SENSITIVITY OF PREFERENCE TO REINFORCEMENT AMOUNT DEPENDS
UPON THE METHOD USED TO MANIPULATE AMOUNT

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

Department of Psychology

University of North Carolina Wilmington

2007

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ABSTRACT

Four pigeons were trained on concurrent variable-interval 30-s schedules. Relative reinforcer amounts arranged across the two alternatives was varied. During Experiment 1, sessions consisted of a mixed concurrent schedule with different ratios of reinforcer amounts arranged for the two alternatives across components. Sessions consisted of 5 components that differed only with respect to the relative reinforcer amounts arranged for each alternative. Reinforcer amount was manipulated by presenting an arranged number of brief (1.2-s) hopper presentations. The amounts presented ranged from one to five presentations and the ratios used were 1/5, 2/4, 3/3, 4/2, and 5/1 (L/R). The order of ratios within each session was randomly determined, and there were no exteroceptive stimuli signaling the particular ratio in effect. After 60 sessions of training, responding for all subjects remained insensitive to reinforcer amount ratios. During Experiment 2, relative reinforcer was held constant within and across sessions until responding became stable, at which point, the absolute amounts arranged for each alternative were switched. The ratios used were 1/7 and 7/1 hopper presentations. After six sessions in each condition, all subjects showed an appreciable shift in preference toward the alternative providing the larger amount, and asymptotic sensitivity was comparable to previous reports using a similar procedure. During Experiment 3, sessions were identical to those used during Experiment 2, except that the amount ratio (either 1/7 or 7/1) presented during each session changed from session to session according to a pseudorandom binary sequence (cf., Hunter & Davison, 1985). After 30 sessions, response ratios within each session for all subjects began to shift in the direction of the amount ratio in effect for that session (i.e., subjects' responding showed a

moderate increase in sensitivity to reinforcer amount). Characteristics of responding

under this procedure were quite similar to responding procedures under which reinforcer

rate and delay were manipulated in much the same fashion. The procedure used in

Experiment 3 may serve as a method for studying the effects of certain environmental

manipulations (e.g., drug administration) on sensitivity to reinforcer amount.

ACKNOWLEDGEMENTS

DEDICATION

I would like to dedicate this work to my parents, Dennis and Patricia Maguire, who's continued and unconditional support has served as a great inspiration and motivation throughout all of my endeavors.

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INTRODUCTION

Studying behavior in choice situations has been an increasingly popular area of investigation in the experimental analysis of behavior (Mazur, 1998, 2001). Choice has been studied empirically under a variety of conditions, ranging from discrete-trials procedures, which involve making single responses among two or more alternatives that result in presentation of the scheduled consequence, to free-operant procedures that arrange two or more concurrently available alternatives, and allow the subject to respond freely and continuously among behavioral options (see Davison & McCarthy, 1988; deVilliers, 1977 ; Findley, 1962). Typically, in these free-operant choice situations, the proportion of total responses emitted on a given alternative is calculated and taken as an index of "preference," or "value," of one alternative in relation to the other, in that situation (e.g., Herrnstein, 1970; McDowell, 1988; Perone, 1991; Rachlin, 1971).

The Matching Law

Much of the research on the behavior analysis of choice has utilized two-response concurrent schedules (see Davison & McCarthy, 1988; deVilliers, 1977). In a concurrent schedule (see Ferster & Skinner, 1957), subjects are presented two operanda (e.g., keys or levers), each associated with a particular consequence (e.g., food) and the characteristics of each consequence differ along some dimension (usually rate, amount, and/or delay). In a seminal study, Herrnstein (1961) exposed pigeons to various concurrent variable-interval (VI) schedules. The schedules associated with each of two responses keys (one illuminated red the other white) were independent of one another. That is, responses on one key did not affect the scheduling of reinforcers on the other, so at any point during the session, reinforcers could be available on one or both keys. Across several

conditions, Herrnstein varied the value of the VI schedules (i.e., the reinforcer rate) associated with each key and, by recording the number of responses emitted on each key throughout the session, was able to derive a measure of preference for each option (the proportion of total responses emitted on each key). In one condition, for example, both the red and white keys produced food according to a VI 3-min schedule. For each option, the first peck after an average of 3 min had elapsed produced food (pecking on each key produced approximately 20 food presentations per hour). In another condition, the schedules were changed to a VI 2.25-min and a VI 4.5-min on the red and white keys, respectively. In this case responding on the red key produced food approximately twice as often as responding on the white key.

Herrnstein (1961) reported that once performance became stable, the proportion of responses emitted on one alternative approximated the proportion of reinforcers obtained from that alternative. For example, in the concurrent VI 3-min, VI 3-min condition, during which approximately half of the obtained reinforcers were produced by responses on the red key, about half of the total responses were emitted on that key. In another condition, in which the alternative associated with the red key produced twice as many reinforcers as the other (e.g., when red was associated with VI 2.25-min, and white was associated with VI 4.5-min), about twice as many responses were emitted on the red key. This relation held across a range of combinations of reinforcer rates. As a result of this finding, Herrnstein proposed what has come to be known as the matching law (Herrnstein, 1961, 1970). This principle states that the proportion of responses allocated to an alternative approximates, or matches, the proportion of reinforcers obtained from that alternative and is given in Equation 1 below:

$$B_1/(B_1+B_2) = R_1/(R_1+R_2) \tag{1},$$

where B represents the number of responses emitted on each alternative and R represents the number of reinforcers obtained from each of the two alternatives (subscripted 1 and 2). According to this equation, relative response allocation on a given alternative ("preference") is an increasing function of the relative rate of reinforcement associated with that alternative. This relation has also been expressed using ratios as given below:

$$B_1/B_2 = R_1/R_2 \tag{2},$$

where B_1/B_2 and R_1/R_2 are the ratio of responses and reinforcers, respectively, for each alternative. It also has been shown that the ratio of times allocated to each alternative, T_1/T_2, may be substituted for the response ratios on the left side of Equation 2 (Baum & Rachlin, 1969; Brownstein & Pliskoff, 1968; Shull & Pliskoff, 1967; Silberberg & Fantino, 1970). Indeed, some have suggested that relative time allocation may be a more fundamental behavioral measure of preference than response allocation (Baum & Rachlin, 1969; Brownstein & Pliskoff, 1968; Shull & Pliskoff, 1967).

