended to primarily show a higher incidence of bout-initiations in SHR rats compared to controls at the same schedule values, suggesting that in SHR rats operant hyperactivity occurs primarily as a result of heightened reinforcer efficacy.

The above study highlights some of the potential utility of the bout analysis. In order to assess whether operant responding is fundamentally represented as two distinct classes of behavior, however, one must assess the generality of this claim. If a bout analysis reveals two-state patterns of responding only in certain species or with certain response topographies, its utility may be limited. Indeed, Bowers et al. (2008) note that:

A prerequisite of the general applicability of a log survivor function as an index of engagement and disengagement is a demonstration that the results found using rats on some variable-interval (VI) schedules will generalize to other organisms, schedules and parameter values. (p. 346)
**Mice.** Several studies also have investigated whether responding in mice can be described by the bout analysis. For example, to determine whether genetic factors influence the bout-like pattern of responding in mice, Johnson, Pesek, and Newland (2009) examined survivor functions in mice pressing lever for food reinforcement. Specifically, C57BL/6 and BALB/c mice were maintained on second-order RI ts (Percentile 10:0.5) schedules of reinforcement such that, following an RI 60 s schedule of reinforcement, lever pressing only produced food if the final IRT was less than the 50% of the previous 10 IRTs. Two manipulations were conducted in order to assess the effects on bout-initiation rate: (1) a running wheel was added to the chamber, thereby increasing the probability that mice would disengage from the target behavior and engage in other behavior and (2) free-feeding was implemented, which should decrease the rate of initiations (e.g., Shull, 2004).

C57BL/6 mice have been shown to engage in high rates of spontaneous locomotor behavior and also spend more time in areas of the chamber that did not have programmed reinforcement. Johnson et al. (2009) suggested that these unique behavioral repertoire features might be construed as a greater sensitivity to reinforcement for alternative behavior. BALB/c mice, on the other hand, do not show these unique patterns of behavior. Rather, these mice have been shown to engage in more forceful responding when compared to C57BL/6 mice. Interestingly, survivor functions were broken-stick in nature for the C57BL/6 mice, but less so for the BALB/c mice (functions were more linear and included more short IRTs), suggesting that genetic differences may modulate the two-state nature of responding. Addition of a running wheel, however, decreased overall rate of the target response for both strains. Inspection of survivor functions
indicated a reduction in the average number of responses per bout and an increase in bout-initiation rate. That the presence of the running wheel altered bout-initiation rate is consistent with findings that reinforcement parameters (i.e., the presence of an alternative reinforcer) alter the propensity to engage in bouts (e.g., Shull et al., 2001). When free-feeding was implemented, decreases in overall response rates tended to be a function of a decrease in bout-initiation rates in both strains. These results are also consistent with previous research showing that deprivation produces its effects primarily by altering bout-initiation rates (e.g., Shull, 2004). Thus, though genetic differences produced differences in the underlying structure of behavior as evidenced by differences in survivor functions, manipulations shown to produce predictable changes in the structure of responding also were observed consistently across strains. Subsequent studies also have shown broken-stick functions in mice lever pressing, further indicating that responding in mice can be characterized with a bout analysis (Johnson, Bailey, & Newland, 2011).

**Hamsters.** Recently, Cabrera, Sanabria, Jimenez, and Covarrubias (2013) evaluated bout responding in both hamsters and rats. Specifically, they assessed the effects of altering lever height on operant level (non-conditioned) behavior in rats and hamsters and plotted survivor functions of operant-level responding under the assumption that exploratory behavior should be organized into bouts similar to other forms of operant responding. Survivor functions showed clear bent-sticks which could be described by a double exponential. That operant-level responding in rats, mice, and hamsters could be described as two-state in nature suggests that perhaps a two-state conceptualization of responding may be general to all species.
**Pigeons.** To address the generalizability of the bout analysis conducted with rats, Podlesnik, Jimenez-Gomez, Ward, and Shahan (2006) investigated the effects of altering unsigned delays to reinforcement on pigeons’ keypecking for grain on a three-component multiple-schedule of reinforcement. Components were composed of a VI 60 s, and two VI + tandem FT schedules of reinforcement (VI 59.5 s + FT 0.5 s and VI 57 + FT 3 s), all providing equal rates of reinforcement. Podlesnik et al. noted that unsigned delays to reinforcement have previously been shown to produce decreases in response rate as well as less resistance to change in behavioral momentum studies (Grace, Schwendiman, & Nevin, 1998). Under these schedules, survivor functions of pigeon keypecking showed some evidence of a broken-stick patterning, but Podlesnik et al. were unable to fit double-exponential functions to these data because of the lack of IRTs below 0.2 s. This lack of IRTs below 0.2 s produced a plateau (i.e., functions which extended out from the y-axis at 1.0 without any initial drop). That is, there seemed to be some lower-limit to the IRTs that individual pigeons could emit. Because a clear bi-modal distribution was not observed, it was impossible to adequately fit these functions with a double-exponential. Instead, Podlesnik et al. relied on the subjective IRT-cutoff method of separating responding into two component parts, described above. Several cutoff criteria were selected (0.5 s, 1.0 s, and 1.5 s); all of which produced similar results. Data obtained via the IRT-cutoff method confirmed results of previous studies (e.g., Shull et al., 2001; 2004; Shull & Grimes, 2003). That is, changes in delay to reinforcement (e.g., reinforcer manipulations) produced changes in overall response rate primarily by altering the rate of bout-initiations.
A study by Bennett et al. (2007), however, raised questions about the utility of the bout analysis for characterizing responding in pigeons. In the Bennett et al. study, four White Carneau pigeons responded on a simple multiple random-interval (RI) 1-min RI 4-min schedule of food reinforcement. Following stable responding, survivor functions were plotted, revealing no clear broken-stick function. As in the Podlesnik et al. (2006) study, a plateau occurred in the function in which relatively few IRTs shorter than approximately 0.2 s were observed. Again, this plateau in responding suggests that pigeons were incapable of emitting responses below a certain IRT. Additionally, although small breaks were evident in some of the survivor functions for pigeons, which suggests that responding was clustered around specific IRTs, the process was not two-state in nature. Rather, survivor functions were better described as having several small break points, each followed by steep slopes, possibly suggesting a process that contained at least three states. Similar results (multiple break points) were observed by Bowers et al. (2008) when they assessed pigeon responding for mixed grain under different schedules of reinforcement than those used by Shull et al. (2001, 2003, 2004): a VI-plus linear feedback schedule as well as yoked VI and VR schedules of reinforcement.

The same multiple-break patterns were also observed by Davison (2004), who constructed survivor functions by graphing IRT distributions of pigeon keypecking from several data sets. These functions showed similar patterns (i.e., multiple break points) to those observed by Bennett et al. (2007). Davison suggested that this multiple break patterning may be a result of a three (or more) -state process occurring within pigeon responding. Davison noted that it was unlikely that pigeon disengagements were all uniform in length, and therefore a single inflection point was improbable. This
interpretation seems implausible, however. Shull et al. (2001, 2004) have shown that multiple breaks are not observed in rats; yet, it is equally likely that rat disengagements would be of varying length. More likely, these multiple breaks may be a function of pigeons’ keypeck IRTs being characterized by IRTs occurring at multiples (i.e., harmonics) of the lowest IRT value (e.g., Bennett et al., 2007; Blough, 1963; Bowers et al., 2008; Weiss & Gott, 1972). If this were the case, pigeon keypecking would be represented on a survivor function by multiple break points: (1) an initial drop, indicative of a distribution of keypecking; and (2) subsequent drops, each indicative of distributions of harmonic pecks, or a keypeck that occurs as a result of a previously missed keypeck. The last portion of these survivor functions, which would consist of the other randomly scattered IRTs on dot plots (e.g., Blough) may, then, be considered disengagement IRTs or indicative of bout-initiation rates.

Bennett et al. (2007) suggested several reasons why a bout analysis failed to generalize to pigeon keypecking. First, it was suggested that keypecking in pigeons may not be purely operant in nature. That is, some keypecks may be elicited, or respondent in nature. If this is the case, then a two-state model of operant responding may be incapable of separating pigeon keypecking into its component parts. This claim that pigeon keypecking is under both operant and respondent control is supported by the autoshaping literature which has shown that response independent hopper presentations that follow the illumination of a key light, for example, produce reliable keypecking in pigeons (e.g., Brown & Jenkins, 1968). Additionally, pigeon keypecking has even been observed when key-light presentation precedes inaccessible grain (Zentall & Hogan, 1975), and when keypecking contingently prevented access to food (Williams & Williams, 1969). These
findings suggest that keypecking, which is typically considered operant in nature, may simultaneously be under respondent control. If this is the case, at least one of the breaks in these survivor functions may very well be a distinct distribution of IRTs, but this distribution may be entirely respondent in nature.

Bennett et al. (2007) also suggested that the programmed rates of reinforcement in their study were not low enough to reveal a two-mode distribution. Speaking to this point, they noted that response rate becomes less sensitive to changes in programmed reinforcement rate as it approaches the maximum rate at which an organism can physically emit. This relation was first described by Herrnstein (1970), who discovered that when response rate on a VI schedules was plotted as a function of reinforcement rate, the relation was well described by a hyperbolic equation which contained a parameter that provided an estimate of the asymptotic (maximum) response rate ($k$), and a parameter that provided an estimate of the rate of extraneous reinforcement ($R_o$).

Investigating the differences in the extraneous reinforcement available to rats and pigeons, Shull (2005) analyzed results from a number of studies which incorporated VI schedules and examined obtained values of $k$ and $R_o$ from each study (see Figure 9). The upper panel indicates estimates of $k$ from these studies. Of interest, however, is the lower panel, which clearly shows that rates of alternative reinforcement ($R_o$) in pigeon studies have been significantly lower than those obtained with rats.

Studies of pigeon responding have often failed to include rates of reinforcement that would have been below values of $R_o$ (see Shull, 2005). That is, in studies with pigeons reinforcement available for the target response was often much greater than that provided by the environment. Essentially, then, previous bout experiments with pigeons
(Bennett et al., 2007; Podlesnik et al., 2006; those reviewed by Shull, 2005) were likely conducted in environments that included extremely low rates of alternative reinforcement when compared to studies assessing the bout-like nature of responding in rats. It is unlikely, then, that pigeon responding could be classified as two-state in nature, as disengagements from keypecking behavior provide only small amounts of alternative reinforcement. The decreased likelihood that a pigeon may engage in alternative behavior does not explain the multiple breaks observed in survivor functions, but may speak generally to the inability of the analysis to extend to pigeon keypecking.

**Refractory model.** Recently, an extension of the Shull et al.’s (2001) model has been proposed that may be better able to account for some of the anomalies observed in data obtained from pigeons as well as a theoretical limitation to the model (Brackney et al., 2011). This model introduces a parameter that accounts for a refractory period after each response. This refractory period was added to Shull et al.’s model in order to account for the inability of an animal to respond immediately after a previous response had been made. That is, Shull and colleagues assumed that there is some minimal amount of time following a target response during which an animal is incapable of responding again, and that this minimal amount of time must be subtracted from each IRT in order to construct meaningful survivor functions. Figure 10 shows Shull et al.’s model with Brackney et al.’s refractory period added. As shown in the figure, once the organism emits a response, there is some period of time after which during which the organism cannot respond. This period of time is likely to be different for different animals. Schedule values, response topographies, experimental manipulations, etc., and must therefore be calculated accordingly. Brackney et al. amended the Shull and Grimes
(2003) double-exponential equation to include the refractory period:

\[ r(t) = (1 - p)e^{w(t-\delta)} + pe^{b(t-\delta)} \]  

such that all parameters are the same as those listed in Equation 1, with the addition of \( \delta \), the refractory period (functionally, the shortest IRT), measured in seconds. Note that setting the refractory period equal to 0 reduces the equation to Equation 2. Removing the refractory period from each individual IRT produces survivor functions with shorter plateaus (produced by infrequent short (< 0.2 s) IRTs), therefore providing a better fit for the double-exponential function. Because the refractory model initially subtracts an estimate of the time in which the organism cannot respond, parameter estimates of \( b \) and \( w \) from the double-exponential functions must to be recalculated after the model is fit to include the previously subtracted time back into parameter estimates. In order to recalculate these parameters, the reciprocal (of \( b \) and \( w \)) is obtained. This reciprocal

provides an estimate of the average within-bout or bout-initiation IRT. The refractory (minimal) IRT is then added back into this estimate and the reciprocal of this resulting value is used to obtain the within-bout or bout-initiation rate. Interestingly, Brackney et al. also showed in this study that increasing the force required to emit a response altered the shortest emittable IRT (or the refractory period), suggesting a change in within-bout rate, while also producing a decline in bout-initiation rate.

Although no study has yet specifically analyzed the extent to which human operant responding can be characterized as pause-bout in nature, the idea that human behavior can be temporally segmented is not new. Gerstner and Cianfrani (1998) observed and recorded human chewing behavior in a naturalistic setting. A computer recorded interresponse times and an IRT-cutoff method (1.5 s) was used to dichotomize behavior into chewing (IRT < 1.5 s) and pausing (IRT > 1.5 s). Gerstner and Cianfrani determined that chewing was organized into a bout-like pattern. That is, chewing occurred in bouts (or multiple chews with pauses in between). Although a survivor analysis was not used to separate bouts from pauses, it is nonetheless interesting that human behavior, too, could be described as occurring in a bout-like manner. A limitation to this study, however, was that the IRT-cutoff method was arbitrary. To better assess responding, a more objective means of defining bouts and pauses of human behavior should be utilized.

To summarize, though the survivor analysis showed generality across response topographies in rats (e.g., Shull et al., 2001, 2004; Shull & Grimes, 2003), some instances of pigeon keypecking (Podlesnik et al., 2006), mouse lever pressing (Johnson et al., 2009, 2011), and hamster lever pressing (Cabrera et al., 2013), the failure of this analysis to
extend to pigeon keypecking (Bennett et al., 2007; Bowers et al., 2008), and the lack of systematic data with humans calls into question the generality of the analysis and the fundamental assumption that behavior is pause-bout in nature. Therefore, further research is needed to better explore the generality of this analysis by examining responding in different species, and examining behavior in rats and pigeons using different response topographies and reinforcers.

**Survivor Functions: Utility in Elucidating Behavioral Mechanisms of Drug Action**

Similar to the arguments presented above for the analysis of operant behavior, some behavioral pharmacologists have argued that a complete characterization of drug effects cannot be attained until we know not only what drugs do to behavior, but also why they have their observed effects (see Branch, 1984). Indeed, it is possible, and likely, given that behavior is multiply determined, that two drugs may produce similar effects on overall response rate, but do so via different mechanisms of action. For example, Drug A may produce decreases in rates of responding by rendering the organism less-capable of emitting the target behavior, whereas Drug B may produce similar decreases in rates of responding by altering the efficacy of programmed reinforcement. Determining why drugs have a specific effect requires an analysis of the behavioral mechanisms of drug action and analyses conducted at a level more detailed than that of response rate.

**Quantitative models and behavioral mechanisms of drug action.**

Because identifying the behavioral mechanisms of drug action can be a difficult and lengthy process, researchers have turned to behavioral models to help identify specific drug-environment relations. A model that has been frequently used to analyze behavioral
mechanisms of drug action is Herrnstein’s (1961) matching law. The matching law is a quantitative model that predicts the relationship between rate of response and rate of reinforcement and has proven a successful descriptor of choice in wild pigeons (Baum, 1974), wheel running in rats (Belke & Heyman, 1994), choice between cocaine and food (Anderson, Valkey, & Woolverton, 2002), as well as animal behavior in a number of other situations. Extension of the matching law to human problem behavior (Borrero & Vollmer, 2002), academic engagement (Martens, Lochner, & Kelly, 1992), basketball shot-taking (Romanowich, Bourret, & Vollmer, 2007; Vollmer & Bourret, 2000) and football play-calling behavior (Reed, Critchfield, & Martens, 2006) has been equally successful.

Plotting the rate of responding as a function of the rate of available reinforcement provides a hyperbolic function and estimates of asymptotic responding ($k$) and alternative reinforcement ($R_o$) (Herrnstein, 1970). Parameter estimates obtained from fitting equations to response rate data have shown that changes in response rate that are produced by altering reinforcer properties (either programmed reinforcement or alternative reinforcement) are accompanied by changes in $R_o$ (Bradshaw, Szabadi, Ruddle, & Pears, 1983; Petry & Heyman, 1997), whereas changes in response rate that are produced by implementing more motoric manipulations (e.g., changes in the operant or the force required to emit the response) are accompanied by changes in $k$ (Bradshaw, Szabadi, & Ruddle, 1983; Heyman & Monaghan, 1987; McSweeney, 1978). The differential effects of these types of manipulations on matching-law parameters are comparable to those observed with survivor functions. That is, manipulating reinforcer properties typically alters the parameter $R_o$, or bout-initiation rate in survivor functions,
whereas altering force requirements typically alters the parameter $k$ or the refractory IRT/within-bout response rate in survivor functions.