The matching relation provides a quantitative description of behavior allocation in concurrent-choice situations. It is arguably one of the most influential findings in the experimental analysis of behavior and has been, and continues to be, the basis of numerous experiments (see Davison & McCarthy, 1988, for an extensive review). Many studies strengthen the case for the generality of the matching law across other reinforcer parameters, reinforcer types, and species. For example, in an experiment reported by Conger and Killeen (1974), humans matched relative time spent engaging in conversation with each of two confederates to the relative rate of social reinforcement (i.e., positive verbal feedback) obtained from each of the two confederates. Schroeder and Holland

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(1969) reinforced humans' eye movements on a spatial location task according to a two-alternative concurrent VI schedule of reinforcement while varying relative reinforcer rates for each alternative and reported that relative eye movements matched relative signal presentation on each alternative. Furthermore, soon after the publication of Herrnstein's (1961) results, researchers began to report that the matching relation holds for variations reinforcer amounts of mixed grain with pigeons (Brownstein, 1971; Catania, 1963; Neuringer, 1967), milk (de Villiers & Millenson, 1972) and brain stimulation in rats (Shull & Pliskoff, 1967), and intravenous cocaine administration in rhesus monkeys (Iglauer & Woods, 1974), as well as for ratios of reinforcer delays (Chung & Herrnstein, 1967). These results suggested that the ratios of amounts (A_1/A_2) and delays (D_2/D_1) could also be substituted in Equation 2 for the reinforcer rate ratios on the right side of the equation. Note that the delay term has been inverted (also referred to as the immediacy of reinforcement) as the data suggest that preference for an alternative is a decreasing function of delay.

Generalized Matching

A substantial body of research has confirmed the utility of the matching equation as a mathematical description of behavioral allocation (see Davison & McCarthy, 1988). However, Baum (1974, 1979) noted that three systematic deviations from strict matching were present in the literature: undermatching, overmatching, and bias. Undermatching is characterized by a shift in preference away from matching toward indifference. Simply put, the individual is allocating fewer responses (or less time) to the richer alternative than predicted by the matching equation. According to Baum, undermatching could emerge as a result of a number of variables including, but certainly not limited to: (a) a

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lack of discriminability between the two options, or (b) the lack of a contingency, such as a changeover delay (COD), that reduces high rates of switching between alternatives (e.g., Herrnstein, 1961). A COD prevents reinforcer delivery within a given interval, usually 1 to 5 s, after a switch from on alternative to the another and effectively eliminates reinforcement of high switching rates on concurrent VI schedules (de Villiers, 1977; Shull & Pliskoff, 1967). In the absence of a COD, as shown by Shull and Pliskoff, high switching rates and responding irrespective of the contingencies arranged on the two alternatives tended to emerge and, thus, the subject's response allocation shifts toward indifference. In contrast, overmatching occurs when response allocation is more extreme than is predicted by the matching equation. Overmatching tends to emerge when the effort required to switch is so great that subjects simply do not switch as often as predicted. An example of this effect was demonstrated in Shull and Pliskoff's report; as the COD length was increased to 20s, a large penalty for a switch, near exclusive preference emerged for an alternative on which the matching equation predicts only a 2 to 1 preference.

A constant proportional preference for one alternative, evident across the range of reinforcer parameters, is referred to as bias. Baum (1974) suggested that bias can develop for a number of reasons, often as a result of extraneous variables in the environment. Some possible sources of bias include: (a) a differential force requirement across the operanda - a rat may, for example, consistently prefer the lever that requires less force to operate and therefore develops a constant preference for that alternative; (b) a particular position or color - a subject may tend to respond on the key or lever associated with a given side or color, regardless of the rate, amount, or delay associated

with the alternatives; and, (c) schedule characteristics - for example, subjects tend to prefer variable (e.g., VI) schedules to fixed (e.g., FI) schedules, even when the rate of reinforcement associated with the alternatives is equal (e.g., Mazur, 1984).

As a result of these deviations from the matching law, Baum (1974, 1979) proposed a modified, less constrained, matching equation that includes two free parameters:

$$B_1/B_2 = k \ (R_1/R_2)^{S_R} \tag{3},$$

where k is the bias parameter and S_R is a sensitivity parameter. Bias (k) is indicated as a constant proportional preference for one alternative, which can take the value of any positive number. Values of k greater than 1.0 indicate a bias for alternative 1, whereas values between 0 and 1.0 indicate a bias for alternative 2, and k=1.0 indicates no bias. The sensitivity parameter (S_R) represents the degree to which changes in reinforcer parameters are reflected in changes in behavior. For example, if $S_R = 1.0$, an increase in relative reinforcer rate by a factor of 2.0 will produce an increase in responding on that alternative by a factor of 2.0 (i.e., $2^{1.0}$). On the other hand, if $S_R = 2.0$, an increase in rate by a factor of 2.0 will produce a change in behavior by a factor of 4.0 (i.e., $2^{2.0}$). Thus, the greater the value of S_R, the more sensitive the response ratio is to the ratio of reinforcer rates (amount or immediacy). Typically, both k and S_R are derived from individual subject data after exposure to a range of rate, amount, and/or delay parameters. In the case where both k and S_R are 1.0, Equation 3 (often referred to as the generalized matching equation) reduces to Equation 2 (often referred to as the strict matching law) (see Davison & McCarthy, 1988). The generalized matching relation also can be transformed logarithmically (Baum, 1974):

$$\log (B_1/B_2) = S_R \log (R_1/R_2) + \log k \qquad (4).$$

When plotted as a function of the ratio of rates, amounts or immediacy (the inverse of the delays), the ratio of responses is an increasing linear function with a slope, S_R, and y-intercept, k.   Figure 1 shows hypothetical subject data from a choice procedure with varying rates of reinforcement on either of the two options. In this figure the logarithm of the ratio of responses on alternative 1 (B_1) to alternative 2 (B_2) is plotted as a function of the logarithm of the reinforcer ratio (R_1/R_2).   This figure demonstrates how sensitivity and bias can be derived from subject data. The thick solid line is an illustration of perfect matching, with a slope of 1.0 and y-intercept, 0. An increase in sensitivity is indicated by an increase in the slope, as illustrated by the dotted line (a decrease in sensitivity would be shown by a decrease in the slope), and a bias will appear as a shift in the y-intercept, as illustrated by the thin solid line (this case shows a bias for alternative 1). Plotting subject data in this fashion provides a quantitative approach to identifying and characterizing environment-behavior relationships. For instance, changes in the slope and y-intercept of these functions may hint to the presence of one or more of the variables suggested by Baum (1974, 1979) that may induce changes in sensitivity or bias. These changes may serve as important quantitative indices of the control exerted by certain variables over responding (see discussion below).

It also has been suggested that the effects of rate, amount, and delay combine multiplicatively to form a construct known as "value" in the strict form (Baum & Rachlin, 1969; Rachlin, 1971) and the generalized form (Davison & McCarthy, 1988) to create a concatenated generalized matching law:

$$B_1/B_2 = k\,(R_1/R_2)^{S_R} \times (A_1/A_2)^{S_A} \times (D_2/D_1)^{S_D} \qquad (5),$$

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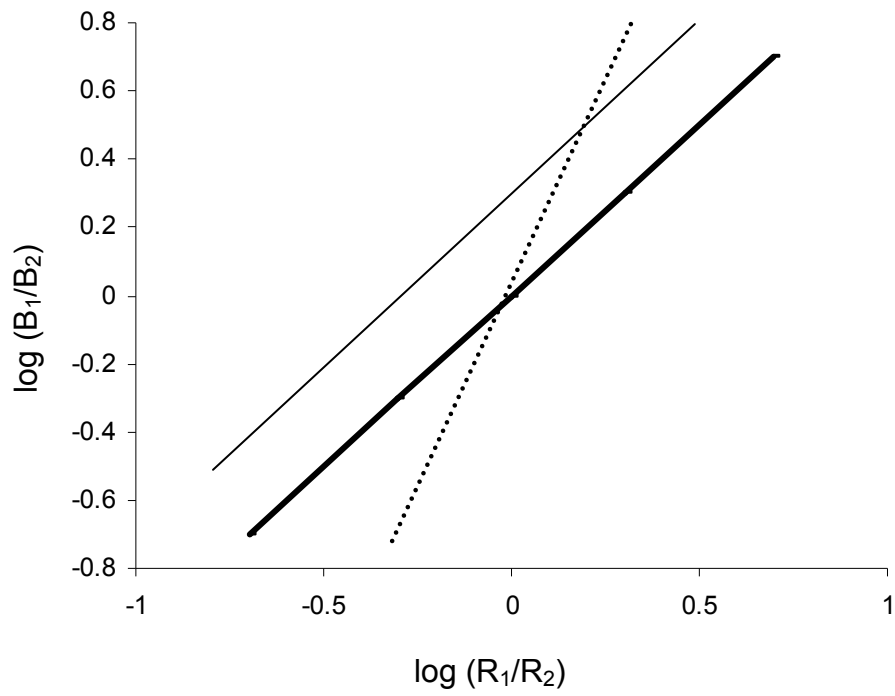
Fig. 1.. Hypothetical subject data. Plotted are the log response ratios on each of two alternatives (subscripted 1 and 2) as a function of the log amount ratios. The darker line, dotted line, and thin line represent perfect matching, increased sensitivity, and increased bias, respectively.

When Equation 5 is transformed logarithmically, the effects of each of these reinforcer variables are additive:

$$\log (B_1/B_2) = S_R \log(R_1/R_2) + S_A \log(A_1/A_2) + S_D \log (D_2/D_1) + \log k \qquad (6),$$

As it stands, the generalized matching equation provides behavior analysts with a quantitative model that describes behavior in a variety of situations where the consequences of making choices may vary in a number of dimensions, such as rate, amount, and delay. Although it may run into some problems in more complex choice situations, such as those involving concurrent-chains schedules (see Davison, 1987; Grace 1994) , this model is still a very useful tool in the experimental analysis behavior.

Self Control

Often in the natural environment an organism must allocate its behavior among numerous operants, each of which may lead to consequences that vary along multiple dimensions of reinforcement. Important choices in the natural environment often involve alternatives that involve multiple dimensions of reinforcement. Choices that produce consequences that differ in both amount and delay of reinforcement have received particular attention. Suppose a college student who has an exam on Friday morning also receives an invitation to go to a party Thursday evening; in this situation he or she has a choice between two alternatives, study or go to the party. Presumably, all else being equal, the decision to study ultimately yields a more important outcome, or larger reinforcer (e.g., good grades, graduation), and going to the party yields relatively less important consequence, or smaller reinforcer (e.g., a few hours of social interaction and involvement). In this case, however, many of the relevant consequences for

studying are more delayed than those for going to the party (months or years versus a few hours). In this situation, what will the student choose to do?

According to a conceptualization proposed independently by Ainslie (1975) and Rachlin (1974), choice between two alternatives that differ in reinforcer amount and delay depends on the relative "value" of each alternative at the time a choice is made; the more valued alternative at that moment always will be selected. Subsequently, Mazur (1987) proposed a mathematical account of value that includes amount and delay variables. He reported that the matching equation fails to fit the data in a number of ways, particularly at certain extreme values, as is the case when reinforcement is immediate, and proposed a model stating that reinforcers are discounted hyperbolically by delay according to the following equation:

$$V=A/(1+kD) \tag{7},$$

where V represents the "value," A and D represent amount and delay, respectively, and k is a free parameter which characterizes the degree to which reinforcers are discounted. This model predicts that when a reinforcer is delivered immediately (i.e., when $D=0$), its value is equal to its amount. As the delay to the reinforcer increases, its value decreases at a decelerating rate. A larger k values suggest a sharper decrease in value as the delay grows. The relative values of the alternatives 1 and 2, V_1/V_2, is calculated by dividing the discounting function for alternative 1 by that of alternative 2 as given below:

$$V_1/V_2= (A_1/A_2) \text{ x } [(1+kD_2)/(1+kD_1)] \tag{8}.$$

Much like the matching equation, the hyperbolic-discounting function predicts that the relative value of an alternative is an increasing function of amount and a decreasing function of delay. In choice situations where both alternatives have equal delays, the

alternative which provides the largest reinforcer amount will be preferred, consistent with findings reported in early choice studies which manipulated amount ratios (see Catania, 1963; Neuringer, 1967; White & Pipe, 1987). Similar predictions can also be made about choices between alternatives with equal amounts and unequal delays; the alternative with the shortest delay will be preferred (see Chung & Herrnstein, 1967).

What, then, will the student in the above example do? The hyperbolic-discounting model predicts that the option that has the highest value at the time the choice is made will determine which option he chooses; obviously, in this situation, the size and delay of the consequences associated with each alternative are not easily quantified or even identified. With subjects responding in operant-conditioning chambers, however, experimenters are able to gain explicit control over such variables as delay and amount of reinforcement. Under these conditions, subjects typically choose between a smaller reinforcer (A_S) delivered immediately or after a relatively smaller delay (D_S) and a larger reinforcer (A_L) delivered after a relatively larger delay (D_L) (e.g., Logue, 1988). Experiments that arrange such situations are typically referred to as "self-control" studies.

In the self-control literature, choice of a smaller, more immediate reinforcer is considered an "impulsive" choice, whereas choice of a larger, more delayed reinforcer is said to show "self-control" (e.g., Ainslie, 1974, 1975; Logue, 1988; Rachlin & Green, 1972). If making a good mark and, ultimately, graduating as a result of studying is in fact a larger, more delayed reinforcer, relative to going to the party, then studying would be considered the self-control decision, whereas going to the party would be considered the impulsive decision. In this case, making an impulsive decision would provide

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immediately available reinforcers, perhaps at the expense of the larger delayed

reinforcers. Therein lies a possible problem: in some cases impulsive decisions not only

forfeit some larger reinforcers, but may also be accompanied by delayed negative

consequences, and it may be in the individual's best interest to induce self-control

choices.