**Matching law and behavioral mechanisms of drug action.** The matching law has served as the primary mathematical model used to elucidate behavioral mechanisms of drug action (e.g., Egli, Schaal, Thompson, & Cleary, 1992; Heyman, 1983, 1992; Heyman, Kinzie, & Seiden, 1986; Morley, Bradshaw, & Szabadi, 1985). Typically, responding on various interval schedules is measured before and after drug administration, and Equation 3 is fit to these response-rate functions. The parameter ($k$ or $R_o$) that changes from no-drug to drug conditions provides evidence as to how behavior is affected by the drug. For example, drugs which produce changes in response rate primarily by altering the parameter $k$ may have motoric effects on responding; that is, a reduction in response rate under the drug may occur because the organism is no longer physically able to respond at a high rate. On the other hand, a drug that produces a change in response rate primarily by altering the parameter $R_o$ may alter reinforcer efficacy; that is, a reduction in response rate may be occurring because the relative value of the programmed reinforcer is reduced by administration of the drug.

**Problems with Herrnstein’s matching analysis.** Although the matching law has provided a useful description of responding in a variety of contexts, researchers have questioned the independence of $k$ and $R_o$. For example, Dallery and Soto (2004) noted that manipulations to the value of reinforcers (those designed to alter only $R_o$) sometimes produce concomitant changes in $k$, and that motoric manipulations (those designed to alter only $k$) sometimes produce concomitant changes in $R_o$. Moreover, Dallery and Soto also cited studies in which manipulations thought to exclusively alter $k$
instead produce changes in only the parameter $R_o$ or vice versa. If $k$ and $R_o$ are not representative of independent aspects of reinforced responding, it is impossible to separate motoric effects of drugs from reinforcer-efficacy based mechanisms of action.

Another drawback of using matching-law analyses to assess behavioral mechanisms of drug action is that the analysis is time-consuming and labor intensive. In order to construct a hyperbola, a multiple schedule must be used (often comprised of five or more schedule values). With the behavior-analytic emphasis on steady-state behavior, simultaneously achieving stability on numerous components of a multiple schedule prior to drug administration can prove a difficult task. Once steady-state responding is attained, the effects of the drug on responding must be measured under each component of the entire multiple schedule and multiple determinations of each dose of the drug are typically required. Furthermore, the extent to which behavior can be reliably brought under stimulus control of five component stimuli may be questioned. Given these limitations of a matching-law analysis, it is important to develop other quantitative methods for elucidating behavioral mechanisms of drug action.

**Bout analysis and behavioral pharmacology.** As described above, Shull et al. (2001) showed that different environmental variables produce distinct changes to the two limbs of the log-survivor function. That the bout analysis, like the matching law, can identify distinct effects of environmental manipulations on behavior also suggests that survivor functions may prove useful in classifying drug effects. Manipulations that affect motor functioning, for example, may produce unique changes to the initial limb of the survivor function (e.g., by altering the shortest emittable IRT), whereas manipulations that alter reinforcer efficacy may produce changes unique to the secondary limb of the
survivor function. As mentioned, the matching law parameters may not be entirely independent. Additionally, the amount of time to obtain steady-state responding on a 5-component multiple schedule warrants investigation into the possible utility of the bout analysis in elucidating behavioral mechanisms of drug action and provides an additional rationale for investigating the generality of the bout approach.

**Purpose**

Previous research has examined the extent to which a two-state conceptualization of responding, first studied with rat nose-poking, can be generalized to other operant responses (Shull & Grimes, 2003), operant-level (non-reinforced) responding (Cabrera et al., 2013), species (Bennett et al., 2007; Bowers et al., 2008; Cabrera et al.), and other reinforcers (Brackney et al., 2011). However, no study has yet to assess whether rat lever pressing for liquid reinforcers (such as milk) or human responding can be described as two-state in nature. Thus, the present research was conducted to accomplish three goals. The first goal, addressed in Experiment 1, was to assess the extent to which lever pressing in rats can be described as a two-state process when a different type of reinforcer is used, i.e., sweetened milk instead of food or sucrose pellets. Sweetened milk was chosen as a reinforcer, as this reinforcer was used in Heyman’s (1983) seminal work analyzing behavioral mechanisms of drug action with the matching law. Responding was investigated across several manipulations that have previously been shown to affect only specific portions of log-survivor functions. Lever pressing in eight rats was reinforced with sweetened milk under a multiple RI 15 s RI 60 s schedule of reinforcement (Condition 1) and a multiple RI 15 s RI 60 s schedule with addition of a tandem (RR 3) requirement added to each schedule (Condition 2). Changes in schedule values typically
produce changes in the slope of the secondary limb, and the addition of a tandem requirement has been shown to produce changes in the steepness of the initial limb (e.g., Brackney et al., 2011; Shull et al., 2001, 2004; Shull & Grimes, 2003). Because response rates were not well maintained under these conditions and survivor analysis necessitated the collapsing of IRTs across several sessions, however, under the last condition rats were exposed to a single, intermediate RI (RI 30 s) schedule (Condition 3).

The second goal, addressed in Experiment 2, was to evaluate the generality by investigating whether human responding could be characterized as two-state in nature. Again, schedule manipulations which have shown to differentially affect specific bout components were manipulated in order to assess the extent to which changes in schedule value produced changes which are congruent with those observed in previous studies. Specifically, 16 adult human participants responded under a multiple RI 60 s, RI 120 s, RI 240 s schedule of reinforcement for hypothetical monetary reinforcers.

A third goal of this research, addressed in both Experiments 1 and 2, was to determine whether survivor functions could be generated that could serve as good baselines for administering drugs. Survivor functions useful for evaluating the behavioral mechanisms of drug action would need to be consistent across sessions, and show clear broken- or bent-stick patterns. Although clear and reliable survivor functions have been obtained with rats nose-poking or lever pressing for food pellets, none have been obtained with rats responding for milk deliveries (as investigated by Heyman, 1983), and none have been obtained with humans.
EXPERIMENT 1

Method

Subjects and Apparatus

Subjects were eight experimentally naïve male Sprague-Dawley rats, each identified by number and each with no pharmacological experience. At the start of the experiment, rats were approximately 10-months-old. Rats were housed individually in a colony room. Colony room lights operated on a reversed 12:12 hour light/dark cycle with all experimental sessions occurring at the same time each day. Rats were maintained at approximately 80% free-feeding weight via post-session feeding. Water was freely available in each of the rat’s home cages.

Eight identical MED Associates® (St. Albans, VT) experimental chambers were used. Each of these chambers measured 28 cm long, 21 cm wide, and 21 cm high. Two response levers were mounted 7 cm above the floor of the chamber, each below a stimulus light that could be illuminated white. Only the left lever was used in the study. A 7-W house light was mounted on the back wall of the chamber. A white-noise machine (WNG-100, Mystic Marvels LLC) hooked to a stereo was placed in the experimental room to mask extraneous noise. Each chamber was connected to a laptop computer. MED-Associates® software was used for programming experimental events and data collection.
Behavioral Procedure

Each rat was adapted to an individual chamber by placing the rat in a darkened chamber for 1 hr. During experimental sessions, the house light and lever light were illuminated. Rats were trained to lever press for sweetened milk via shaping by successive approximation. The sweetened milk was mixed by combining three parts water, one part instant nonfat dry milk mix (Spartan®), and one tablespoon of sugar per quart (Heyman, 1983). Next, rats were exposed to three experimental conditions. Condition 1 (Mult) consisted of a multiple random-interval (RI) reinforcement schedule. Each component of the multiple schedule was associated with a unique stimulus (i.e., either blinking or steady lever light), which was counter-balanced across rats. The blinking light was programmed to flash on and off every 0.5 s. Rats were first exposed to a multiple RI 1-s RI 1-s schedule and then the RI schedules were gradually increased. The schedules were programmed by sampling a probability gate (e.g., 0.17 for an RI 1 min) once per second. Initially, attempts were made to maintain responding on an RI 60-s RI 240-s multiple schedule to be consistent with prior studies investigating log-survivor functions of rat lever pressing (e.g., Shull et al., 2003). However, because response rates decreased to low levels when increasing RI schedule values, the terminal schedule was a multiple RI 15-s RI 60-s schedule. The first component during each session was randomly selected. After this, components alternated and each was presented twice per session. Each component of the multiple schedule was in effect for 300 s and a 50 s blackout period, in which all chamber lights were darkened, operated between components. Responding during this period had no programmed consequence and was not recorded.
During Condition 2 (Tand), rats were exposed to tandem (tand) schedules. Tandem schedules were programmed so that rats were required to complete a random-ratio (RR) 3 schedule following the completion of each RI schedule. Subjects S6 and S10 did not meet stability criteria in Condition 1 (Mult), and were, therefore, not exposed to the tandem schedule. Response rates for S3 decreased over time during this condition, and S8 often showed little to no responding during the second presentation of each component during this condition. Therefore, the stability criteria (see below) were not reached for these subjects. The data for these two subjects during the tandem schedules, however, are still presented.

Because response rates were relatively low in the RI 60-s schedule and because clear, broken-stick survivor functions were not obtained in the RI 15-s schedules in Conditions 1 and 2, in Condition 3 (Single RI), all rats were exposed to a single RI 30-s schedule. The stimulus associated with reinforcement in this condition was either a blinking or steady lever light, whichever had been previously associated with the richer schedule of reinforcement for each rat on the multiple schedule. For this condition, components lasted for 120 s each and were presented five times per session.

**Stability Criteria**

Each condition lasted for a minimum of 20 sessions and until responding was stable. Similar to Shull et al. (2001), responding was considered stable when rates of responding in each component show minimal variability and no trend across 5 sessions. Table 1 shows the sequence and number of sessions per condition for each rat.
Table 1

Sequence and Number of Sessions per Condition (in Parentheses) for Each Rat

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mult</td>
<td>(39),</td>
<td>(39),</td>
<td>(39),</td>
<td>(71),</td>
<td>(92),</td>
<td>(65),</td>
<td>(39),</td>
<td>(97),</td>
</tr>
<tr>
<td>Tand</td>
<td>(74),</td>
<td>(65),</td>
<td>(25),</td>
<td>(20),</td>
<td>(33),</td>
<td>(27),</td>
<td>(13),</td>
<td>(24)</td>
</tr>
<tr>
<td>Single</td>
<td>(20),</td>
<td>(24),</td>
<td>(28),</td>
<td>(50),</td>
<td>(39),</td>
<td>(44),</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(33)</td>
<td>(32)</td>
</tr>
</tbody>
</table>

Note. Mult = Multiple schedule (RI 15 s RI 60 s); Tand = Tandem schedule (RI 15 s RI 60 s + RR 3); Single = Single RI schedule (RI 30 s).

Data Analysis

Overall response rates were calculated in order to assess progression through training schedules, and to assess stability during the multiple, tandem, and single schedules. Individual responses were also time-stamped from response onset. These data were used to construct log-survivor functions. For the log-survivor functions, the IRTs were organized into 0.1 s bins, omitting the first response following reinforcement and component changes. Similar to Shull et al. (2001), the proportion of IRTs longer than each bin size (on a logarithmic scale) were then plotted as a function of bin size up to 20 s and all IRTs longer than 20 s were included in the final bin. Survivor functions were
constructed for the final session, and the final 3 stable sessions of each condition (see below).

Double-exponential functions were fit to the data. Fits were obtained with the regression wizard in SigmaPlot© 12.3. As described above, curves were fit using a double-exponential fit with four parameters and reciprocal-y weighting. Shull and Grimes (2003) found that parameters were similar without this weighting, but that the weighting often improved the fits. As an added constraint, \( p + (1 - p) \) was set equal to 1, such that all responses were classified as either within-bout or bout-initiation responses. This regression wizard determined through an iterative process the parameters that minimized the sum of the squared deviations from obtained data. Double exponential fits eliminate the need for subjective selection of a break point and a linear segment of the secondary limb, as these fits utilize the entire range of recorded IRTs. To assess goodness of fit, \( r^2 \) and \( SS \) residual values were obtained for all survivor functions.

**Results**

**Terminal Schedules**

**Overall response rates.** Average response rates from the last 3 sessions of the terminal schedules are presented in Figure 11. All rats exhibited schedule control in that response rates were consistently higher during the RI 15-s schedule than the RI 60-s schedule. Overall, response rates varied between 12.7 and 48.1 responses per min on the RI 15-s schedule, and from 2.7 and 20.9 responses per min on the RI 60-s schedule.
Figure 11. Response rates (in responses per minute) for all rats during the multiple RI 15-s RI 60-s schedule. Response rates during RI 15-s schedules are represented by black bars and response rates during RI 60-s schedules are represented by grey bars. Error bars show standard deviations.

Table 2 shows the response rates in responses per minute for all rats during each component for all conditions. Response rates tended to show marked decreases within the session from the first to second presentation of the components. Inclusion of IRTs from both components, however, did not alter interpretation of the data, and therefore all IRTs collected during the session were included in the analysis.
Table 2

Response Rates (in Responses per Minute) for all Rats During Each Component for all Conditions (Mult Condition, Tand Condition, and Single RI 30-s Schedule)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Schedule</th>
<th>Responses per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Multiple</td>
</tr>
<tr>
<td>S1</td>
<td>RI 15 s</td>
<td>27.6</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>6.1</td>
</tr>
<tr>
<td>S2</td>
<td>RI 15 s</td>
<td>30.0</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>12.1</td>
</tr>
<tr>
<td>S3</td>
<td>RI 15 s</td>
<td>31.78</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>10.14</td>
</tr>
<tr>
<td>S5</td>
<td>RI 15 s</td>
<td>42.0</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>20.9</td>
</tr>
<tr>
<td>S6</td>
<td>RI 15 s</td>
<td>21.6</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>6.9</td>
</tr>
<tr>
<td>S7</td>
<td>RI 15 s</td>
<td>48.1</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>9.8</td>
</tr>
<tr>
<td>S8</td>
<td>RI 15 s</td>
<td>18.7</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>6.3</td>
</tr>
<tr>
<td>S10</td>
<td>RI 15 s</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Survivor functions. Initially, as in prior research (Shull et al., 2001, 2004; Shull & Grimes, 2003), survivor functions were constructed for IRTs in each component during the last stable session, shown in Figure 12. Reference lines represent the best-fitting double-exponential function. As can be seen in Figure 12, many of the functions showed multiple breaks, similar to those observed in pigeon responding (see Bennett et al., 2007). Multiple breaks were most often observed during the RI 60-s component. For example, note the multiple breaks during the RI 60-s component for rat S3 at 2.5 s, 5 s,
and 7 s on the x-axis. A similar pattern is observable for rat S5 at approximately those same times.

It was speculated that the multiple break points may have been caused by the low response rate and resulting small sample size of IRTs obtained within individual sessions. With a small sample size, a few outlying IRTs could have a large influence on the shapes of survivor functions. R. Brackney (personal communication, May 27, 2013) recently reported cleaner (i.e., better visual fits by a double-exponential function) survivor plots when IRTs were collapsed across several sessions. Further justification for this method was provided by Clifton (2000), who collapsed IRTs across multiple subjects. Therefore, survivor functions also were analyzed by collapsing IRTs across the last three stable sessions of a condition, which eliminated the influence of outlying IRTs. Figure 13 shows survivor functions created by combining the last three sessions of each condition for all rats. Again, clear breaks in the functions were not reliably observed. However, for four of the eight rats (S3, S6, S8, and S10) survivor functions were bent-stick in nature in both the rich (RI 15-s) and lean (RI 60-s) components. When clear bent-stick functions were observed in both components, survivor functions did not typically bend at the same point during rich and lean components. The break occurred at a lower y-axis value during the RI 15-s schedule than during the RI 60-s schedule. In addition, the RI 60-s component functions tended to be show a shallower slope during what might be considered the initial limb, indicating a lower within-bout response rate. For the other four rats (S1, S2, S5, and S7), log survivor functions were bent-stick in nature during the RI 60-s schedule but were more linear during the RI 15-s schedule. Functions from all eight rats seemed to show a
greater slope during the secondary portion of the function in RI 15-s schedules than during RI 60-s schedules, indicating a higher bout-initiation rate.

Table 3 shows $r^2$ and sum of square (SS) residual values from the double exponential equations that were fit to single-session and three-session survivor functions. Mean $r^2$ and SS residual values from curves fit to the single-session survivor functions were 0.98 and 0.40, respectively, whereas mean $r^2$ and SS residual values from curves fit to the three-session survivor functions were 0.99 and 0.21, respectively. Thus, although $r^2$ and SS values were similar across curves constructed from data from a single session and three sessions, these values were slightly larger or smaller, respectively, when data were collapsed across three sessions. Because plots from the three-session data were smoother, seemed to be fit better by double-exponential functions, and were accompanied by an increase in $r^2$ and decrease in SS, data were collapsed across three sessions for all subsequent conditions.