Several possible methods for inducing self control have been proposed and used

in both the experimental and applied settings. Skinner (1953) conceptualized self control

as a class of responses ("controlling" responses) that alter the probability of emitting

other responses. For example, arranging the environment that prevents one from

engaging in impulsive behaviors, or engaging in behaviors incompatible with impulsive

choices would be examples of "self-control" in Skinner's formulation. From this

perspective, "commitment" responses (e.g., Rachlin, 1974; Mazur, 1998) also could be

considered examples of self-control. A common example of a commitment response is

putting a portion of a monthly paycheck into a savings account on payday for use later

rather than having it available at any time to spend.

Commitment responses are unlikely to appear spontaneously, they likely require

appropriate supporting contingencies. A possible preparation for studying the impact of

making such responses available has been investigated explicitly in a laboratory setting.

Rachlin and Green (1972), using pigeons, arranged a situation that was very similar to

what one might do if making a commitment choice such as putting money in the bank.

Responses on one key (the commitment response) ensured delivery a larger reinforcer

after a fixed delay and eliminated the possibility of choosing a smaller, more immediate

smaller reinforcer. Responses on another key at the beginning of a trial resulted in a

delay followed by a choice situation, where both the larger, delayed reinforcer and the smaller, immediate reinforcer were available. The conditions were arranged such that choosing the larger-delayed reinforcer in either situation produced more food overall and, in that sense, was the optimal choice. The issue was whether or not pigeons would make the commitment response. As absolute delay from the choice point at beginning of the trial increased, pigeons choose the "commitment" response more reliably. Theses results suggest that, when given an opportunity, pigeons will make a commitment response (i.e., emit a "self-control" response); however, in some situations, particularly when the initial choice period neared the delivery of the immediate reinforcer, they choose the smaller reinforcer. This finding is characteristic of the "preference reversal" phenomenon in self-control choices. Preference typically shifts to the larger, more delayed reinforcer as the absolute delays to both reinforcers are increased, even as the ratio of delays is unchanged (see Logue, 1988).

The likelihood of choosing a larger, delayed reinforcer can be increased using behavioral techniques such as shaping. In a study reported by Mazur and Logue (1978), two groups of pigeons choose between 2-s and 6-s access to grain. In both groups the larger amount was delayed by 6 s; however, the delay to the smaller reinforcer was 2 s and 6 s for the control and experimental groups, respectively. In the control group, pigeons simply choose between the smaller-immediate and the larger-delayed reinforcers and showed near exclusive preference for the smaller alternative. Pigeons in the experimental group initially were given a choice between larger and smaller reinforcers, each delayed by 6 s. As would be expected, the pigeons chose the larger reinforcer exclusively. The delay to the smaller reinforcer then was shortened gradually (i.e., faded

over 11,000 choice trials) until it reached 2 s. At this point, these pigeons were faced

with an identical choice situation as the control group. As the delay was faded,

preference for the larger reinforcer remained much higher than that obtained in the

control group (and than that predicted by the matching law). These results suggest that

behavioral history is a potent determinant of an individual's inclination to choose larger,

delayed rewards. In addition to providing behavioral histories that might increase self-

control (i.e., the likelihood to choose larger, more delayed reinforcers), pharmacological

manipulations have also been investigated as a means to induce self control.

Behavioral Pharmacology of Self-Control

More recently, as pharmacological regimens increasingly have been incorporated

into treatments for behavioral disorders which appear to involve high rates of "impulsive"

behavior (e.g., ADHD; see Greenhill, 2001), behavioral pharmacologists have turned

their attention to the effects of drugs on responding maintained under self-control

procedures. Effects of some classes of drugs appear to be mixed. For example, Bizot, Le

Bihan, Puech, Hamon, and Thiebot (1999) and Evenden and Ryan (1996) reported that

benzodiazepines alprozalam and diazepam increase choice of larger, delayed reinforcers

while others reported the tendency of alprozalam and chlordiazepoxide to decrease such

choices (see Cardinal, Robbins, & Everitt, 2000; Wolff & Leander, 2002). Ethanol has

also produced mixed results. Several studies reported the tendency of ethanol to reduce

self-control (see de Wit, Crean, & Richards, 2000; Evenden & Ryan, 1999; Feola, de Wit,

& Richards, 2000); however, its has also been reported to have no effect on delay

discounting in humans (see Richards, Zhange, Mitchell, & de Wit, 1999). On the

contrary, effects of other classes of drugs appear to be relatively consistent. For example,

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some reports suggest serotonin reuptake inhibitors (e.g., fluxotenine and paroxetine), at higher doses, tend to increase the choice of larger, delayed reinforcers (see Bizot, et al., 1999; Bizot, Thiebot, Le Bihan, Soubrie, & Simon, 1988; Wolff & Leander, 2002); whereas, opiods (e.g., morphine) tended to decrease the choice of larger, delayed reinforcers (see Kieres, Hausknecht, Farrar, Acheson, de Wit, & Richards, 2004; Pitts & McKinney, 2005).

The effects of drugs classified as psychomotor stimulants, such as amphetamine and methylphenidate, have received substantial attention (Solanto, 1998). These drugs are commonly used in the treatment of children, and increasingly in adults, who are diagnosed with behavioral disorders that often characterized as impulsive (Greenhill, 2001). Although a few of the early studies produced contrary effects (e.g., Charrier & Thiebot, 1996; Evenden & Ryan, 1996; Logue, Tobin, Chelonis, Wang, Geary, & Schachter, 1992), the majority of studies have shown that acute stimulant administration increases the likelihood of making self-control choices, primarily demonstrated by increasing preference for larger, delayed reinforcers. This effect has been replicated in a number of species and in a variety of self-control choice procedures including rats (Cardinal et al., 2000; Pitts & McKinney, 2005; Richards, Sobol, & de Wit, 1999; Wade, de Wit, & Richards, 2000), mice (Isles, Humby, & Wilkinson, 2003), pigeons (Pitts & Febbo, 2004), and humans (Pietras, Cherek, Lane, Tcheremissine, & Sternberg, 2003). Although the specific procedures used differed slightly across these studies, the basic features were all present (i.e., subjects were faced with choices between smaller, more immediate reinforcers and larger, more delayed reinforcers), and in each case choices of the larger, delayed reinforcer were increased subsequent to acute injections of the drug.

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Stimulants have also been shown to reduce impulsivity measures in rats and humans on responding on non-choice "impulsivity" tasks that presumably assess the ability to inhibit responding (de Wit, Enggasser, & Richards, 2002; Feola et al., 2000).