High $r^2$ values and low SS values were likely attributable to the nature of the log-survivor functions. Because survivor functions are constructed using cumulative data, the frequency of IRTs in each successive bin was constrained such that each bin, by definition, had to contain equal or fewer IRTs than the bin preceding it. With such a constraint, $r^2$ and SS values are likely to be high and low, respectively, and may provide little information about goodness of fit. That is, even when the function was not well-described by the double-exponential equation according to visual analysis, the constraints imposed on the data produced inflated $r^2$ values and low SS values. In fact, 75% of the $r^2$ values for the single-session data were above 0.98. Nonetheless, the SS values appeared
to vary in consistent ways with visual analysis of fits, and therefore may be useful in comparing fits across conditions.

Figure 12. Survivor functions of the last stable session of the Mult condition for all rats. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Solid and dashed lines indicate responding during RI 15 s and RI 60 s, respectively.
Figure 13. Survivor functions for all rats collapsed across the last 3 stable sessions of the Mult condition. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Solid and dashed lines indicate responding during RI 15 s and RI 60 s, respectively. Fitted functions represent the best-fitting double-exponential.
Table 3

Obtained Values of $r^2$ and Sum of Squared Residuals (SS) From Double Exponential Equations fit to Single-session and Three-session Survivor Functions

<table>
<thead>
<tr>
<th>Subject</th>
<th>Schedule</th>
<th>Single Session</th>
<th>Three Sessions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r^2$</td>
<td>SS</td>
<td>$r^2$</td>
</tr>
<tr>
<td>S1</td>
<td>RI 15 s</td>
<td>0.989</td>
<td>0.185</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.952</td>
<td>0.957</td>
</tr>
<tr>
<td>S2</td>
<td>RI 15 s</td>
<td>0.995</td>
<td>0.119</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.957</td>
<td>0.609</td>
</tr>
<tr>
<td>S3</td>
<td>RI 15 s</td>
<td>0.995</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.980</td>
<td>0.375</td>
</tr>
<tr>
<td>S5</td>
<td>RI 15 s</td>
<td>0.988</td>
<td>0.115</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.973</td>
<td>0.433</td>
</tr>
<tr>
<td>S6</td>
<td>RI 15 s</td>
<td>0.982</td>
<td>0.393</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.993</td>
<td>0.121</td>
</tr>
<tr>
<td>S7</td>
<td>RI 15 s</td>
<td>0.988</td>
<td>0.134</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.985</td>
<td>0.279</td>
</tr>
<tr>
<td>S8</td>
<td>RI 15 s</td>
<td>0.988</td>
<td>0.327</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.951</td>
<td>1.310</td>
</tr>
<tr>
<td>S10</td>
<td>RI 15 s</td>
<td>0.988</td>
<td>0.226</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.972</td>
<td>0.672</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>--------</strong></td>
<td><strong>0.980</strong></td>
<td><strong>0.395</strong></td>
</tr>
</tbody>
</table>

Note. Obtained values of $r^2$ and sum of squared residuals (SS) for all rats and components when survivor functions were constructed using single session data and when functions were constructed using data collapsed across three sessions for the Mult condition.

**Bout-estimate calculations.** Table 4 shows the parameter estimates for the double exponentials functions during all experimental conditions. The parameters $\lambda$-$\gamma$ and
provide estimates of the proportion and rate of within-bout responding (in responses per second), respectively. The parameters $p$ and $b$ provide estimates of the proportion of responses that are classified as bout-initiations and the rate of bout-initiations (in responses per second), respectively. For S1 and S2 during the RI 15-s component, within-bout and bout-initiation rates were the same. This occurred because the survivor functions were best described by a single exponential. As there is no way to determine whether these responses should be classified as within- or between-bout, comparisons between the RI 15-s and RI 60-s schedules for these two subjects were not made.

Figure 14 plots the parameter estimates (within-bout rate, bout-initiation rate, and average number of responses per bout) as a function of schedule of reinforcement for all rats, save S1 and S2 (see above). These plots show that for three of the six rats (S5, S6, and S7) differences in responding between the RI 15-s schedule and RI 60-s schedule were produced primarily by lower bout-initiation rates in the RI 60-s schedule. For S5 and S7, an increase in bout length was also observed. For the other three rats, schedule differences were primarily the result of shorter bout lengths in the RI 60-s schedule.

Tandem Schedules

Overall response rates. Average response rates for the last three sessions of the multiple-schedule with the added tandem schedule requirement are presented in Figure 15. For all six rats exposed to this condition, response rates were consistently higher during the RI 15-s schedule than the RI 60-s schedule.
<table>
<thead>
<tr>
<th>Subject</th>
<th>Schedule</th>
<th>Multiple</th>
<th>Tandem</th>
<th>Single RI 30 s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$l-p$</td>
<td>$w$</td>
<td>$l/p$</td>
</tr>
<tr>
<td>S1</td>
<td>RI 15 s</td>
<td>0.64*</td>
<td>0.57*</td>
<td>2.78*</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.93</td>
<td>0.42</td>
<td>14.29</td>
</tr>
<tr>
<td>S2</td>
<td>RI 15 s</td>
<td>0.63*</td>
<td>0.65*</td>
<td>2.70*</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.88</td>
<td>0.37</td>
<td>8.47</td>
</tr>
<tr>
<td>S3</td>
<td>RI 15 s</td>
<td>0.99</td>
<td>0.65</td>
<td>76.92</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.75</td>
<td>0.70</td>
<td>3.98</td>
</tr>
<tr>
<td>S5</td>
<td>RI 15 s</td>
<td>0.40</td>
<td>2.45</td>
<td>1.66</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.86</td>
<td>0.96</td>
<td>6.90</td>
</tr>
<tr>
<td>S6</td>
<td>RI 15 s</td>
<td>0.66</td>
<td>0.70</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.65</td>
<td>0.49</td>
<td>2.85</td>
</tr>
<tr>
<td>S7</td>
<td>RI 15 s</td>
<td>0.36</td>
<td>1.85</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.75</td>
<td>0.71</td>
<td>3.97</td>
</tr>
<tr>
<td>S8</td>
<td>RI 15 s</td>
<td>0.99</td>
<td>0.45</td>
<td>100.00</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.93</td>
<td>0.19</td>
<td>13.70</td>
</tr>
<tr>
<td>S10</td>
<td>RI 15 s</td>
<td>0.85</td>
<td>0.56</td>
<td>6.45</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.65</td>
<td>0.65</td>
<td>2.82</td>
</tr>
</tbody>
</table>

Note. Parameter $1 - p$ estimates the proportion of responses that are classified as within-bout responses; $w$ estimates rate of within-bout responding (in responses/s); $1/p$ estimates the average number of responses per bout; $b$ estimates rate of bout-initiations (in responses/s). Asterisks (*) indicate estimates in which within-bout and bout-initiation rate were identical (i.e., the function was best described by a single and not a double exponential).
**Response-rate effects of tandem schedules.** To better show the effects of the tandem schedule requirement on response rates, mean response rates on no-tandem schedules (shown in Figure 11) and tandem schedules (shown in Figure 15) for the RI 15-s (top panel) and RI 60-s (lower panel) schedule components are re-plotted in Figure 16. The effects on response rates of adding the tandem schedule requirement differed across rats. For two rats (S1 and S7), during the RI 15-s component, the addition of the tandem schedule produced increases in overall response rate. For the other four rats, addition of a tandem schedule produced decreases in overall response rate. During the RI 60-s component, addition of a tandem schedule produced decreases in response rates for all rats.

**Survivor functions.** Figure 17 shows survivor functions constructed for all rats during the last three stable sessions on tandem schedules. All characteristics of this figure are the same as Figure 12. Once again, clear breaks in the functions were not observed. However, survivor analyses did produce functions that were bent-stick in nature. For two rats (S5 and S7), survivor functions were nearly linear on the RI 15-s schedule, similar to that observed in the Mult condition. Data from S8 showed multiple breaks in the function in both the RI 15-s and RI 60-s schedule and thus functions could not be characterized as broken- or bent-stick in nature. For the other three rats (S1, S2, and S3), responding in both components typically produced survivor functions that were bent-stick in nature. For S1 and S2, survivor functions did not typically break at the same point during rich and lean components. Rather, functions tended to break earlier in the RI 60-s component than in the RI 15-s component, suggesting shorter bout lengths. Additionally, the slope of the
secondary limb tended to have a steeper slope during the RI 15-s component than during the RI 60-s component, suggesting higher rates of bout initiation.

*Figure 14.* Estimated within-bout and bout-initiation response rates (in responses per second; left y-axis) and average number of responses per bout (right y-axis) obtained from double-exponential fits for the RI 15-s and RI 60-s components of the Mult condition for all rats, save S1 and S2 (see text). Axes are individually scaled.
Bout-estimate calculations. Visual inspection suggested that all survivor functions, save RI 60 s for S5 and both RI 15 s and RI 60 s for S8, were fit well by the double exponential function. Table 5 provides quantitative values of goodness of fit ($r^2$ and SS residuals). The average $r^2$ value was 0.99 and the average SS value was 0.31. These $r^2$ values were slightly lower and SS values were slightly higher, respectively, than those obtained in Mult conditions. Figure 18 plots parameter estimates (within-bout rate, bout-initiation rate, and average number of responses per bout) as a function of RI component on tandem schedules. There were few consistencies across rats in terms of the parameters that best accounted for differences across schedules. For three of six rats (S1, S2, and S8), parameters indicated that the differences in responding between the RI 15 s

![Graph](image)

**Figure 15.** Response rates (in responses per minute) for all rats during the Tand condition. Rates of responding during RI 15 s schedules are represented by black bars and rates of responding during RI 60 s schedules are represented by grey bars. Error bars indicate standard deviations.
Figure 16. Response rates (in responses per minute) for all rats on the multiple (No-Tandem) and multiple plus tandem (Tandem) schedules. The upper panel represents rates of responding during RI 15-s schedules and the lower panel represents rates of responding during RI 60-s schedules. Error bars indicate standard deviations.
Figure 17. Survivor functions for all rats collapsed across the last 3 stable sessions of the Tand condition. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Solid and dashed lines indicate responding during RI 15 s and RI 60 s, respectively. Fitted functions represent the best-fitting double-exponential.
Table 5

Obtained Values of $r^2$ and Sum of Squared Residuals (SS) for all Rats and Components During the Tand and Single RI Conditions

<table>
<thead>
<tr>
<th>Subject</th>
<th>Schedule</th>
<th>Tandem Condition</th>
<th>Single RI 30 s Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$r^2$</td>
<td>SS</td>
</tr>
<tr>
<td>S1</td>
<td>RI 15 s</td>
<td>0.992</td>
<td>0.175</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.993</td>
<td>0.122</td>
</tr>
<tr>
<td>S2</td>
<td>RI 15 s</td>
<td>0.993</td>
<td>0.207</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.995</td>
<td>0.116</td>
</tr>
<tr>
<td>S3</td>
<td>RI 15 s</td>
<td>0.979</td>
<td>0.496</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.976</td>
<td>0.311</td>
</tr>
<tr>
<td>S5</td>
<td>RI 15 s</td>
<td>0.978</td>
<td>0.158</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.974</td>
<td>0.388</td>
</tr>
<tr>
<td>S6</td>
<td>RI 15 s</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>S7</td>
<td>RI 15 s</td>
<td>0.995</td>
<td>0.072</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.993</td>
<td>0.119</td>
</tr>
<tr>
<td>S8</td>
<td>RI 15 s</td>
<td>0.973</td>
<td>1.183</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>0.979</td>
<td>0.387</td>
</tr>
<tr>
<td>S10</td>
<td>RI 15 s</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>RI 60 s</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>--------</strong></td>
<td><strong>.985</strong></td>
<td><strong>.310</strong></td>
</tr>
</tbody>
</table>
Figure 18. Estimated within-bout and bout-initiation response rates (in responses per second; left y-axis) and average number of responses per bout (right y-axis) obtained from double-exponential fits for the RI 15-s and RI 60-s schedules during the Tand condition. Axes are individually scaled.
to RI 60 s schedules could be attributed primarily to differences in the average number of responses per bout, which was lower in the RI 60 s schedule for all three rats. Rat S2 also showed an increase in bout-initiation rate. For two rats (S5 and S7), differences across schedules could be attributed primarily to lower bout-initiation rates and longer bout lengths in the RI 60-s schedule. For rat S3, differences in responding across schedules could be attributed primarily to higher within-bout response rates.

**Effects of tandem schedules on survivor functions.** In Figures 19 and 20, survivor functions from Figure 13 (no tandem schedules) and Figure 17 (tandem schedules) are re-plotted to better compare the effects of the tandem schedule on survivor functions from the RI 15-s and RI 60-s components, respectively. Again, because parameter estimates could not accurately be obtained for rats S1 and S2, data from these two subjects were excluded from RI 15-s no-tandem vs. tandem comparisons. Figure 19 shows that the addition of a tandem schedule to the RI 15-s schedule did not produce a systematic change in survivor functions. That is, for rats S5 and S7 whose survivor functions were roughly linear, the tandem schedule produced a small leftward shift in the function indicating a relatively greater proportion of short IRTs. For S3, the tandem schedule produced changes in both the initial limb (i.e., within-bout responses) and the secondary limb (i.e., bout initiation responses). For S8, the addition of a tandem schedule requirement tended to produce a general upward shift across the entire survivor function, indicating of a greater proportion of longer IRTs.
Figure 19. Survivor functions from data collapsed across the last 3 stable sessions of the Mult and Tand RI 15-s components for all rats, save S1 and S2 (see text). Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Solid and dashed lines indicate responding during the no-tandem and tandem conditions, respectively. Fitted functions represent the best-fitting double-exponential.

Figure 20 shows that during the RI 60-s component the addition of a tandem schedule tended to produce steeper slopes in the initial limb of the survivor function, indicating a relatively greater proportion of short IRTs. Interestingly, the addition of a tandem requirement also tended to produce a decrease in the slope of the secondary limb, which eventually crossed over that of the no-tandem schedule. This crossover point is indicative of a greater proportion of longer IRTs. For some of these plots, the tandem function became almost horizontal in the secondary limb, indicating a relatively greater proportion of IRTs in the longest (20-s) bin.
Figure 20. Survivor functions from data collapsed across the last 3 stable sessions of the Mult and Tand RI 60-s components for all rats. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Solid and dashed lines indicate responding during the no-tandem and tandem conditions, respectively. Fitted functions represent the best-fitting double-exponential.
Figure 21. Estimated within-bout and bout-initiation rates (in responses per second; left $y$-axis) and the average number of responses per bout (right $y$-axis) obtained from double-exponential fits for the RI 15 s no-tandem (Mult) and tandem (Tand) schedule for all rats, save S1 and S2 (see text). Axes are individually scaled.

**Effects of tandem schedules on bout-estimate calculations.** Figure 21 shows a comparison of parameter estimates (within-bout rate, bout-initiation rate, and average number of responses per bout) from the double-exponential equations fit to survivor functions in no-tandem and tandem schedules in the RI 15-s component. Again, S1 and S2 were excluded from this analysis (see above). For most rats, the changes in responding observed across no-tandem and tandem schedules could be accounted for changes in several response-bout parameters. All subjects, save S7, showed changes in bout length when the tandem schedule was added, although the changes were idiosyncratic. For rats S3 and S8, the tandem schedule decreased bout length, whereas for
S5 the tandem schedule increased bout length. For S7, the tandem schedule primarily produced changes by increasing the rate of within-bout responding.

Figure 22 shows a comparison of parameter estimates from the double-exponential functions on no-tandem and tandem schedules in the RI 60-s component. For all rats, the rate of within-bout responding increased when the tandem schedule was added. The addition of the tandem schedule requirement slightly decreased the rate of bout-initiations for S2 and S3. Bout length was either unchanged, or tended to show small non-systematic variation when tandem-schedule requirements were added.

**Single Schedules**

**Overall response rates.** Figure 23 shows response rates during the single RI 30-s schedule along with those from the Mult condition (re-plotted from Figure 11) for comparison. Across the final three sessions, average response rates varied between 10 and 20 responses per minute. For six of eight rats (S1, S2, S3, S6, S7, and S8), response rates were between those obtained on the RI 15-s and RI 60-s components of the multiple schedule. Response rates for S5 and S10 were lower than rates obtained on either component of the multiple schedule.