Although differences in effects across drug classes surely point to the importance of pharmacological and neurobiological processes, it is also important to consider the relevant behavioral processes involved. Labeling behavior as "impulsive" or "self-controlling" may suggest important variables, but doing so does not specifically identify them. In an attempt to identify these processes, many have turned to the field of behavioral pharmacology to provide a more in-depth analysis of the interaction of drugs and behavior (Branch, 1984; Thompson & Schuster, 1968). Behavioral pharmacology is a field in the biological sciences, created from the integration of the experimental analysis of behavior and pharmacology, which has facilitated an increase in our understanding of drug effects. The techniques employed in this field have improved our ability to identify and characterize the effects of psychoactive substances, primarily in terms of drug-behavior interactions and the behavioral processes involved in the expression of drug effects.

Typically in the experimental analysis of behavior, operant behavior is studied in highly controlled conditions which contain several significant environmental components. Operant-conditioning preparations typically involve some establishing operation (perhaps food deprivation) which establishes the effectiveness of the consequence, a discriminative stimulus (signal which indicates what contingencies are in place at the moment), the target response(s) (usually key pecks or lever presses in nonhuman studies), and the arranged response-stimulus contingency (the schedule of

reinforcement). By analyzing the change in a dependent measure of behavior across changes of some environmental variable, experimenters are able to make meaningful statements about behavior-environment relationships.   In behavioral pharmacology, experiments are conducted in a similar manner. The subject undergoes training under a certain set of conditions until behavioral stability emerges with respect to some dependent measure (baseline performance), and then several doses of a drug are administered across several conditions. The effects of each dose of the drug are then analyzed and interpreted in terms of the change in behavior relative to baseline. As with operant behavior where behavior patterns are determined by the past and present environmental conditions, the effects of drugs also depend on the environmental conditions surrounding the introduction of a drug. The goal of such an analysis is to identify precisely what drug effects emerge and what variables determine the degree to which certain effects will be expressed (see Branch, 1984; 1991; Thompson & Schuster, 1968).

Some of the earliest work in the field was done with rats and pigeons responding under intermittent schedules of reinforcement. By comparing baseline performance (usually in terms of response rates) to drug performance, experimenters interpreted drug effects in terms of how the drug might affect the environmental conditions controlling behavior. Early research in behavioral pharmacology focused on the schedule (e.g., Clark & Steele, 1966; Dews, 1955; Herrnstein & Morse,1957; Kelleher & Morse, 1968). However, results of a number of studies (e.g., Dews, 1958; Kelleher & Morse, 1964) seemed to suggest that it was the rate generated by the schedule, rather than the schedule contingencies, that best predicted the drug effect. This led to the formulation of one of

the first principles of drug action commonly referred to as rate-dependency (Dews &
Wenger, 1977).

Rate-dependency theory holds that (1) a change in baseline rate will change the
behavioral effect of the drug; (2) there is a systematic relationship between baseline
response rate and the effect of a drug; (3) the rate under drug conditions, or "drug rate"
(expressed as a percentage of the rate under non-drug conditions, or "control rate") is a
linear, usually decreasing, function of control rate (when plotted on log-log coordinates);
and (4) the baseline rate of responding is a primary determinant of the effect of a drug at
a given dose and other variables likely do so indirectly through response rate. A number
of studies have shown that the behavioral effects of a variety of drugs are rate dependent
(see Dews & Wenger, 1977; Sanger & Blackman, 1976). Effects of drugs typically
classified as stimulants (e.g., amphetamines) are prototypically rate-dependent (i.e.,
moderate doses increase low rates and decrease or do not affect high rates) (Clark &
Steele, 1966; Dews, 1958; Dews & Wenger, 1977; Sidman, 1956). In addition, it also
has been shown that effects of a variety of drugs on responding maintained by other
reinforcers often are indistinguishable from that which is maintained by food (Kelleher &
Morse, 1964, 1968; Rapport, DuPaul, & Smith, 1985), indicating that rate-dependent
effects are general across reinforcer types. Rate-dependent effects also appear to be a
general effect across species (see Dews & Wenger, 1977; Sanger & Blackman, 1976).
Behavioral Mechanisms of Drug Action

Rate-dependency was offered as one of the first general principles of the
behavioral actions of a variety of drugs, under a variety of conditions (Dews & Wenger,
1977; Sanger & Blackman, 1976). Indeed, for many behavioral pharmacologists, it

offered the most effective general account of the behavioral actions of drugs available (e.g., McKearney, 1970) and could potentially explain the ability of stimulant drugs to increase self-control (i.e., that is, the drug typically increases choice of the larger delayed reinforcer (a previously low-rate response) and decrease choice of the smaller, immediate reinforcer (a previously high-rate response). For others, however, the case for rate-dependency as a general principle was weakened substantially by a number of exceptions (see Branch, 1984, for an extensive discussion). Notably, behavior under strong stimulus control can be resistant to rate-dependent effects (e.g., Carey & Kritkausky, 1972; Laties, 1972; Laties & Weiss, 1966). For example, Laties and Weiss reported that typical rate-dependent effects under FI schedules were eliminated by an "added clock."

In addition to responding maintained by strong stimulus control, responding reduced by punishment or by conditioned-suppression procedures can be resistant to amphetamine's rate-dependent effects (i.e., low rates were not increased as predicted by the rate-dependency principle). For example, Hanson, Witoslawski, and Campbell (1967) reported *d*-amphetamine decreased high response rates maintained by VI schedule of reinforcement (as predicted by rate-dependency) as well as increased responding previously suppressed by extinction (also predicted by rate-dependency). In contrast, however, response rates suppressed by punishment, which were very similar to those during extinction, were not increased at any dose. In fact, rates were suppressed even further. These results, and those of other studies (see Brady, 1956; Geller, Kulak, & Seifter, 1962), suggest that baseline rates alone do not always predict drug effects, and that the contingencies which produce these rates should also be considered in an analysis of drug effects. In fact, some have suggested that variables other than baseline rate may

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predict drug effects more accurately than baseline response rates. For example, Ruddle, Morley, Bradshaw, and Szabadi (1984) attempted to characterize drug effects using Herrnstein's (1970) matching equation and found that baseline reinforcer rate predicted the effects of pentobarbitone better than response rates. Lancaster and Dallery (1999) reported similar findings for morphine. If it is the case that factors other than baseline responding can predict drug effects more accurately, then it surely must the case that other variables may be utilized to describe and interpret drug effects.