**Survivor functions.** Figure 24 shows survivor functions from the final 3 sessions of the single-schedule condition. For five of the eight rats (rats S1, S3, S5, S7, and S10) survivor functions were bent-stick in nature. One of these functions (rat S6) was nearly linear and two other functions (rats S2 and S8) showed multiple break points. Figure 25 shows the single RI 30-s-schedule survivor functions from Figure 24 along with the survivor functions from the multiple RI 15 s RI 60 s schedule from Figure 13 for
comparison. Typically, survivor functions constructed from the RI 30-s schedule fell between those from the RI 15-s and RI 60-s schedules. This was the case with all functions except those constructed for S3, S5, and S10 for which the slope of the RI 30-s function was slightly shallower than that for the RI 60-s function. For five of the eight rats, across increasing schedule values there were systematic changes in the slope of the secondary limb of the survivor function. That is, across increasing schedule value the slope of the secondary limb became shallower. For the other three rats, S3, S5, and S10, the secondary limb of the survivor function for the RI 15-s schedule showed the steepest slope, however, for S3 and S5 the RI 60-s showed a steeper slope than the RI 30-s, and for subject S10, slopes for the secondary limbs of the RI 30-s and RI 60-s functions were nearly identical.

**Bout-estimate calculations.** Visual inspection indicated that log survivor plots were well fit by the double-exponential function, save those for S1 and S8. Table 5 provides quantitative values of goodness of fit ($r^2$ and $SS$ residuals). The average $r^2$ value was 0.995 and the average $SS$ value was 0.077. These $r^2$ and $SS$ values differed little from those obtained in Mult and tandem schedules.

Figure 26 shows a comparison of parameter estimates (within-bout rate, bout-initiation rate, and average number of responses per bout, see Table 4) as a function of schedule requirement. Included in this figure are the parameter estimates from the RI 30-s schedule as well as those from the RI 15-s and RI 60-s schedules from the Mult condition (re-plotted from Figure 4). As described above, for rats S1 and S2, RI 15-s data are omitted. It is evident from these plots that differences across schedules could not be consistently attributed to changes in any one parameter value. For three of six rats (S5,
Figure 22. Estimated within-bout and bout-initiation rates (in responses per second; left y-axis) and the average number of responses per bout (right y-axis) obtained from double-exponential fits for the RI 60 s no-tandem (Mult) and tandem (Tand) schedules. Axes are individually scaled.
Figure 23. Response rates (in responses per minute) for rats during the Single RI (RI 30-s) condition, re-plotted with response rates from the Mult condition (from Figure 11). Error bars indicate standard deviations.

S6, and S7) in which schedule comparisons could be made between RI 15 s and RI 30 s, bout-initiation rates tended to decrease as schedule value increased. For the other three rats, bout length decreased as schedule values increased. Comparisons between RI 30 s and RI 60 s also showed unsystematic differences in the primary variable responsible for changes in responding when schedule values were increased: three (S1, S6, and S8) of eight rats showed a decrease in bout-initiation rate, whereas S2 showed an increase in bout-initiation rate and a decrease in bout length. S3 and S7 showed increases and decreases, respectively, in bout length when schedule values were increased.
Figure 24. Survivor functions for all rats in the Single RI 30 s condition. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Fitted functions represent the best-fitting double-exponential.
Figure 25. Survivor functions for all rats collapsed across the last three stable sessions for all schedule values in Experiment 1. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Solid, dotted, and dashed lines represent the RI 15 s, RI 30 s, and RI 60 s component, respectively. Fitted functions represent the best-fitting double-exponential.
Figure 26. Estimated within-bout and bout-initiation response rates (in responses per second; left y-axis) and average number of responses per bout (right y-axis) from double-exponential fits for all rats during the single RI 30-s schedule, and during the RI 15-s and RI 60-s components of the multiple schedule (replotted from Figure 4). Graphs for S1 and S2 show only data from RI 30 s and RI 60 s (see text). Axes are individually scaled.
Experiment 1 Discussion

The present study was designed to evaluate whether a bout analysis could be extended to rats’ lever pressing for milk reinforcers. Brackney et al. (2011) showed that rat lever pressing for sucrose reinforcers produced functions that were indicative of a two-state characterization of responding. It was, therefore, expected that rat lever pressing for milk reinforcers would produce similar results. Milk was chosen as a reinforcer because of its previous use in studies designed to elucidate the behavioral mechanisms of drug action (e.g., Heyman, 1983). Lever pressing for milk was investigated across several procedural manipulations that have been shown to systematically affect survivor functions in prior rat nose-poke and lever-press studies, including varying the schedule values (e.g., Brackney et al., 2011; Shull et al., 2001, 2004; Shull & Grimes, 2003), (RI 15 s, RI 30 s, and RI 60 s) and including a tandem (RR 3) schedule requirement (e.g., Brackney et al.; Shull et al., 2001, 2004; Shull & Grimes).

Overall, results only partially replicated prior research.

Multiple Schedules

In Condition 1, the multiple RI 15-s RI 60-s schedule, log survivor functions were first constructed from single session data, however, these functions often showed multiple breaks. These multiple breaks were believed to be a result of graphing relatively few IRTs. If IRT survivor functions are constructed with relatively few data points, outliers can have a large influence on the shape of the function. Therefore survivor functions were reconstructed using data from the last three sessions of each condition.
These survivor functions were more bent-stick in nature and showed fewer instances of multiple breaks.

It was expected that survivor functions would look similar to those obtained in earlier studies with rats (e.g., Brackney et al., 2011, 2012; Hill et al., 2012; Shull & Grimes, 2003), showing an initial decrease (steep slope) in the initial limb followed by a gradual shift to a shallower slope in the secondary limb of the function. Survivor functions often showed this pattern, and looked more similar to those produced by rat lever pressing for food pellets (e.g., Shull & Grimes) than those produced by rat nose poking (e.g., Shull et al., 2001) for pellet reinforcers. That is, they were more bent-then broken-stick. Shull and Grimes suggested that procedural differences may account for the differences in shapes between survivor functions produced by nose poking and lever pressing. That is, if more time is required to complete a lever press than a nose poke, than the shortest possible IRT would be longer for lever pressing than nose poking. As a result, the distribution of shortest IRTs would be shifted rightward, resulting in more overlap between the two underlying distributions. If this were the case, survivor function would show a more gradual shift between the initial and secondary limbs. That survivor functions were also bent stick in this study provides further evidence that differences in response topography between nose poking and lever pressing were responsible for the differences in the shapes of the survivor functions reported in prior research.

Previous studies have shown that increasing the schedule value affects survivor functions by decreasing the slope of the secondary limb, indicating a decrease in the bout-initiation rate (e.g., Brackney et al., 2011; Shull et al., 2001, 2002, 2004; Shull & Grimes, 2003). Thus, in this study it was expected the slope of the secondary limb would
be steeper in the RI 15-s component of the multiple schedule than in the RI 60-s component. It was also expected that bout-initiation rates would be higher in the RI 60-s schedule. As Figure 13 shows, the slopes of the survivor functions typically differed in the predicted direction across the two RI schedules, but the differences were not as robust as those observed in previous studies of rat lever pressing (e.g., Hill et al., 2012; Shull et al., 2004; Shull & Grimes). Furthermore, survivor functions for the RI 15-s schedule were nearly linear for several rats. At least one prior study (see Hill et al.) has also found near linear functions when RI 15-s schedules of reinforcement were used. Survivor functions may be linear in shape when response distributions are comprised of all one type of responding (either entirely within-bout or between-bout) or if rate of within-bout responding is not considerably greater than the rate of within-bout responding. This similarity in within- and between-bout rates produces underlying distributions that overlap considerably.

To better compare the effects of schedule value on response patterning, double-exponential equations were fit to log survivor functions to estimate bout parameters. Data from RI 15-s conditions showing linear survivor functions were omitted. Parameters of the double-exponential functions indicated that differences in responding between the RI 15 s and RI 60 s schedules for three of six rats could be attributed primarily to differences in bout-initiation rates, which were consistently lower under the RI 60-s schedules. These effects were consistent with the visual analyses of log-survivor functions. As mentioned above, however, these differences were not as robust as shown in prior studies, and differences were also observed in other parameters. That is, parameter
estimates for most rats also indicated unsystematic differences in both bout length and within-bout response rates as a function of schedule value.

That the parameter values obtained in Condition 1 (Mult) only partly replicate results of prior studies is likely the result of the unusual parameter estimates for the RI 15-s schedule. As previously described, for two of the rats (S1 and S2) parameter estimates for within- and between-bout response rate were the same, suggesting that the data were best fit by a single exponential. For several others (S3, S5, S7, and S8) parameter estimates suggested that there was considerable overlap between distributions, either because 99% of responding was considered within-bout (S3 and S8) responding, or because bout-initiation rates were higher than within-bout rates of responding (S5 and S7).

One possible reason for the near-linear survivor functions under the RI 15 s schedule is that the RI 15 s schedule provided such a rich rate of reinforcement that it generated few periods of disengagement. Prior research on the matching law has indicated that when the programmed reinforcement rate is high and sources of alternative reinforcement are low, organisms allocate nearly all of their responding towards the programmed reinforcement schedule (e.g., Herrnstein, 1961). Thus, if a rat obtains a relatively low rate and/or small amount of reinforcement from alternative sources, it is unlikely to sample from those sources for extended periods of time and enter a long periods of between-bout responding. Manipulations that would affect the value of $R_o$ (reductions in rate of reinforcement, decreased deprivation levels, or shorter milk presentations) would be of interest in further studies, as these may produce longer disengagement times and produce more separation between the two distributions of
responding. Another manipulation that has been shown to increase the values of $R_o$ is to introduce some form of extraneous reinforcement into the chamber during an experimental session. Petry and Heyman (1997) studied rat responding on a number of VI schedules of varying rates and attempted to manipulate values of $R_o$ by introducing cardboard tubes into the chambers. These tubes effectively increased values of $R_o$ and left estimates of $k$ unchanged. These manipulations, all of which serve to increase the values of extraneous reinforcement, may cause rats under richer schedules to respond more in a bout like pattern – engaging in longer-lasting alternative behaviors and thus increasing the duration of between-bout intervals.

**Tandem Schedules**

Prior research has shown that adding a tandem schedule requirement to an interval reinforcement schedule increases rates of responding and does so primarily by increasing the bout length (e.g., Brackney et al., 2011; Shull et al., 2001, 2004; Shull & Grimes, 2003). Thus, in Condition 2 (Tand) it was expected that the tandem schedules would increase rates of responding by producing increases in bout length. In contrast with previous studies (e.g., Brackney et al.; Shull et al., 2001; Shull & Grimes), the addition of a tandem schedule requirement did not produce a lengthening of the initial limb of the survivor functions, which would be indicative of an increase in the average bout length. Rather, the tandem schedule produced unsystematic results on the RI 15-s component, primarily altering bout length in three of four subjects, but producing an increase in length in only one subject. In the RI 60-s component results were more consistent across subjects: Five of six rats primarily showed increases in within-bout response rates when
tandem manipulations were added, although these were, at times, accompanied by a decrease in the rate of bout initiations.

It is unclear why these results are inconsistent with previous studies investigating the effects of tandem schedules on survivor functions. Perhaps the most likely reason was that the tandem schedule requirement had the unexpected effect of decreasing response rates. Prior studies have shown that the addition of a tandem ratio schedule requirement produced a consistent increase in response rates (e.g., Brackney et al., 2011; Ferster & Skinner, 1957; Shull et al., 2001, 2004; Shull & Grimes, 2003), as this requirement increases the likelihood that reinforcement will follow shorter IRTs (Zeiler, 1977). However, only two of six rats in the present study showed clear increases in response rates under the RI 15 s schedule when tandem manipulations were added. Addition of a tandem manipulation for the other four rats produced a decrease in responding. Similarly, when tandem manipulations were added to the RI 60 s schedule, slight increases in response rate were observed for only one rat, while four others showed decreases in response rate and another showed no change.

It is unclear why response rates decreased when the tandem schedule requirement was added. It is likely, however, that given the low rates of responding obtained during this study (see below) that bursts of responses (e.g., multiple responses in quick succession) did not frequently occur and thus the tandem contingency was not quickly met. If this were the case, then the addition of a tandem schedule may have lowered rates of reinforcement. Indeed, for subjects exposed to the tandem condition, obtained reinforcement rates (reinforcers per minute, averaged across the last three sessions) were considerably lower during Condition 1 (Mult) (RI 15 s: $M = 3.68$, $SD = 0.40$; RI 60 s: $M$
= 0.81, $SD = 0.21$) than during Condition 2 (Tand) (RI 15 s: $M = 1.95, SD = 0.86$; RI 60 s: $M = 0.37, SD = 0.13$).

As in Condition 1 (Mult), patterns of responding also were compared across the Tandem RI 15-s RR 3 component and the tandem RI 60-s RR 3 component. Again, it was expected that the secondary limb of the survivor function show a decreased slope under the RI 60s schedule than the RI 15-s schedule, indicating a decrease in bout-initiation rate (e.g., Brackney et al., 2011; Shull et al., 2001, 2002, 2004; Shull & Grimes, 2003). Although survivor functions were often bent-stick in nature, differences in survivor functions across the two components were not systematic, and many functions under the Tand RI 15-s RR 3 schedule were, again, nearly-linear in nature, complicating comparisons. Consistent with visual analysis, across components the differences in parameter estimates from fits of the double-exponential equations were somewhat idiosyncratic. Parameter estimates revealed that for only two rats (S5 and S7), a decrease in bout-initiation rate was the primary variable responsible for changes in responding when schedule values were decreased. For all other rats, differences in survivor functions between the two components were primarily attributable to differences in the bout length (decreases in three subjects) and within-bout response rate (an increase in one subject). These results differed from those observed in the Mult condition during which differences in survivor functions were primarily due to differences in bout-initiation rate and are in contrast with those observed in previous studies which have manipulated reinforcer properties (e.g., Brackney et al.; Shull et al., 2001, 2002, 2004; Shull & Grimes). One likely reason for the discrepancies observed here was again the unusual
parameter estimates from RI 15-s schedules, which tended to show nearly linear survivor functions.

**Single Schedules**

Because survivor functions were nearly linear during the RI 15-s component and rates were low during the RI 60-s component in Condition 1 (mult), rats were exposed to a third condition consisting of a single RI schedule, the value of which was intermediate between the two multiple schedule components. This condition was conducted in order to produce responding that was bent-stick in nature while obtaining a larger sample size of IRTs than that produced by the RI 60-s schedule. Overall, response rates were between those produced by the RI 15 s schedule and RI 30-s schedule. The survivor functions from the RI 30 s schedule of reinforcement were generally bent- or broken-stick in nature and the secondary limb of these functions was usually less steep than that observed in the RI 15-s component, but steeper than that observed in the RI 60-s component.

When response-bout parameters were compared across the RI 15 s schedule from Condition 1 (Mult) and the RI 30 s schedule, the differences were inconsistent with previous studies (e.g., Hill et al., 2012; Shull et al., 2004; Shull & Grimes, 2003). That is, the RI 30-s schedule produced lower bout-initiation rates in only three of six subjects and bout length was a major contributor to changes in responding. When response-bout parameters were compared across the RI 30-s schedule and the RI 60 s schedule from Condition 1 (Mult), the same type of pattern was observed. Only four of eight subjects showed decreases in bout-initiation rates and bout length, again, changed significantly across schedule values.
Response Rates Across Conditions

Although lever pressing showed sensitivity to the reinforcement schedule, in that response rates were higher in the RI 15-s schedule than those observed in the RI 60-s schedule, one of the limitations observed across all conditions in Experiment1 was the difficulty in maintaining responding under the RI 60-s schedule despite the fact that the schedule was lower than those used in prior studies (e.g., Heyman, 1983; Shull et al., 2001). Shull et al. maintained lever pressing during a 70-min session on a multiple VI 60-s VI 120-s schedule for pellet reinforcement, and Heyman maintained lever pressing throughout a 75-min session on a five-component multiple schedule for the same milk reinforcer provided here. As mentioned previously, the initial intent was to investigate responding on an RI 1 min RI 4 min schedule as used by Shull et al. in their initial investigation of bout analysis. However, increasing the schedule value above 60 s decreased response rates to near-zero levels. That decreases across sessions were observed here is not in direct conflict with previous studies (see McSweeney, Hatfield, & Allen, 1990), but the near extinction of responding suggest that something about the procedural manipulations here prevented maintenance of responding. As described in the results, the low response rates necessitated collapsing across multiple sessions in order to obtain a sufficient number of IRTs to produce orderly survivor functions.

It is unclear why response rates obtained in this study were lower than those obtained in prior research and why rates decreased markedly across component presentations. One possible reason for the relative low response rates is that the rats quickly became satiated on the milk reinforcer. Some evidence for this comes from the fact that response rates decreased across components. Indeed, there were some instances
in which rats did not respond during the second presentation of components (most often during RI 60-s schedules), suggesting possible satiation. However, Heyman (1983) maintained responding for the same concentration of milk reinforcers (at a higher reinforcer magnitude: 0.1 cc) under a variety of schedules and obtained higher rates of responding than those observed here, even during a VI 80 s schedule. As further evidence against this “satiation” hypothesis, rats initially responded on an FR 1 schedule of milk reinforcement in the present study. Under this schedule of reinforcement, rats would often respond for approximately 100 reinforcers in a single, brief session, suggesting that the reinforcers obtained during the RI schedule components would not be enough to produce satiation. Regardless of the evidence against this hypothesis, it would be of interest to include a water bottle into the chamber. Previous research (Shull, 1996) has shown that rats with free access to water during sessions are more likely to maintain responding for food reinforcers across sessions when compared to rats without free access. The same may be true for rats responding for milk reinforcers.