Furthermore, it may be the case that rate-dependent effects in some cases are results of the method of analysis used to investigate these effects. Branch and Gollub (1974) found that rate-dependency under FI schedules could be considered an artifact. Their molecular analysis indicated that *d*-amphetamine essentially shortened pauses and decreased high rates under FI. The apparent intermediate rates in the early and middle parts of FI were artifacts of averaging. When the distribution of response rates across tenths of the interval were analyzed, results revealed that the "average" rates reported during the middle segments of an interval were actually the result of averaging periods of zero-responding in some intervals with periods of rapid-responding in others. The analysis revealed that *d*-amphetamine did not result in increased rates during earlier portions of the interval, per se; instead it increased the likelihood to begin responding, thus shortening pauses. Similar results are reported by Weiss and Gott (1972) in their molecular analysis of the effects of amphetamine, pentobarbital, and imipramine on FR responding. These results suggest, as does Pickens (1977), that rate of responding is a product of behavioral mechanisms such as stimulus conditions, reinforcer parameters, and schedule of reinforcement. Thus, although rate-dependency certainly describes the

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effects of many drugs, another approach might be to provide accounts of these and other effects in terms of the *behavioral mechanisms* of action (Branch, 1984; Thompson, 1984).

A behavioral mechanisms approach involves a systematic analysis of drug effects in terms of the variables that control behavior under non-drug conditions (see Branch, 1984; Thompson, 1984; Thompson & Schuster, 1968). According to this approach, identification of behavioral mechanisms of action requires (a) descriptive accounts and experimental control of variables that affect behavior under non-drug conditions (e.g. deprivation level; discriminative stimuli; conditioned reinforcement; and, rate, amount, and delay of reinforcement) and (b) the means to identify and quantify exactly how control by these variables is affected by drug administration. Fortunately, the experimental analysis of behavior is well suited for meeting both requirements. One possible method for elucidating such mechanisms may be the use of quantitative methods.

Quantitative Analysis and Behavioral Pharmacology

For some time now the use of quantitative methods in the experimental analysis of behavior has been quite useful in identifying and precisely characterizing the functional relationships between the environment and behavior (see Shull, 1991). With the proper experimental control over behavior, behavior analysts are able to measure and quantify behavior across a range of changing conditions, identify regularities in the data, and develop mathematical models that aid in the development of theories regarding behavior-environment relationships (see Nevin, 1984).

Given the success of quantitative methods and mathematical models in the analysis of behavior under non-drug condition, it is not surprising that this approach has been used in behavioral pharmacology. In many cases, a drug may produce an effect that could be the result of its effect on one mechanism, several possible mechanisms working in conjunction, or a differential effect across mechanisms; the use of a mathematical model may be helpful in teasing apart and revealing these mechanisms. Researchers have made several attempts to characterize drug effects in such a way.

Some investigators (e.g., Appel & Dykstra, 1977; Dykstra & Appel, 1974) have used signal-detection analyses (cf. Green & Swets, 1966) to characterize effects of amphetamine, chlorpromazine, LSD, and marijuana, all of which have been alleged to cause "perceptual distortion" in some form or another. In their signal-detection tasks, Dykstra and Appel had rats or pigeons respond on one or the other of two operanda depending upon the intensity of the stimulus that had been presented. For instance, on trials in which a higher intensity tone was presented, a right-side lever press was followed by food or water presentation, and a left-side lever press was under extinction, or punished. On trials in which a lower intensity tone was presented, a response on the left-side lever was reinforced while a response on the right lever was under extinction or punished. They presented a range of comparison stimuli, which differed along one dimension such as color, pitch, or duration, changed the probability of reinforcement following correct responses, and measured the number of correct responses and errors. A signal-detection analysis separates stimulus control into two components, the "discriminability" of a stimulus (d'), which presumably characterizes the ability of the subject to detect a stimulus (or a difference between two stimuli) against background

"noise," and response bias (β), which is a measure of the likelihood the subject will report the presence or absence of a stimulus (or difference in stimuli), independent of discriminability. Dykstra and Appel obtained values of d' and β for baseline and drug conditions and were able to quantify the drug effects in terms of shifts in stimulus discriminability and/or response bias, two possible mechanisms of the drug effect.

For example, in one experiment, rats were presented a range of tone intensities (2000Hz-5000Hz). LSD produced a dose-dependent shift in bias, though not systematically in one direction, and produced no change in sensitivity. In a similar experiment rats responded with respect to tone durations (1.25s -2.25s), and LSD shifted response bias independent of a shift in sensitivity. A shift in response bias suggests a drug-induced change in the effects of the establishing operation (see Nevin, 1969; Nevin, Olson, Mandell, & Yarensky, 1975). In a later experiment, rats and pigeons were trained to respond according to tones and lights of varying durations and, in addition to LSD, amphetamine, chlorpromazine, and marijuana were tested. The results from each of these experiments suggested amphetamine, chlorpromazine, and marijuana all produced decrements in discriminability without changing bias, while LSD, again, produced a shift in bias (Appel & Dykstra, 1977).

Although the shift in either bias or discriminability by drug administration can occur independently (which may suggest two possible mechanisms of drug action), and the model describes the data well, it is unclear whether or not this means that behavioral mechanisms have been identified conclusively. For example, response bias can be influenced by a number of variables (e.g., rate of reinforcement, establishing operations). Thus, it is unclear whether or not each parameter of the signal-detection model represents

a unitary phenomenon. Therefore, this model may serve better as an organizational principle to describe drug effects rather than a tool to identify mechanism of drug action (cf. Dallery & Soto, 2004).

Behavioral Mechanisms and the Matching Law

More recently, researchers have focused on the use Herrnstein (1970)'s single-alternative matching equation to identify behavioral mechanisms of drug action. Herrnstein (1970) suggested that even when one alternative is available (e.g., a single lever in an operant chamber which produces food) other forms of unidentified, extraneous reinforcement are also available as a result of other behaviors (e.g., resting, sniffing, cleaning). This arrangement, then, can be conceptualized as a concurrent schedule of reinforcement (i.e., the individual may either engage in the target response (maintained by the specified reinforcer) or other behaviors (maintained by unmeasured, often referred to as "extraneous," reinforcers)(de Villiers, 1977; Herrnstein, 1974; Mazur, 1998). As a result of this conceptualization Herrnstein, proposed the single-alternative matching equation, which is a modification of Equation 1 and given below.

$$B = kR/(R+R_e) \tag{9}$$

This equation describes an increasing, negatively accelerated hyperbolic function relating the rate of the target response (B) to the rate of reinforcement obtained for that response (R). The shape of the hyperbola is characterized by two parameters: the asymptote (k) and the rate at which the function reaches asymptote (R_e). According to Herrnstein's (1970, 1974) conceptualization, k is the maximum rate of responding of all possible behaviors in a particular situation (maintained by specified and extraneous reinforcers and scaled in terms of the programmed operant) and directly reflects the individual's

motoric capacity. Generally, k can be manipulated through changing characteristics of the target response (e.g., force required to operate the lever). Parameter R_e is the reinforcer rate necessary to maintain one half of the maximum response rate and reflects the rate of reinforcement from other concurrently available, but unmeasured, sources or reinforcement. Changes in R_e reflect changes in the efficacy of either specified reinforcers (often manipulated by altering reinforcer magnitude, subject deprivation levels) or changes in the efficacy of extraneous reinforcers (often manipulated by providing alternative sources of reinforcement). These two processes are, presumably, independent of one another (i.e., manipulations that affect k should not affect R_e, and vice versa) (see Dallery & Soto, 2004).