Another possibility is that an aversion developed towards consuming large quantities of milk. Most mammals lose the ability to digest lactose soon after birth (see Scrimshaw & Murray, 1988), and ingesting milk can result in gastrointestinal (GI) distress. Previous research has shown that high levels of lactose ingestion can produce levels of GI distress and conditioned taste aversion (see DiBattista, 1990). The levels of milk consumption in the present study, however, were generally low and unlikely to produce such distress. Additionally, rats still continued to respond for milk reinforcers at the beginning of sessions and, on several occasions, were provided free access to milk following the session and still engaged in drinking behavior. It is unlikely that this pattern
of behavior would occur if rats were suffering from GI distress as a function of intolerance to lactose. Finally, the high rates of responding observed during RI 15-s components combined with the fact that rats were of equivalent age in this experiment and those conducted by Heyman (1983) argue that intolerance was unlikely.

It seems most likely that procedural differences between this and prior rat studies were responsible for the lower response rates maintained here. Rats in Heyman’s (1983) study were exposed to a five-component multiple schedule and this may have led to contrast effects (e.g., McSweeney & Norman, 1979; Reynolds, 1961) which assisted in maintenance of responding for milk reinforcers under leaner VI schedules of reinforcement. Indeed, McSweeney, Dougan, and Farmer (1986) found that the presence of richer or leaner components in multiple schedules produced either increases or decreases in overall rate of responding when compared to a same-valued simple schedule of reinforcement. Thus, because Heyman’s study included a leaner schedule of reinforcement (i.e., VI 160 s) alongside the schedule which was most comparable to that used here (i.e., VI 80 s), it is possible that this created some form of behavioral contrast that was partially responsible for the slightly higher rates and longer maintenance of responding he observed (rates were about six responses per minute higher in Heyman’s study and were maintained throughout a 75-min experimental session). Perhaps inclusion of a third component (e.g., an RI 160 s) in the present study would have engendered higher rates of responding under the RI 60 s schedule of reinforcement.

Another procedural difference between this study and the Heyman (1983) study was the force of the response lever. The force required to emit a lever press in Heyman’s study was 15 N, whereas the force required in the current study was 25 N. It is possible
that the higher force required to emit lever pressing here may have contributed to the lower rates of responding under the leaner reinforcement schedules.

Rats were food deprived in this study and it has been previously shown that food deprivation is not required to maintain responding for sweet reinforcers (e.g., sucrose pellets) or to produce survivor functions which are well described by a double exponential (see Brackney et al., 2011). It should be noted, however, that rats in Heyman’s (1983) study were also food deprived. As such, this does not seem to be the variable responsible for the difference in findings. Nonetheless, it would be of interest to assess whether water deprivation under the same experimental conditions might increase the efficacy of a liquid reinforcer (milk) and increase rates of responding.

Finally, difficulty in maintaining lever pressing for milk reinforcers may not be uncommon. E. Jacobs (personal communication, July 2, 2013) reported that to maintain responding for milk reinforcers across experimental sessions it was necessary to initially give rats an extensive history of responding under rich ratio schedules of reinforcement. The training procedures used here consisted of brief exposure to FR1 schedules and a fairly quick transition to rich RI schedules. Though rats were exposed to these rich RI schedules for an extended period of time, it is possible that the initial training period was not sufficient to engender continued responding.

Summary

In summary, log-survivor plots constructed from rat lever pressing for milk reinforcers were well described by a double-exponential function, but only under some conditions. Survivor functions seemed to be two-state in nature when the schedules of reinforcement in effect were RI 30 s and RI 60 s, but did not show evidence of a clear
broken- or bent-stick when RI 15-s schedules were in effect. This suggests that high-rate operant behavior (i.e., responding characterized primarily by short IRTs) is not described well by a survivor analysis. Shull et al. (2004) argued a similar point after failing to find broken-stick survivor functions under a RI 15-s schedule. Increasing the value of the reinforcement schedule tended to produce changes that were congruent with those observed in previous studies only in the multiple-schedule condition. That is, increases in schedule requirements only occasionally produced decreases in bout-initiation rate. Increases in schedule requirements across components the tandem- schedule condition did not show systematic changes in bout parameters. The addition of a tandem requirement did not produce expected increases in bout length. Rather, changes in responding were idiosyncratic across rats, especially during the RI 15-s component. The effects of the tandem manipulation were likely attributable to unreliable estimates during the RI 15-s component and the low rates of responding generated by the tandem manipulation during the RI 60-s component.
EXPERIMENT 2

Experiment 2 was conducted to assess the extent to which human operant responding can be described as bout-like in nature. Though previous studies have suggested that human behavior can be temporally segmented in a naturalistic setting via an IRT-cutoff method (e.g., Gerstner & Cianfrani, 1998), no study has utilized survivor functions to separate behavior into bouts in a human operant setting. Therefore, Experiment 2 sought to assess the extent to which responding for hypothetical monetary reinforcers can be described by a bout analysis.

The first group of participants pressed buttons in order to earn hypothetical monetary reinforcers. Responding was reinforced according to an RI 60 s RI 120 s RI 240 s multiple schedule. Response rates in these participants were high, however, and the survivor functions were nearly linear in nature across all components. This suggested that responding seemed to be comprised mostly of within-bout responding. Because of the high rates of responding and nearly linear survivor functions, a second group of participants were exposed to the same multiple schedule using what was considered to be a more effortful response (pressing a footswitch). Increases in response effort have been shown to decrease bout-initiation rates (e.g., Brackney et al., 2011). As such, it was expected that requiring participants to engage in a more effortful response may produce a more-pronounced secondary limb.
Method

Subjects

Approval of all procedures and materials was obtained from Western Michigan University’s Human Subjects Institutional Review Board (HSIRB). Participants were 16 adult human subjects (undergraduates) between the ages of 18 and 29 years with no previous behavioral research experience. Participants were recruited by advertisements requesting volunteers for a research study on decision making. Individuals were excluded from participation if they had previously taken any upper-level psychology courses, or if they reported current drug abuse or use of psychiatric medications.

During informed consent, participants were told that they could receive extra credit in their psychology classes for participating in the current study, depending on their class policies, and that the participant who earned the most hypothetical money (out of each group of five participants) during experimental sessions would receive a $50 prize. These prizes were awarded via random drawings, of which participants were informed. Participants were informed of whether they had won the prize at the conclusion of the experiment.

Apparatus

Experimental sessions were conducted in one of two cubicles located in a 3.5 x 2.1 m windowless room. Each cubicle measured 1.3 x 1.8 m, was separated by 2.1 m high walls, and contained a desk, computer monitor, swivel chair, and a 10.2 x 43.8 x 25.7 cm custom made response panel (see Pietras, Cherek, Lane, & Tcheremissine, 2006) with three buttons labeled A, B, and C (Button-pressing group), or a footswitch (StealthSwitch...
II programmable USB foot switch with an FS-4 Slave Switch; H-Mod Inc., Highland Park, IL; Footswitch-responding group). On the aluminum response panel, response buttons were mounted in a horizontal row. The force required to press buttons was 0.6 N. The footswitch was approximately 7.6 x 12.7 x 7.6 cm. Participants were instructed to press this switch with their foot only. Because the footswitch was beneath the table, however, it was impossible to assess if participants were emitting responses with the same foot throughout experimental sessions. The force required to press this footswitch was approximately 3.5 N. Also, in each cubicle was a white noise generator (Marsona model TSC-330) and headphones that each participant wore to help mask extraneous noise. A video camera was located above the apparatus to allow for real-time monitoring of each participant and to ensure compliance with the instruction to use their feet only when operating the footswitch. Sessions were controlled and monitored and data were recorded via computers located in another room using Microsoft Visual Basic® software.

**Procedure**

Eight participants were assigned to the Button-press group and eight were assigned to the Footswitch-responding group. Participants in both groups were first exposed to an initial training session in which they experienced a three-component multiple schedule. Each component was signaled by a different background color (blue, yellow, or purple) on the computer monitor. First, each component was programmed with the same random-interval (RI) schedule value (RI 10 s, RI 10 s, RI 10 s). Next, RI schedules were gradually increased across sessions (i.e., from RI 10 s to RI 30 s to RI 60 s) until responding during all components was maintained under RI 60 s schedules. During initial training, components were 90 s in length, were presented only once per
session, and were separated by a 30 s inter-trial interval (ITI) during which the computer screen was dark. Responding during the ITI had no programmed consequence and was not recorded.

Following this initial training, the schedule operating during one of these components was maintained at 60 s, while the others were increased to 120 s and 240 s. At these terminal schedule values, components during experimental sessions were 240 s in length and each component was experienced twice each in random order. A 30 s ITI operated between each component. Each participant was exposed to four experimental sessions and data from the last experimental session was used in the analysis.

A set of instructions were read to each participant prior to their first scheduled session of the experiment and was placed inside the chamber prior to each session. These read (instructions substituted for response panel-use are in parentheses):

You will be able to earn hypothetical money amounts by working at the computer (response console). You will not actually receive the money amounts, but remember, for every five people who participate, the person who earns the most hypothetical money will win a $50 bonus. (The response panel contains three buttons labeled A, B and C.) When the session starts, the letter B and a counter will appear on the computer screen. The counter will be at zero. Pushing the footswitch (B button) will cause the letter B to go off the screen and will cause other letters to appear. Pushing the footswitch (button corresponding to the letter on the screen) will add money to the counter. Please remain seated. When you see the words session over appear on the screen you may return to the waiting area.

Participants completed four 25.5-minute sessions within a single day. At the beginning of each session, a counter that showed session earnings (colored red) appeared at the top center of the computer screen. Each session began with the letter B on the screen. Each press to the letter B on the response panel (or a press of the footswitch) caused the font color of the letter to change from white to grey for 25 ms to provide feedback for
responding. Reinforcers consisted of the delivery of a hypothetical $0.25. When this reinforcer was available, a separate letter (i.e., either A or C) appeared on the screen and a corresponding button press was required as a consummatory response. During reinforcer-delivery periods, the font size of the earnings counter increased for 0.5 s, $0.25 was added to the counter, and then the font size of the counter returned to its normal size. At the start of each component the font color of the earnings counter was red, but once participants obtained hypothetical monetary reinforcement ($0.25), the color of the counter changed to green and remained green for the remainder of the component.

Participants were given a one-minute break between training sessions and a five-minute break between experimental sessions. Following completion of all sessions, participants were asked to complete several post-experimental questionnaires and were partially debriefed; they were told that the purpose of this study was to investigate how positive response outcomes influence behavior and whether the frequency of these outcomes influenced the pattern or frequency of their responding. These materials are provided in Appendix A.

**Data Analysis**

During experimental sessions, individual responses were time-stamped from response onset and organized into 0.2 s bins. The proportion of IRTs exceeding each bin size (on a logarithmic scale) was then plotted as a function of bin size. Many of the functions obtained via this method produced a plateau extending from the y-axis at 1.0, given that very few short IRTs were emitted. Thus, in order to obtain better fits of the double exponential function, the method used by Brackney et al. (2011), described above, was used to construct log-survivor functions prior to fitting the double exponential
functions to these data. Recall that with this method, the shortest IRT, which is viewed as a refractory period (i.e., a period during which responding is limited by the capability of the organism to respond immediately after a response), is removed from the analysis. Because the refractory model initially subtracts an estimate of the refractory period, parameter estimates of $b$ and $w$ from the double-exponential functions need to be recalculated after the model is fit to account for those missing values. In order to recalculate these parameters, the reciprocals of $b$ and $w$ were obtained to provide estimates of the mean within-bout and bout-initiation IRTs. The refractory (minimal) IRT was then added back into this estimate and the reciprocal was again calculated to provide an estimate of the within-bout and bout-initiation rates. Though the model can be fit to each survivor function using the refractory period as a free parameter, this would result in different refractory values for each schedule. Because the refractory period is theorized to be an estimate of the physical limitations of an organism, its value should remain constant. Thus, the proposed method was used as it yielded a single refractory value.

**Results**

**Button-press Group**

**Overall response rates.** Overall response rates for participants in the Button-press group are shown in Figure 27. Response rates are averaged from all exposures to components during the final experimental session. There was no systematic difference between response rates across the RI 60 s, RI 120 s, and RI 240 s schedules. Responses rates ranged from 9.6 to 194.4 responses per minute ($M = 105.13, SD = 59.00$) across all components.
**Figure 27.** Response rates (in responses per minute) for all participants during the multiple RI 60 s RI 120 s RI 240 s schedule. Response rates during RI 60 s schedules are represented by black bars, rates during RI 120 s schedules are represented by light grey bars, and rates during RI 240 s schedules are represented by dark grey bars.

**Survivor functions.** Figure 28 shows log-survivor functions for all participants from the final experimental session. In six of the eight participants (all but P-267 and P-312), there were few short IRTs (e.g., IRTs less than 0.2s), resulting in a horizontal line extending from 1.0 on the y-axis prior to the smallest IRT values which then produced an initial drop. This can most clearly be observed in data from P-264. This participant emitted very few IRTs shorter than 1 s, and therefore the log survivor functions produced an initial “plateau” (approximately 1 s in length). Because of these plateaus in responding, functions were reconstructed according to the method proposed by Brackney et al. (2011), described above. These modified functions are presented in Figure 29. As
Figure 28. Final session survivor functions for all participants in Button-press group. Log proportion of IRTs > t are plotted as a function of time (t - s: time in seconds). Closed circles represent the RI 60 s component, open circles represent the RI 120 s component, and closed triangles represent the RI 240 s component.
Figure 29. Log survivor functions for all human button pressing during the final completed session with the refractory period subtracted from IRTs. Log proportion of IRTs > t are plotted as a function of time (t - s: time in seconds). Closed circles represent RI 60 s, open circles represent RI 120 s, and closed triangles represent RI 240 s. Fitted functions represent the best-fitting double-exponential.
can be seen in these plots, for many participants, the initial plateaus are no longer present (e.g., those observed previously in P-262, P-263, P-265, and P-307). For others, the length of the plateau was shortened but it was not entirely eliminated (e.g., in P-264 and P-305). This occurred because, as described above, the shortest IRT observed during an experimental session was considered the refractory period. However, because the shortest obtained IRT was not the same across all multiple-schedule components, the removal of the lowest IRT did not necessarily eliminate the plateau across all three RI schedules.

As noted above, eliminating or reducing the influence of these plateaus generates better fits of the double-exponential to data. Therefore, functions were fit to the plots in Figure 29. The bends/breaks of functions occurred at very short values (~ ≤ 1 s) making it difficult to visually separate within and between bout response. Survivor plots of many participants extended over only a few seconds, indicating very rapid responding. Responding in only half of the participants (P-262, P-264, P, 267, P-312) produced survivor functions with IRTs longer than 2 s in duration. For two of these participants (P-262 and P-264) most IRTs were contained within 4 s.

In most participants, there were apparent differences in the slope of what might be considered the right-hand limb of survivor functions across the three RI schedules (P-262, P-264, P-265, P-267, P-305, P-307 and P-312), though richer schedules were not always associated with a steeper slope, as would be expected if lower schedule values generated higher bout initiation rates. In P-312, there was also an apparent difference in break point between RI 120-s and RI 240-s schedule values, suggesting longer bout lengths in the RI 240-s schedule. For P-263, there was no difference in survivor functions across the three RI schedule values.
**Bout estimate calculations.** Visual inspection of double-exponential fits suggested that for all participants but P-264, survivor functions tended to fit the data reasonably well. Table 6 provides quantitative values of goodness of fit ($r^2$ and $SS$ residuals). As Table 6 shows, $r^2$ values were high ($M = 0.975, SD = 0.023$) and $SS$ values were low ($M = 0.157, SD = 0.158$) across all participants, although, as mentioned in Experiment 1, these measures of goodness of fit data must be interpreted with caution (see above).

Table 7 provides parameter estimates for all double-exponential fits. Several instances occurred in which estimates of $w$ and $b$ were equivalent (i.e., all schedules for P-263 and P-264; and during RI 120 s and RI 240 s for P-305). The equivalence of these parameters suggests that responding was best described by a single exponential and therefore, could not be described as two-state in nature. For P-267, there were slight decreases in bout-initiation rate as schedule values increased. For two participants (P-262 and P-312), the primary difference across the RI schedules was the average number of responses per bout, with bout length increasing as a function of increasing schedule value in P-312, and RI 60-s and RI 240-s schedules producing the longest bout lengths for P-262. For five participants, there were differences across schedules in multiple parameters (e.g., bout-length and bout-initiation rate for P-307; within-bout and bout-initiation rate for P-265).