This version of the matching law, which has been very successful in describing the relationship between reinforcer rate and response rate in single-alternative arrangements (see de Villiers, 1977; Davison & McCarthy, 1988), identifies two possible behavioral mechanisms of drug action. That is, a drug may alter the effects of motoric (k) and/or motivational (R_e) variables (Dallery & Soto, 2004). In a series of experiments, researchers have assessed the effects of a variety of drugs using this analysis. In these experiments, rats typically lever pressed under a multiple VI schedules of reinforcement. The values of the VI (i.e., rate of reinforcement) were varied across components (i.e., within sessions) which enabled them to fit lines to response rate data using the matching equation and compare R_e and k across conditions (Belke, & Neubauer, 1997; Heyman, 1983; Heyman, 1992; Heyman, Monaghan, & Clody, 1987; Heyman, Kinzie, & Seiden, 1986; Heyman, & Seiden, 1985; Murray & Kollins, 2000; Willner, Sampson, Phillips, & Muscat, 1990) .

Early research using this matching analysis suggested that the rate-decreasing effects of moderate doses of dopamine antagonists (e.g., pimozide and chlorpromazine) were correlated with increases in R_e (decreased motivation to respond) but relatively little change in k (motor capacity) (Heyman, 1983; Heyman, et al., 1986; Willner, et al., 1990); higher doses of these drugs tended to decrease both R_e and k (Heyman, 1983; Heyman et al. 1986). These results are similar to those reported by Willner, et al.(1990) with the dopamine antagonists sulpiride and SCH-23390, which suggests that, at low to moderate doses, these drugs decrease reinforcer efficacy (i.e., decrease relative-effectiveness of scheduled reinforcers) rather than reducing the subject's ability to respond. Another dopamine antagonist, *cis*-flupenthixol, has been reported to decrease k with relatively little change in R_e (see Heyman, et al., 1987) which suggests an effect on motoric ability. Some proposed this difference may result from the substances' affinities to bind at different dopamine sub-receptors (see Dallery & Soto, 2004, for a brief discussion). Dopamine agonists (e.g., amphetamine and methylphenidate), across a range of doses, tended to produce mixed results with respect to R_e and k. For example, some have reported that *d*-amphetamine decreased R_e (i.e., increase relative effectiveness of scheduled reinforcers) at lower doses with little change in k (Heyman, 1983; Belke and Neubauer, 1997). Other studies reported lower to moderate doses of *d*-amphetamine and methylphenidate have been reported to decrease R_e whereas the highest doses increased both parameters (see Heyman, 1992; Heyman & Seiden, 1985). Recently, Murray and Kollins (2000) assessed the effects of methylphenidate on children diagnosed with ADHD responding on VI schedules. The only dose tested (10 mg) increased both parameters, as well as improved the fit of the matching equation to response rate data,

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suggesting methylphenidate increased motoric capacity, decreased reinforcer efficacy, and, potentially, increased the subject's sensitivity to reinforcer rate; however, these effects remain unclear. Nevertheless, these results suggest that drugs altering the dopamine system may, in fact, affect reinforcer effectiveness to a greater degree than ability to respond. In contrast, similar studies using opioids suggested that morphine (Lancaster & Dallery, 1999), methadone, and buprenorphine (Egli, Schaal, Thompson, & Clearly, 1992) generally produced decreases in k which suggested that the rate-decreasing effects of some opioids are the result of a decreased ability to respond rather than reinforcer effectiveness.

The results reviewed above suggested that Herrnstein's (1970) matching equation may be an effective tool for identifying behavioral mechanisms of action. Some drugs at certain doses clearly produce effects on the capacity of the reinforcer to maintain responding whereas others affect the subject's ability to respond. Dallery and Soto (2004) pointed out, however, that the utility of a given quantitative model in identifying behavioral mechanisms of drug action depends on the validity of its theoretical implications. As discussed above, Herrnstein's (1970, 1974) conceptualization includes two independent processes which characterize the relationship between reinforcer and response rates (the reinforcer efficacy and the subject's motoric capacity). Following a review of the relevant literature, Dallery and Soto concluded that while some basic tenets of the matching law were upheld (i.e., changing response and reinforcer characteristics, indeed, alter k and R_e, respectively), they are not entirely independent. For example, changes in reinforcer magnitude and deprivation have been shown to affect k (see Lancaster & Dallery, 1999; McDowell & Dallery, 1999) suggesting that this particular

model may not the optimal model for identifying behavioral mechanisms of action.

However, despite the issues associated with the validity of the matching law, quantitative

methods may still be a useful avenue to investigate behavioral mechanisms.

Stimulants, Delay-Discounting, and a Quantitative Model

Pitts and Febbo (2004) used quantitative methods to characterize effects of

methamphetamine on a self-control choices in pigeons. They suggested that two possible

mechanisms may be involved in any drug effect on self control: (1) a drug-induced

change in the sensitivity to delay and/or (2) a drug-induced change in the sensitivity to

amount. Theoretically, changes in the effects of both variables, in conjunction or

separately, could influence preference of larger delayed reinforcers. The stimulant-

induced increase in choices of larger, delayed reinforcers typically reported (Cardinal et

al., 2000; Isles, et al., 2003; Pietras, et al., 2003; Pitts & Febbo, 2004; Pitts & McKinney,

2005; Richards, et al., 1999; Wade, et al., 2000), then, could be the result of a decrease in

the sensitivity to delay (i.e., delay has a reduced effect on responding) and/or an increase

in sensitivity to amount (i.e., amount has a enhanced effect on responding).

In their experiment, pigeons chose between two amounts of food, 4-s access to

grain and 1-s access to grain, each associated with a signaled delay (a red or green

houselight uniquely correlated with a particular delay and amount). The delay to the

smaller amount remained constant at 2-s, while the delay to the larger amount increased

within session from 2-s to 40-s across five components, enabling an investigation of the

effects of several delays on choice within sessions. They used a modified version of

Equation 6 to describe the effect of delay on choice. To accommodate the finding that

delay discounting appears best described by a hyperbolic discounting function (Mazur,

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1987), the delay term from the matching law, D_L/D_S, was replaced with $[(1+D_L)/(1+D_S)]$ as given by the following equation:

$$\log (B_L/B_S) = S_A\log (A_L/A_S) - S_D\log [(1+D_L)/(1+D_S)] \qquad (10).$$

In this study, the ratio of amount (A_L/A_S) was held constant at 4 (4/1), and the ratio of delays, $[(1+D_L)/(1+D_S)]$, ranged from 1 to approximately 20 (from 2/2 to 40/2). According to this equation, preference for the larger, delayed reinforcer is a decreasing linear function of its delay, with the slope of S_D and y-intercept of $0.6(S_A)$. Thus, in this formulation, a change in sensitivity to delay appears as a change in the slope, whereas a change in the sensitivity to amount appears as a change in the y-intercept .