**Footswitch-responding Group**

**Overall response rates.** Overall response rates for participants exposed to the footswitch manipulandum are shown in Figure 30. Again, there were no systematic differences between response rates under the different RI schedule values. Responses
rates ranged from 77.63 to 289.88 responses per minute ($M = 185.09$, $SD = 64.10$ across all components), and were generally higher than those observed in the Button-press group.

Table 6

*Obtained Values of $r^2$ and Sum of Squared Residuals (SS) for all Human Button Pressing for Hypothetical Monetary Reinforcers*

<table>
<thead>
<tr>
<th>Subject</th>
<th>RI 60 s $r^2$</th>
<th>SS</th>
<th>RI 120 s $r^2$</th>
<th>SS</th>
<th>RI 240 s $r^2$</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-262</td>
<td>0.984</td>
<td>0.059</td>
<td>0.982</td>
<td>0.069</td>
<td>0.969</td>
<td>0.134</td>
</tr>
<tr>
<td>P-263</td>
<td>0.952</td>
<td>0.147</td>
<td>0.941</td>
<td>0.189</td>
<td>0.952</td>
<td>0.150</td>
</tr>
<tr>
<td>P-264</td>
<td>0.972</td>
<td>0.446</td>
<td>0.963</td>
<td>0.507</td>
<td>0.971</td>
<td>0.486</td>
</tr>
<tr>
<td>P-265</td>
<td>1.000</td>
<td>0.000</td>
<td>0.995</td>
<td>0.014</td>
<td>1.000</td>
<td>0.000</td>
</tr>
<tr>
<td>P-267</td>
<td>0.990</td>
<td>0.126</td>
<td>0.990</td>
<td>0.181</td>
<td>0.988</td>
<td>0.201</td>
</tr>
<tr>
<td>P-305</td>
<td>0.934</td>
<td>0.311</td>
<td>0.923</td>
<td>0.339</td>
<td>0.946</td>
<td>0.243</td>
</tr>
<tr>
<td>P-307</td>
<td>0.999</td>
<td>0.002</td>
<td>0.985</td>
<td>0.042</td>
<td>0.998</td>
<td>0.005</td>
</tr>
<tr>
<td>P-312</td>
<td>0.994</td>
<td>0.014</td>
<td>0.976</td>
<td>0.067</td>
<td>0.986</td>
<td>0.032</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.978</strong></td>
<td><strong>0.138</strong></td>
<td><strong>0.969</strong></td>
<td><strong>0.176</strong></td>
<td><strong>0.976</strong></td>
<td><strong>0.156</strong></td>
</tr>
</tbody>
</table>

**Survivor functions.** Figure 31 shows survivor functions for participants in the Footswitch-responding group. All data were collected and are presented in the same manner as those in Figure 27. Again, because some of these functions produced plateaus in responding (e.g., P-352, P-374, P-377, P-378, and P-383), functions were reconstructed according to the method proposed by Brackney et al. (2011). These functions are presented in Figure 32. As can be seen in these plots, removing the shortest IRT from the analysis eliminated (e.g., P-352, P-374, P-377, and P-378) or truncated (P-383) these initial plateaus. Double exponential functions were then fit to the plots in
Table 7

Obtained Parameter Estimates From the Fitted Double Exponential for all Humans Engaging in Button Pressing

<table>
<thead>
<tr>
<th>Subject</th>
<th>RI 60 s</th>
<th>RI 120 s</th>
<th>RI 240 s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$l-p$</td>
<td>$w$</td>
<td>$1/p$</td>
</tr>
<tr>
<td>P-262</td>
<td>0.96</td>
<td>3.96</td>
<td>24.39</td>
</tr>
<tr>
<td></td>
<td>2.21</td>
<td>0.44</td>
<td>2.22</td>
</tr>
<tr>
<td>P-263</td>
<td>0.73*</td>
<td>4.80*</td>
<td>3.73*</td>
</tr>
<tr>
<td></td>
<td>3.24*</td>
<td>3.24*</td>
<td>3.37*</td>
</tr>
<tr>
<td>P-264</td>
<td>0.64*</td>
<td>0.62*</td>
<td>2.78*</td>
</tr>
<tr>
<td></td>
<td>0.52*</td>
<td>0.52*</td>
<td>0.64*</td>
</tr>
<tr>
<td>P-265</td>
<td>0.81</td>
<td>6.60</td>
<td>5.24</td>
</tr>
<tr>
<td></td>
<td>3.68</td>
<td>1.61</td>
<td>4.69</td>
</tr>
<tr>
<td>P-267</td>
<td>0.37</td>
<td>3277</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>8.31</td>
<td>0.38</td>
<td>8.33</td>
</tr>
<tr>
<td>P-305</td>
<td>0.99</td>
<td>3.08</td>
<td>83.33</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>0.01</td>
<td>2.44*</td>
</tr>
<tr>
<td>P-307</td>
<td>0.82</td>
<td>10.21</td>
<td>5.59</td>
</tr>
<tr>
<td></td>
<td>3.88</td>
<td>1.54</td>
<td>2.85</td>
</tr>
<tr>
<td>P-312</td>
<td>0.45</td>
<td>424229</td>
<td>1.82</td>
</tr>
<tr>
<td></td>
<td>8.33</td>
<td>2.71</td>
<td>7.82</td>
</tr>
</tbody>
</table>

Note. Parameter $l-p$ estimates the inverse of the proportion of responses that are classified as within-bout responses; $w$ estimates rate of within-bout responding (in responses/s); $1/p$ estimates the number of responses per bout; $b$ estimates rate of bout-initiations (in responses/s). Asterisks (*) indicate estimates in which within-bout and bout-initiation rate were identical (i.e., the function was best described by a single and not a double exponential). Parameters in **bold** are recalculated refractory parameters (see text).
Figure 3. Most survivor plots extended over only a few seconds, indicating very rapid responding. The first second of all response distributions contained at least 90% of responses. Some slight breaks in survivor functions were observed for only one participant (P-377). Data from this participant suggested a difference in survivor functions across the three RI values. For this participant, survivor functions for the RI 60-s schedule showed evidence of a higher rate of bout initiations when compared to the RI 120-s and RI 240-s schedules.

**Bout estimate calculations.** Double-exponential functions were fit to survivor functions shown in Figure 3. Visual inspection suggested that functions tended to fit the data reasonably well, save P-383. Table 8 provides quantitative values of goodness of fit ($r^2$ and $SS$ residuals). As Table 6 shows, $r^2$ values were high ($M = 0.971$, $SD = 0.038$) and $SS$ values were low ($M = 0.116$, $SD = 0.180$) across all sessions for all participants.

![Response rates](image)

*Figure 30.* Response rates (in responses per minute) for all participants during the RI 60 s RI 120 s RI 240 s multiple schedule. Response rates during RI 60 s schedules are represented by black bars, rates during RI 120 s schedules are represented by light grey bars, and rates during RI 240 s schedules are represented by dark grey bars.
Figure 31. Log survivor functions for all human footswitch responding during the final completed session without the refractory period subtracted from IRTs. Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). Closed circles represent RI 60 s, open circles represent RI 120 s, and closed triangles represent RI 240 s. Fitted functions represent the best-fitting double-exponential.
Figure 32. Log survivor functions for all human footswitch responding during the final completed session with the refractory period subtracted from IRTs. Log proportion of IRTs > t are plotted as a function of time (t - s: time in seconds). Closed circles represent RI 60 s, open circles represent RI 120 s, and closed triangles represent RI 240 s. Fitted functions represent the best-fitting double-exponential.
Table 8

*Obtained Values of $r^2$ and Sum of Squared Residuals (SS) for all Human Footswitch Responding for Hypothetical Monetary Reinforcers*

<table>
<thead>
<tr>
<th>Subject</th>
<th>RI 60 s $r^2$</th>
<th>SS</th>
<th>RI 120 s $r^2$</th>
<th>SS</th>
<th>RI 240 s $r^2$</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-352</td>
<td>0.998</td>
<td>0.006</td>
<td>1.000</td>
<td>0.001</td>
<td>0.999</td>
<td>0.002</td>
</tr>
<tr>
<td>P-353</td>
<td>0.987</td>
<td>0.036</td>
<td>0.992</td>
<td>0.019</td>
<td>0.989</td>
<td>0.032</td>
</tr>
<tr>
<td>P-354</td>
<td>1.000</td>
<td>0.000</td>
<td>0.971</td>
<td>0.074</td>
<td>1.000</td>
<td>0.000</td>
</tr>
<tr>
<td>P-374</td>
<td>0.973</td>
<td>0.057</td>
<td>0.983</td>
<td>0.043</td>
<td>0.988</td>
<td>0.029</td>
</tr>
<tr>
<td>P-377</td>
<td>0.969</td>
<td>0.116</td>
<td>0.975</td>
<td>0.076</td>
<td>0.953</td>
<td>0.181</td>
</tr>
<tr>
<td>P-378</td>
<td>0.957</td>
<td>0.150</td>
<td>0.924</td>
<td>0.306</td>
<td>0.973</td>
<td>0.085</td>
</tr>
<tr>
<td>P-383</td>
<td>0.881</td>
<td>0.675</td>
<td>0.866</td>
<td>0.557</td>
<td>0.916</td>
<td>0.327</td>
</tr>
<tr>
<td>P-386</td>
<td>1.000</td>
<td>0.000</td>
<td>1.000</td>
<td>0.000</td>
<td>0.998</td>
<td>0.003</td>
</tr>
</tbody>
</table>

**Average** 0.971 0.130 0.964 0.135 0.977 0.082

Table 9 provides parameter estimates for all double-exponential fits. As in the Button-press group, there were many instances in which estimates of $w$ and $b$ were equivalent. This occurred under all schedule values for P-353, P-374, P-383, and P-386. Two of three schedules also produced this same result for P-354 and P-378. Again, the equivalence of these parameters suggests that responding was best described by a single function. Because none of the functions for these participants produced different within- and between-bout rates across two schedules, comparisons across schedules could not be made. However, two participants (P-352 and P-377) showed different bout-initiation and within-bout rates across schedules. For P-352, within-bout and bout-initiation rates increased and the number of responses per bout decreased as a function of increasing schedule value. For P-377, the number of responses per bout increased across schedule values and bout-initiation rates were higher in RI 60 than in other schedules.
Table 9

Obtained Parameter Estimates From the Fitted Double Exponential for all Humans Engaging in Footswitch Responding

<table>
<thead>
<tr>
<th>Subject</th>
<th>RI 60 s</th>
<th>RI 120 s</th>
<th>RI 240 s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1-p$</td>
<td>$w$</td>
<td>$1/p$</td>
</tr>
<tr>
<td>P-352</td>
<td>0.99</td>
<td>4.00</td>
<td>142.86</td>
</tr>
<tr>
<td></td>
<td>2.94</td>
<td>0.01</td>
<td>3.27</td>
</tr>
<tr>
<td>P-353</td>
<td>0.71*</td>
<td>5.19*</td>
<td>3.42*</td>
</tr>
<tr>
<td></td>
<td>4.70</td>
<td>4.70</td>
<td>5.20</td>
</tr>
<tr>
<td>P-354</td>
<td>0.60*</td>
<td>8.49*</td>
<td>2.53*</td>
</tr>
<tr>
<td></td>
<td>4.39</td>
<td>4.39</td>
<td>3.69</td>
</tr>
<tr>
<td>P-374</td>
<td>0.60*</td>
<td>6.48*</td>
<td>2.48*</td>
</tr>
<tr>
<td></td>
<td>4.27</td>
<td>4.27</td>
<td>4.45</td>
</tr>
<tr>
<td>P-377</td>
<td>0.96</td>
<td>3.90</td>
<td>23.81</td>
</tr>
<tr>
<td></td>
<td>2.81</td>
<td>0.36</td>
<td>3.31</td>
</tr>
<tr>
<td>P-378</td>
<td>0.73*</td>
<td>4.17*</td>
<td>3.75*</td>
</tr>
<tr>
<td></td>
<td>2.94</td>
<td>2.94</td>
<td>2.97</td>
</tr>
<tr>
<td>P-383</td>
<td>0.72*</td>
<td>2.59*</td>
<td>3.61*</td>
</tr>
<tr>
<td></td>
<td>1.77</td>
<td>1.77</td>
<td>2.44</td>
</tr>
<tr>
<td>P-386</td>
<td>0.59*</td>
<td>7.86*</td>
<td>2.41*</td>
</tr>
<tr>
<td></td>
<td>5.98</td>
<td>5.98</td>
<td>6.08</td>
</tr>
</tbody>
</table>

Note. Parameter $1-p$ estimates the inverse of the proportion of responses that are classified as within-bout responses; $w$ estimates rate of within-bout responding (in responses/s); $1/p$ estimates the number of responses per bout; $b$ estimates rate of bout-initiations (in responses/s). Asterisks (*) indicate estimates in which within-bout and bout-initiation rate were identical (i.e., the function was best described by a single and not a double exponential). Parameters in **bold** are recalculated refractory parameters (see text).
Experiment 2 Discussion

A primary aim of Experiment 2 was to assess the extent to which human responding for hypothetical monetary reinforcers could be considered two-state or bout-like in nature, and whether it would be well-described by a survivor function. A second aim was to determine whether, as in nonhuman studies, changing the schedule value (see Shull et al., 2001), would affect bout parameters. A third aim was to determine whether different response topographies that were assumed to require different effort (button pushing and pressing a footswitch) would affect bout parameters in ways predicted by prior nonhuman studies (e.g., Shull & Grimes, 2003).

Survivor Analysis

**Button-press responding.** Interresponse times during button-press conditions were consistently shorter than those obtained with other species (e.g., Bennett et al., 2007; Shull et al., 2001; 2002, 2004; Shull & Grimes, 2003) and most functions did not contain IRTs longer than 5-s in length. As such, clear breaks or bends were generally not observed and many functions were well described by a single exponential. For the functions that did appear bent stick, however, the bends/breaks occurred at short IRTs. Given that, and the fact that IRTs distributions were typically confined to just a few seconds in length (e.g., for P-263 and P-307, all IRTs in the survivor function were shorter than 2 s in length), it seems unlikely that two distributions of responding were actually responsible for the break in the survivor functions.

Rates of button pressing were similar across all RI schedule components and there was no clear evidence of schedule control. Most participants (e.g., P-262, P-264, P-265,
P-267, P-305, and P-307), however, seemed to show some small difference across RI schedules in the slope of the secondary limb (i.e., bout initiation rate), although these were unsystematic. It is unclear why these slopes were different in some participants’ data when no clear schedule control was apparent, though it is possible that the difference was a result in decreases in rate in some (later) components as a function of time within the session. No analyses were conducted to test this hypothesis. Two participants showed differences in the break point (e.g., P-263 and P-312) across schedules (i.e., bout length). When bout parameters were estimated from double-exponential fits, however, it was evident that changes in survivor functions were not confined solely to changes in bout-initiation rate. Rather, differences in survivor functions across schedules tended to be produced in some participants by differences in bout length, whereas in others differences occurred in bout-initiation rates and within-bout rates.

In summary, human button-press responding for hypothetical monetary reinforcers did not consistently produce the same clear bent-stick function that has been observed in prior animal research. Additionally, schedule manipulations that have previously been shown to produce clear changes in bout-initiation rate, did not produce changes in bout initiation rate.

**Footswitch responding.** For the Footswitch-press group, it was predicted that because the footswitch required greater force (i.e., 0.6 N for the button press and 3.5 N for the footswitch), overall rates would be lower than in the button press group and survivor functions would be more broken- or bent-stick in nature. Prior studies have shown that increases in response effort produce a decrease in the shortest emittable IRT (Brackney et al., 2011). As such, it was hypothesized that survivor functions in the
Footswitch-press group would show shallower slopes in the initial limb of the function compared to the Button-press group. Unexpectedly, survivor functions in the Footswitch-press group were also typically linear in nature, and were linear for more participants than in the Button-press group.

The linear shape of the survivor functions suggest that responding was not two-state but rather was comprised of only one type of response (either entirely within- or between-bout responding). Fits of the double-exponential function confirmed the visual analysis and indicated that for most participants the survivor functions produced parameters for within-bout and between-bout rate that were equivalent, indicating that the data were best described by a single exponential.

For only one participant in the Footswitch-press group (P-377), after the refractory period was subtracted, did survivor functions show evidence of a bending point. Furthermore, the $y$-axis value of the bend point differed across RI schedule values. Parameter estimates indicated that differences observed in survivor functions across the RI schedules were attributable primarily to differences in the bout-initiation rate and bout length, with leaner RI schedules producing lower bout-initiation rates and longer bout lengths. The finding that schedule values produced changes in bout-initiation rate is congruent with those observed in previous rat studies (e.g., Shull et al., 2001, 2004; Shull & Grimes, 2003).

**Comparisons Between Button-press and Footswitch Responding**

When data appears to be of a single-state (i.e., best fit by a single exponential), no methods are available to determine whether responses are bout initiations or within-bout responses. Given the high response rates, however, it would follow most logically that
functions showed primarily within-bout responses. Responding could therefore be conceptualized as being comprised of a single bout (i.e., no breaks to engage in “other” responses) with all responses occurring within that single bout.

Because there is no quantitative way to determine which type of response comprised many of the response distributions in the Button-press and, especially, the Footswitch-press groups, meaningful analysis of differences in survivor functions and parameter estimates across groups could not made. Visual analysis of survivor functions indicate, however, that the footswitch manipulandum produced responding which was less broken-stick in nature and was possibly comprised completely of within-bout responding, as it is unlikely that disengagements occurred at such short IRTs. Because of the steeper slope in the function, one could infer that the higher response rates in the Footswitch-press group were produced primarily by an increase in the rate of within-bout responding.

As observed in previous nonhuman studies (e.g., Bennett et al, 2007; Bowers et al., 2008), for some subjects few IRTs below around 0.2 s existed, resulting in a plateau (horizontal line) in the function extending out from the y-axis. This has been most-commonly observed in pigeon keypecking. Because functions showed this plateau, a refractory model proposed by Brackney et al. (2011) was used to reconstruct survivor functions by effectively removing the shortest IRT within each IRT distribution for each participant. Survivor functions for both groups were reconstructed according to the Brackney et al. model showed less evidence of this plateau. Most (seven of eight functions) appeared broken- or bent-stick in nature. This analysis was less effective for the Footswitch-press group, primarily because responding occurred at a higher rate.
Overall, however, the data from the Button-press group indicates that this method may be useful for transforming survivor functions into functions that can be more readily quantified.

**Response Rates**

Human button-press and footswitch-press responding for hypothetical monetary reinforcers under both button-press and footswitch manipulations occurred at high rates ($M = 105.13$, $SD = 59.01$ and $M = 185.09$, $SD = 64.10$, respectively), though interval schedules provide a relatively constant reinforcement frequency regardless of rate of responding. The exact reason for these high rates of responding is unknown, but they are not inconsistent with results from prior research with humans using real monetary reinforcers that also found high response rates. For example, Bradshaw, Szabadi, and Bevan (1976) found that humans consistently responded at rates above 200 responses per minute under VI 51-s and VI 157-s schedules of reinforcement. The high response rates suggest that the opportunity to earn $50 may have been a potent reinforcer.

It is also possible that the initial training, consisting of an exposure to low RI schedule values (e.g., RI 5 s), contributed to later high rates of responding. Previous studies in our laboratory using similar training procedures and the same button panel have also shown comparable high rates of behavior (Pietras, Brandt & Searcy, 2010). Additionally, because participants were initially exposed to low-value RI schedules (e.g., RI 5 s), self-rules may have been generated regarding the initial correlation between high response rate and reinforcer rate (e.g., “The more I respond, the more frequently I obtain reinforcement”), which led to persistent high response rates as the RI schedule values increased. The instructions given to participants about how to respond on the task may
have aided in the generation of rules and/or inadvertently generated high rates of responding. Informal analysis of participants’ verbal reports collected at the end of the experiment, however, did not indicate that participants reliably generated self-rules.

Responding in most participants was also insensitive to RI schedule value across the range of RI schedules tested here. That is, response rates were generally indistinguishable between RI 60 s, RI 120 s, and RI 240 s schedules of reinforcement. This insensitivity could possibly be due to the use of hypothetical monetary reinforcers. Though attempts were made to increase the value of the hypothetical money deliveries by telling participants that the individual who earned the most money would win a $50 prize, these rewards were probabilistic and provided at a later date. Thus, hypothetical money deliveries may have been weak reinforcers. As noted above, however, response rates in most participants were high. Thus, if points were weak reinforcers it is unclear why response rates were maintained at such high rates.

Another possibility is that behavior was simply insensitive to the differences in reinforcement rate. Bradshaw et al. (1976) observed increases in response rate in humans as a function of increasing reinforcement rate on variable-interval (VI) schedules and other studies from their laboratory have produced similar results (e.g., Bradshaw et al., 1977, 1979). Other studies, however, have documented limitations in the procedures used in these studies. For example, Horne and Lowe (1993) noted that reinforcement rate in the Bradshaw et al. studies was related to the ordinal stimuli associated with each schedule of reinforcement. With such a relation, humans could have constructed rules that modulated response rates when the “best” (i.e., left-most stimulus light) or “worst” (i.e., right-most stimulus light) schedules of reinforcement were in effect. Horne and
Lowe replicated these studies without the correlation between ordinal position of stimuli and schedule of reinforcement and found insensitivity of human responding to changes in reinforcement rates, suggesting that rule-control and salience of schedule-correlated stimuli may play a large role in obtaining differential response rates with humans on VI schedules. Similarly, Madden and Perone (1999) found insensitivity to VI schedule values unless an observing response was required, and suggested that the relative salience of stimuli in animal (e.g., bright lights in dark chambers) and human (e.g., colors on a computer screen in a well-lit room) studies may play a large role in gaining schedule-control. Although the present study required a consummatory response to collect reinforcers, it is possible that the stimuli associated with each schedule in the current experiment were not salient enough to produce schedule-control.

It may also be useful to assess survivor functions in participants who have had longer exposure to schedule values, as participants in this study were only briefly exposed (e.g., approximately two hours) to experimental conditions. It is unclear whether behavior had reached a steady-state, as only several sessions of responding were collected. Indeed, other have suggested that the brief exposures often implemented in human-operant literature may be one of the reasons why discrepancies are observed when comparisons are made to animal literature (see Baron, Perone, & Galizio, 1991).

Contrary to our hypothesis, response rates were higher in the Footswitch-press group than in the Button-press group. One possibility was that the footswitch was easier to operate than the button. Although the force required to operate the footswitch was higher than that required to engage in button pressing, because the topography by which responses were emitted (via hand/finger or foot) differed between the two manipulanda, it
is possible that the button press actually required more effort. That is, it is possible that pressing a footswitch with a force of 3.5 N was actually easier than button pressing with 0.6 N of force. It would be of interest to investigate human responding on the footswitch when participants were required to operate the switch with their hand. If rates were lower, it would indicate that using the leg to operate the device was a less effortful response. Additionally, evaluating participant’s preference between the button and footswitch on a simple choice procedure might provide some insight into the relative effort required by the two options. Prior studies also have used progressive-ratio (PR) schedules to assess the relative reinforcing efficacy of reinforcers (Hodos, 1961). This has been accomplished by exposing organisms to increasing PR values (interpreted as an increased effort required to obtain reinforcement) and then analyzing the point at which organisms no longer respond for reinforcers, i.e., the break point. Higher break points are viewed as indicating reinforcers that have greater reinforcer efficacy. This analysis could be conducted using button and footswitch responses for hypothetical money reinforcers to determine whether one manipulanda produces higher break points. Higher PR break points would likely indicate a less effortful response.

Another reason for the higher response rates in the Footswitch-press group than the Button-press group is that it may have been easier to engage in “other” activities while engaging in footswitch responding. If footswitch responding, more so than button-press responding, allowed a participant to concurrently engage in activities it is likely that response rates would be higher during these conditions. That is, while engaging in button-press responding, alternative responses that would require two hands (e.g., stretching, altering the height of the chair, etc.) would be impossible to emit concurrently
and participants would have to stop button pressing to switch to these other activities. Alternatively, a participant may be able to engage in these activities while still engaging in footswitch responding, as their hands would still be free to manipulate objects. As such, it may be of interest to assess the effects of adding a secondary response (i.e., a disengagement response) that would require the subject to disengage entirely from the target behavior (button or footswitch presses) in order to obtain reinforcement. The addition of this response may produce a more bout-like pattern of behavior. This manipulation is similar to that suggested by Bennett et al. (2007) with pigeons to combat low values of $R_o$. That is, because there is relatively little else for a pigeon to do in the experimental chamber other than engage in the target response, it seems unlikely that a bout-like pattern would emerge. If some other source of reinforcement were added, however, then responding may become more bout like. A changeover response (e.g., Findley, 1958) may be required, though, such that only one response or reinforcer was available at a time. Alternatively, the response required to obtain this alternative reinforcement could preclude button-pressing behavior or footswitch-pressing behavior (e.g., a response which can only be emitted in another part of the chamber).

As mentioned previously with respect to the rat data, manipulations that increase $R_o$ could produce functions that are more broken- or bent-stick in nature by engendering more periods of disengagement. Indeed, recent research from our laboratory has shown some evidence of reduced response rates when a distractor has been introduced into the experimental chamber (unpublished data). In an adult human, button pressing was maintained on a multiple RI 20 s RI 60 s schedule of points exchangeable for money. Under disruptor conditions, a laptop was introduced into the test chamber and the
introduction of this disruptor produced decreases in response rates for one of three participants. When survivor functions of individual IRTs were plotted under no-disruptor vs. disruptor conditions for this participant (using the model proposed by Brackney et al., 2011), these functions were clearly bent-stick in nature (see Figure 33). The top panel of this figure represents functions obtained when responding was maintained under an RI 20 s schedule and an RI 20 s + laptop schedule. The bottom panel of this figure represents functions obtained when responding was maintained under an RI 60 s schedule and an RI 60 s + laptop schedule. Responding was clearly broken- or bent-stick in nature during all conditions. It is unclear why responding seemed two-state here when such functions were less likely to occur during Experiment 2. However, response rates for this participant were relatively low (e.g., 112.0 and 24.6 during RI schedules and RI schedules + laptop, respectively) when compared to many of those observed in Experiment 2 (data from two other participants exposed to the laptop manipulation did not show clear bent-stick functions). When response rates were lower in the current study, responding was more bent-stick in nature, further suggesting that reductions in response rate may increase the probability of obtaining bent-stick functions in a human operant setting. One might speculate that the addition of a laptop would act similar to the introduction of extraneous reinforcers into rat experimental chambers (e.g., Petry & Heyman, 1997). That is, the laptop would effectively reduce the relative rate of reinforcement for emitting the target response and produce a shallower slope in the secondary limb of the survivor function. This, however, was not the case, as addition of a laptop disruptor did reduce overall response rates, but did so by shifting the entire survivor function upward and altering the break point while leaving the slope of the secondary limb generally unaffected. That is,
Figure 33. Log survivor functions constructed from human button pressing data during a multiple RI 20-s RI 60-s schedule and a multiple RI 20-s + laptop RI 60-s + laptop schedule (see text description). Log proportion of IRTs > t are plotted as a function of time (t – s: time in seconds). The top frame represents responding maintained on an RI 20-s schedule (solid line) and its corresponding RI 20-s + laptop schedule (dashed line). The bottom frame represents responding maintained on an RI 60-s schedule (solid line) and its corresponding RI 60-s + laptop schedule (dashed line).
the length of the initial limb was affected and bout lengths were shorter when a laptop was introduced. It is possible that internet-browsing behavior provides reinforcers that are most efficiently obtained by disengaging from the target behavior for brief, but frequent periods of time (e.g., loading or scrolling down a webpage and returning to the target response while reading). This method of acquiring these alternative reinforcers is likely in contrast to the way in which rats may obtain reinforcement from “rat toys.” That is, it is more likely that the rat must stay disengaged from the target response for some extended period of time in order to obtain reinforcers for engaging in toy play. Finally, although this manipulation produced a decrease in button-press responding in some participants, the same manipulation may not be successful in reducing rates in participants engaging in footswitch responding, as one can be concurrently engaged in both internet browsing and the target response.

**Summary**

In conclusion, human responding on RI schedules of reinforcement did not generally show a bout-like patterning. Although it is possible that this may represent a species difference, it is more likely that the failure to generalize from rats to humans is attributable to the high response rates obtained here, as a bout-like pattern of responding is unlikely to emerge with such a prevalence of short IRTs. In support of this, rats in Experiment 1 also failed to showed bout-like patterning under rich RI schedules when response rates were high. As such, it would be of importance to assess manipulations in future studies with humans that produce lower response rates to determine whether responding is more bout-like. Several of these types of manipulations, mentioned above, include removing instructions (to prevent rule control) and providing alternative sources
of reinforcement. Lower response rates may also be produced by increasing the force requirement of the manipulanda (e.g., a button which requires 1.5 N of force), and providing non-contingent reinforcement.
DISCUSSION

Researchers have argued that operant responding is fundamentally bout-like in nature, consisting of periods of engagement and disengagement (e.g., Gilbert, 1958; Shull et al. 2001), and methods have been developed to evaluate this notion and assess whether this conceptualization of responding can help identify orderly behavior-environment relations that are obscured when response rate is averaged across a session (e.g., Shull et al., 2001, 2004; Shull & Grimes, 2003). Shull et al. (2001) suggested that plotting IRTs as log-survivor functions can depict and describe how responding is dichotomized into periods of engagement and periods of disengagement. Shull et al.’s (2001) initial analyses, along with those from more naturalistic investigations of behavior (e.g., Clifton, 1987; Gerstner & Cianfarani, 1998; Tolkamp & Kyriazakis, 1999), and additional laboratory investigations (Brackney et al., 2011; Cabrera et al., 2013; Hill et al., 2012; Johnson et al., 2009, 2011; Shull & Grimes) have provided support for the two-mode conceptualization of responding. Indeed, the analysis has been extended to other topographies in rats (e.g., Shull & Grimes), operant-level (unconditioned) responding (Cabrera et al.), other species of small mammals (Johnson et al., 2009; 2011; Cabrera et al.), and other reinforcers (Brackney et al.). If survivor functions of IRT distributions show broken- or bent-stick shapes across species, response topographies, and procedures, the bout nature of responding may be considered to be a fundamental property of operant responding. However, studies with pigeons have consistently failed to show a clear two-state function (e.g., Bennett et al., 2007; Bowers et al., 2008; Podlesnik et al., 2006).
The primary goal of the present two experiments was to further explore the generality of the bout analysis by examining whether rat lever pressing for liquid (milk) reinforcers (Experiment 1) and human button- and footswitch pressing (Experiment 2) could be described by a bout analysis. The present results suggest that responding may be characterized as bout-like only under certain response rates. That is, when response rates were low, such as under the lean RI schedules with rats during Experiment 1, the bout-like nature of responding was only apparent if data were collapsed across multiple sessions. This finding suggests that sample size limitations (see Shull et al., 2002) are a problem for IRT log-survivor analyses. Alternatively, when response rates were high, such as under rich RI schedules with rats during Experiment 1 and under all RI schedules with humans during Experiment 2, responding appeared to occur as a single-state. Under these conditions, log-survivor functions were linear. That the log-survivor analysis does not consistently produce clear broken- or bent-stick functions suggests that the analysis may prove useful for characterizing responding only with certain species (e.g., rats and small mammals), reinforcers (e.g., food and sucrose pellets), topographies (e.g., nose pokes or low-effort lever presses), or reinforcement schedule conditions (e.g., those that generate intermediate response rates). Limitations of the present results, the log-survivor analysis, and the bout-conceptualization of responding will be discussed below.

**Limitations of the Present Research and Future Directions**

One limitation of the present research was that response rates in Experiment 1 (rat lever pressing) were very low, and response rates in Experiment 2 (human button pressing and footswitch responses) were rather high. For the rats, the reason why it was difficult to maintain responding for milk reinforcers was unclear, and several hypotheses
were presented in the Experiment 1 discussion (e.g., satiation, GI distress, force requirement, etc.). Future studies could evaluate some of these hypotheses and determine the condition under which responding for milk reinforcers could be maintained across various schedule values. As mentioned by Shull (2006), providing rats free access to water during experimental sessions produced persistent responding for pellet reinforcers throughout sessions when compared to rats without free access. Thus, it would be interesting to see if this same finding extends to rat responding for milk reinforcers. Additionally, it may be interesting to decrease the force required to emit a lever press. If decreased responding across successive component presentations was a combined function of the effort required to emit a response and the decreasing efficacy of a reinforcer (e.g., rats were “unwilling” to emit responses for reinforcers after a certain number had been obtained), a decrease in response effort may maintain responding for reinforcers for a longer period of time. Similarly, a decrease in reinforcer magnitude accompanied by a decrease in the force required to emit a lever press may result in more persistent responding, especially if rats were becoming satiated or if the milk was causing some level of GI distress. Finally, examining lever pressing in rats given a training history with rich VR schedules (E. Jacobs, personal communication, July 2, 2013) might function to sustain responding throughout multiple presentations of the components and eliminate the need for collapsing across sessions to obtain a greater number of IRTs.

With regard to the high rates of responding observed with the human participants, it would be important for future studies to investigate the bout-like nature of responding under conditions that generate lower response rates. Possibly, removing instructions may produce lower rates of responding. Leaner training schedules (e.g., perhaps beginning at
RI 1 min) also may eliminate the possibility of self-generated rules that lead to persistent high rates. Additionally, increasing the force required to press a response button (as lower rates were observed with this manipulandum) and/or providing alternative reinforcers throughout the session may decrease response rates. Finally, using real monetary as opposed to hypothetical money as consequences may produce greater schedule-control.

Limitations of Log-survivor Analysis of Responding

**IRT sample size considerations.** Survivor functions produced by rat lever press from single-session data showed some evidence of multiple inflection points. This likely occurred because of the low response rates and the influence of outlier IRTs on the shape of the survivor function. Consistent with this, Shull et al. (2002) noted that constructing survivor functions from a small number of IRTs can lead to unreliable parameter estimates when attempting to examine functions across extinction (e.g., declining response rates). Because of the small sample size obtained in a single session, IRTs were collapsed across three sessions. The functions obtained via this method showed less evidence of multiple break points and were better described by a double-exponential equation. Prior researchers also have collapsed IRTs across subjects or sessions in order to construct survivor functions (see Clifton, 2000; R. Brackney, personal communication, May 27, 2013). Collapsing IRTs across multiple sessions produced more stable limbs (especially the secondary limb) of the function, suggesting that a large IRT sample size is necessary to construct two-state functions.

In order to assess the effects of sample size on parameter estimates, simulations based on the model proposed in Figure 2 were conducted. The simulations were similar to those conducted by Shull et al. (2001). For these simulations, a modified version of a
spreadsheets constructed by Killeen (2006) were used to generate IRT distributions according to predetermined parameter values for the mean IRT between bouts \((l/b)\), mean within-bout IRT \((l/w)\), and the mean probability of disengaging from a bout \((l-p)\). These values were set to 5 (mean IRT between bouts), 0.5 (mean within-bout IRT), and 0.25 (mean probability of disengaging from a bout). These values are arbitrary and distributions based upon other values could have been calculated, but the outcomes of the analyses should be similar. A description of how the model generated IRTs is presented in Appendix B. This simulation was run 60 times: 20 times each when the sample size was 500, 1000, and 4000 IRTs. Once these values were obtained, double-exponential functions were fit to the data, and parameter estimates were obtained. Because the parameter \(p\) indicates the point at which the double-exponential function shows an inflection point and also provides an estimate of bout-length \((l-p)\), the values of this parameter estimate were plotted as a function of simulation sample size. If simulations produced survivor functions which were well-described by a double exponential, and if the parameter estimates provided were reliable and valid, values of \(p\) should be closely centered around 0.75.

The results of parameter estimates for \(p\) as a function of IRT sample size are shown in Figure 34. This figure shows that parameter estimates for \(p\) did tend to center around those which were used construct simulated IRT distributions (0.75). However, there are striking differences in the variability of the parameter estimate across sample sizes. Parameter estimates were most-closely centered around the expected value when the sample size was 4000 IRTs \((M = 0.75, SD = 0.03)\), but showed greater variability as sample size decreased to 1000 IRTs \((M = 0.73, SD = 0.07)\) and 500 IRTs \((M = 0.70, SD\)
These simulations therefore illustrate that a large number of IRTs must be collected in order to obtain reliable and valid parameter estimates from double-exponential functions. Thus, procedures that generate low numbers of IRTs are unlikely to show systematic changes in the parameter values of double-exponential functions as a function of experimental manipulations.

Figure 34. Parameter estimates for $p$ (predicted value = 0.75) as a function of IRT sample size. Plots were constructed from simulations of IRT distributions and parameter estimates were obtained by fitting double-exponential functions to data from these simulations. Each x indicates the estimate for $p$ from a single simulation.

Schedule and rate considerations. Many of the survivor functions generated from rat data under the RI 15-s schedule, and most of the survivor functions generated from human data were not broken or bent-stick in nature and were best described by a single exponential. These findings are consistent with results of several previous studies (Hill et al., 2012; Shull et al., 2004) that showed that responding under rich (e.g., RI 15 s)
reinforcement schedules is not well classified as multiple state. This may occur when the 
assumed within-bout and bout-initiation distributions exhibit a great deal of overlap. 
Figure 35 illustrates why overlapping distributions are problematic for a survivor 
analysis. This figure shows hypothetical combined double-exponential functions along 
with their underlying single exponential functions, which represent within-bout and bout-
initiation IRT distributions. Individual exponential functions were obtained by 
substituting values into the within- and between-bout portions of the double-exponential 
equation (Equation 2).

Figure 35. Hypothetical single exponentials for within-bout response distributions (dot-
dashed lines) and bout-initiation distributions (dashed lines) and the combined double-
exponential function (solid lines; obtained from the sum of the two single exponentials) 
for differing within-to-between-bout response ratios. Parameter values used to construct 
these functions are located in the bottom right corner of each figure. Figures represent 
(from right to left and top to bottom): 8:1, 4:1, 3:1, and 2:1 ratios.
Graphs in Figure 35 illustrate how distributions change across changes in the ratio of within- to between-bout response rate, as all other parameter values used to construct these functions were equal (i.e., \( p \) was set equal to 0.75 for all functions). As can be seen here, the greater the ratio of within- to between-bout response rates, the less the overlap between the two underlying exponential functions. These graphs illustrate that, as the ratio decreases (i.e., from 8:1 to 4:1, etc.) and as one type of responding predominates, the double-exponential function may be unable to differentiate the distributions and reliably provide parameter estimates.

In order to quantify the influence that increasingly overlapping single exponentials have on parameter estimates, simulations were conducted using the method described above (again, see Appendix B for a full description of methods). For these simulations, different within- to between-bout ratios were used to produce IRT distributions. Distributions were obtained using within:between-bout ratios (\( w:b \)) of 8:1, 4:1, 3:1, and 2:1. Parameter estimates of \( p \) were then estimated by fitting double-exponential functions to obtained data. The results of these simulations are shown in Figure 36. This figure shows that parameter estimates for \( p \) again centered around those which were used to construct IRT distributions from the simulation (0.75). However, when the ratio of within-to-between-bout response rate was small (i.e., 2:1), average parameter estimates tended to be slightly lower than predicted and showed a great deal of variability (\( M = 0.72, SD = 0.15 \)). Other ratios tended to show less variability and more consistency with predicted parameter values: 3:1 (\( M = 0.76, SD = 0.04 \)); 4:1 (\( M = 0.75, SD = 0.03 \)); 8:1 (\( M = 0.74, SD = 0.02 \)). These results suggest that a \( w:b \) ratio of at least 3:1 was necessary to obtain reliable estimates of bout parameters. Schedules which
produce high rates of responding are likely to produce overlap in underlying exponential distributions (low within-to between bout ratios) are parameter estimates and are unreliable.

![Parameter estimates for \( p \) (predicted value = 0.75) as a function of \( w:b \) ratio. Plots were constructed from simulations of IRT distributions using the parameters from Figure X and parameter estimates were obtained by fitting double-exponential functions to data from these simulations. Each x indicates the estimate for \( p \) from a single simulation.](image)

**Figure 36.** Parameter estimates for \( p \) (predicted value = 0.75) as a function of \( w:b \) ratio. Plots were constructed from simulations of IRT distributions using the parameters from Figure X and parameter estimates were obtained by fitting double-exponential functions to data from these simulations. Each x indicates the estimate for \( p \) from a single simulation.

**Other Methods for Analyzing Responding as Two-state in Nature**

It should be noted that a new method to analyze two-state responding has been proposed by Hoffman and Newland (May 27, 2013) who suggested a means of defining bouts using cumulative records and a change-point algorithm to split behavior into “activity epochs.” This analysis may have an important advantage over the survivor
analysis, as quantifying bout-initiation and within-bout responses with double-exponentials does not clearly reveal the moment-to-moment patterning of responding. That is, probabilistic guesses must be made to determine whether any individual IRT is classified as within- or between-bout, and the structure of each hypothesized bout of responding is lost when aggregating IRTs into a single distribution. Hoffman and Newland’s method, however, observes responding at a more momentary level and can possibly classify individual responses as being either bout initiations or responses within a bout, while also assessing the acquisition and maintenance of bout-like responding both within and across experimental sessions. It is unclear whether this analysis can better deal with some of the limitations presented here. It seems, though, that the analysis may be somewhat immune to the sample size limitation, as bouts of responding are viewed in real time and, theoretically, the effects of environmental manipulations may be assessed on a relatively small sample size of engagement periods under different experimental conditions. However, the extent to which this analysis would be limited by high-rate behavior is less clear and is likely dependent upon the statistical criteria used (whether conservative or liberal) for selecting disengagement periods. As the specifics of this model have yet to be published, its usefulness in overcoming these limitations is only speculative.

**Behavioral Mechanisms of Drug Action**

As noted in the introduction, it was speculated that survivor analysis may prove useful in elucidating the behavioral mechanisms of drug action. In fact, one of the initial goals of this research was to obtain a baseline in rats on which to assess drug effects using milk reinforcers to replicate the results of Heyman (1983). However, clear broken-
or bent-stick functions were not reliably obtained and, when they were, the inability to maintain responding for extended periods of time (e.g., sessions long enough to capture the behavioral effects of a drug) and IRT sample size prevented analysis of drug effects. In order to obtain functions that were reliably described by a double-exponential function, data needed to be collapsed across multiple sessions. Such a baseline may be impractical for the study of drug effects. The multiple breaks obtained during single-session functions suggest that some minimum number of IRTs is necessary to construct two-state survivor functions. Because response rates were already relatively low, any administration of a drug which also produced reductions in overall response rate would likely produce functions that show multiple break points, making it necessary to collapse data across multiple sessions to obtain bent-stick functions. To analyze drug effects on responding, the drug therefore would need to be administered across multiple consecutive days. Problems inherent in this approach include possible carryover effects of the drug and drug tolerance. Thus, it was determined that drug effects could not be reliably assessed under these experimental conditions.

That data in Experiment 1 were not well suited for analyzing drug effects does not, however, preclude the use of the bout analysis to analyze drug effects in conditions under which responding is well-maintained and IRT distributions are well-described by a double exponential function. For example, future studies could assess the congruence of results of previous drug studies (e.g., Heyman, 1983) with those produced by analyzing survivor functions under drug and non-drug conditions in rat lever pressing or nose poking for food pellets. Such studies would need to be cautious, however, when constructing survivor functions from drug conditions. As described above, survivor
parameter estimates from the fits of double-exponential functions may be unreliable if the administered drug produces response rates that are too high (e.g., as evidenced by nearly linear functions) or too low (e.g., see section on IRT sample-size considerations).

**Possibility of a One-state Model**

The fact that studies with various small mammals have found that distribution of IRTs, when plotted on a log-survivor graph, show a broken- or bent-stick function suggests that responding consists of two classes of IRTs (short and long). However, these data only suggest that responding *may* be operating according to a two-state (periods of engagement alternating with periods of disengagement) model. Indeed, it is possible to obtain similar functions from responding that is single-state in nature and simply comprised of two distributions of IRTs of differing length (Shull, personal communication, 2013). If the relative frequency of short to long IRTs is high, for example, a model that selects from each with a constant probability could produce survivor functions that are broken-stick in nature. That is, if responding is comprised of 70 percent short (S) IRTs and 30 percent long (L) IRTs, randomly selecting from a distribution containing both of these IRT types could produce responding which appears bout-like in nature. Indeed, a selection of 10 responses from this overall distribution may appear as: L-S-S-S-L-S-S-L-S-S. This pattern seems to be bout-like in nature (i.e., S responses representing within-bout or engagement periods, separated by L responses which are representative of disengagements), but is merely the unavoidable outcome of sampling from a distribution comprised of two IRT types. A similar result can be obtained by randomly selecting IRTs from any survivor function described well by a double-exponential function.
Utility of the Bout Conceptualization of Responding

Even if it is ultimately determined that operant behavior is not generally characterized as two-state, the bout-analysis may be useful in some circumstances. Regardless of the mechanism by which responding produces multi-modal survivor functions, a survivor analysis has proven useful in classifying the behavior of certain species (e.g., mice, rats, hamsters), with certain response topographies (e.g., lever pressing, wheel running, key poking), and under certain experimental manipulations (e.g., VI schedules of reinforcement which generate moderate rates of responding).

Important information about the relationship between commonly manipulated independent variables and the underlying structure of behavior has indeed been obtained because survivor functions separate responding into two, quantifiable, response distributions. Because of this analysis, studies have determined that changes in overall response rate may be produced by different means. For example, as described above, by adopting a survivor analysis Shull et al. (2001) was able to identify the effects of various independent variables on specific components of response rate. Changes in reinforcer properties tended to produce changes in the slopes of the secondary limb (indicating a change in bout-initiation rate), whereas changes in what the organism had to do to obtain reinforcement produced changes in the steepness of the initial limb (indicating a change in bout length). Moreover, other studies have used this analysis to distinguish the mechanism by which response rates are higher in a rat model of ADHD (Hill et al., 2012). The orderly relations observed at this level of analysis, therefore, justify the use of survivor functions when IRT distributions appear to be multi-modal in nature.
Conclusion

Previous studies (e.g., Branch & Gollub, 1974; Gentry et al., 1983; Shull et al., 2001) have suggested that the use of aggregated responding to describe behavior-environment relations can mask order which might be revealed through the use of more detailed analyses. One type of detailed analysis that has been useful in identifying orderly behavior-environment relations is the analysis of IRTs. Researchers have argued that IRTs occur in two states, short or long, which occur as a result of the bout-like nature of operant responding. Research has shown that responding in small mammals is readily characterized as bout-like using IRT log-survivor plots (e.g., Shull et al., 2001). The present study explored the generality of this bout approach by assessing whether rat lever pressing for milk reinforcers and human button pressing for hypothetical monetary reinforcers could be characterized as two-state via analysis of survivor functions. Rat lever pressing for milk reinforcers produced functions that could be characterized as bout-like in only some conditions and manipulations produced parameter estimates that were often in contrast with those observed in previous studies. Additionally, responding in nearly all humans could not be characterized as bout-like.

The results of this study highlight limitations of log-survivor functions for analyzing the bout-like nature of responding by suggesting that it is not useful when responding occurs at high rate or is not maintained throughout experimental sessions. Possibly, new methods (e.g., Hoffman & Newland, May 27, 2013) can help alleviate some of these issues. More generally, though, these results raise the possibility that either (a) responding sometimes simply occurs as one state (i.e., all within bout responses or bout-initiation responses), or (b) that responding may not be two-state in nature. Future
studies investigating responding using various types of analyses under a wide-range of conditions are necessary to determine which of these conceptualizations prove more useful. Regardless of whether this two-mode conceptualization of responding is supported, the molecular analysis of IRTs will remain an important tool for uncovering behavioral regularities.
REFERENCES


Appendix A

Post-experiment Questionnaire and Debriefing Form
Post-experiment Questionnaire

1. Please describe what happened and what you did during experimental sessions.

2. Please describe any strategies that you may have used to earn money. Did any of your strategies change across the experiment?

3. Did the color of the computer screen influence what you did? If so, in what way?

4. Did you notice any difference between what happened when the background was of a different color?

*Post-experimental questionnaire administered to all subjects after completing the study.*
Debriefing Form

The purpose of this study was to investigate how positive response outcomes influence behavior. You could respond on a footswitch (buttons) to earn hypothetical money. Sometimes the frequency of money presentations was changed. The purpose of this was to determine whether the frequency of monetary gains influenced how often you pressed the footswitch (buttons), or your pattern of pressing. There was no right or wrong way to respond on this task. The study did not measure any aspect of your personality, or how you may behave in other situations.

Please do not discuss what you did and what happened in this study with others until we have finished collecting data for this project. If you discuss the study with others who participate in the study it may influence their behavior and invalidate the results.

All data that we have collected from you will remain confidential. The results of this study will contribute to our understanding of how negative response outcomes influence behavior and may be published in scientific decision-making or psychology journals. If you have any other questions about the study, please ask. We thank you for your participation.

*Debriefing form read to all subjects upon completion of the study.
Appendix B

Generation of Simulated IRTs Based Upon Response-bout Parameters
Generation of Simulated IRTs Based Upon Response-bout Parameters

In order to generate individual IRTs, a random number was generated (between 0 and 1.0). If this number fell above the criteria for exiting a bout (0.25), the organism was considered to be generating within-bout IRTs. As such, a within-bout IRT was calculated by multiplying the mean within-bout IRT by the log of a randomly generated number (to ensure random variability around response parameters). The process for calculating between-bout IRTs was similar. If the initially randomly-generated number was less than the probability of exiting a bout (0.25), the organism was considered to be in a disengaged state and a between-bout (or bout-initiation) IRT was generated. In this case, the mean IRT between bouts was multiplied by the log of a random number (again, to produce random variability around response parameters). The obtained values were then organized into bins and survivor functions of the generated IRT distribution were constructed.
Appendix C

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To: Alan Poling, Principal Investigator

From: Robert Eversole, Chair

Re: IACUC Protocol No. 09-10-01

Your protocol titled "Behavioral Mechanisms of Drug Action: Elucidation via Survivor Functions - Rats" has received approval from the Institutional Animal Care and Use Committee. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: November 12, 2010
Date: November 12, 2009

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