Under control conditions, Pitts and Febbo (2004) reported that preference for the larger reinforcer decreased as a function of its delay, and Equation 10 provided an excellent description of the data. For all four pigeons, at least one dose of methamphetamine decreased the slope of the function which was interpreted as a drug-induced decrease in the sensitivity to delay. In some instances, this decrease in slope also was accompanied by a decrease in the y-intercept which, according to their analysis, could be interpreted as a drug-induced decrease in sensitivity to amount; this effect was particularly pronounced in one of the pigeons. The decrease in y-intercept was a result of the subjects' choice of the smaller reinforcer in the first component when the delays to both the large and small reinforcers were equal; under control conditions they chose the large reinforcer nearly exclusively in the first component. It is possible then, that the size of the larger reinforcer had a diminished effect under drug conditions, and suggests that sensitivity to amount may be a possible mechanism involved in these situations.

As these two mechanisms represent opposing effects of the drug, Pitts and Febbo (2004) suggested that in situations where stimulants decreased choice of larger reinforcers, the decrease in sensitivity to reinforcer amount may have been more readily expressed, and the degree to which either effect is expressed may depend on procedural differences. For example, earlier studies that report a stimulant-induced decreased in the larger, delayed reinforcer (e.g., Charrier & Thiebot, 1996; Evenden & Ryan, 1996) used unsignaled delays (i.e., stimulus conditions were no different between the delay period and the inter-trial interval) while later studies which reported a stimulant-induced increase in choice of larger, more delayed reinforcers (e.g., Richards et al., 1999, Pietras et al., 2003; Pitts & Febbo, 2004; Pitts & McKinney, 2005; Wade et al., 2000) used signaled delays (i.e., a unique stimulus signaling the delay). It could be the case that the signaling conditions during the delay are an important determinant of drug effects under procedures investigating delay to reinforcement (see Pitts & Febbo, 2004; Pitts & McKinney, 2005, for thoughtful discussions). Nevertheless, the reported decrease in y-intercept also warrants further investigation.

Pitts and Febbo (2004) concluded out that while the decrease in y-intercept may suggest a decrease in sensitivity to amount, interpretation of the decreases in y-intercept is challenging because only one reinforcer amount ratio was presented. A change in this parameter could reflect a drug-induced change in sensitivity to amount, but also could reflect a change in bias for one option over the other produced by some unknown source(s) (see Baum, 1974). Thus, sensitivity to effects of reinforcer amount and bias produced by some other factor were completely confounded their procedure.

The original purpose of this study was to investigate effects of methamphetamine on sensitivity to reinforcer amount. A successful characterization of drug-induced changes in sensitivity to amount using the present analyses (i.e., quantitative methods) would perhaps reveal a possible behavioral mechanism involved in drug-induced increases in "self-control" choices (i.e., changes in sensitivity to reinforcer amount) as well as validate further the use of quantitative methods as a means to identify behavioral mechanisms of drug action. To produce a baseline of responding sufficiently sensitive to reinforcer amount, a procedure reported first by Belke and Heyman (1994), and later by Davison and Baum (2003) was used because it arranged for several reinforcer amount ratios to be presented within session and their results suggest that subjects were sensitive to the manipulation. Unfortunately, difficulties replicating the results reported by Davison and Baum (see Experiment 1) precluded investigation of drug effects under this procedure. As a result, the present study became an exploration of the conditions under which pigeons' choices would show sensitivity to reinforcer amount, the results of which are reported in Experiments 2 and 3.

EXPERIMENT 1

Problems that typically arise when studying effects of reinforcer amount on choice include: (a) weight gain during the session, leading to possible satiation, (b) a tendency for responding to be less sensitive to reinforcer amount than other variables, such as reinforcer rate (see Davison & Baum, 2003; Schneider, 1973), and (c) the issue of obtained versus arranged reinforcement, which could bias data analyses (see Baum, 1974). Because the original purpose of this study was an investigation of the effects of pharmacological manipulations on sensitivity to reinforcer amount, while trying to

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minimize the effects of bias, it was important that these issues be addressed. Also, it was important to develop a baseline procedure that allowed within-session assessment of sensitivity to amount. This is important because it might allow for a session-by-session estimate of sensitivity to reinforcer amount with which to compare the effects of methamphetamine.

A procedure used by Davison and Baum (2003) appears to have favorably resolved the issues stated above. In their study, pigeons responded under concurrent VI 30-s schedules. Reinforcer amount ratios were manipulated across components within each session. The order of exposure to the amount ratios was randomly determined and there was no exteroceptive stimulus signaling the amount ratio currently in effect (i.e., a mixed, concurrent VI schedule of reinforcement). Each amount ratio was in effect for ten reinforcers within each component. Davison and Baum reported no instances of excessive weight gain during the session while using this procedure. In addition, behavior appeared to be sufficiently sensitive to amount, albeit less so than is typically the case under steady-state conditions; average sensitivity ranged from 0.22 to 0.31 after nine reinforcer deliveries in each component compared to a range of 0.7 to 1.2 reported under steady state conditions using a variety of reinforcer amount manipulations (see Brownstein, 1971; de Villers & Millenson, 1972; Iglauer & Woods, 1974; Schneider, 1973; Todorov, 1973; Todorov et al., 1984). Finally, instead of using one hopper presentation of a given duration to manipulate reinforcer amount, which could produce lead to a lack of correspondence between presented and actually obtained reinforcement (see Epstein, 1981), amount was manipulated by varying the number of consecutive 1.2-s hopper presentations. This type of procedure for manipulating amount has previously

been used successfully (Davison & Baum, 2000, 2002, 2003; Landon, Davison, & Elliffe, 2002, 2003; Pitts & Malagodi, 1996).

Local Preference

In addition to a component by component analysis of effects of reinforcer amount on preference, the present study also provided a local analysis of preference. In a series of experiments, Davison, Baum, and colleagues (Davison & Baum, 2002, 2003; Landon, Davison, & Elliffe, 2002, 2003) analyzed the effects of reinforcer rate and amount on preference during each inter-reinforcer interval. Generally, they found that following both rate or amount manipulations (usually conducted within sessions), each delivery of a reinforcer, from either alternative, produces an immediate, brief shift in preference toward the most recently reinforced alternative followed by a return toward indifference, similar to the "positive recency effect" which has been previously noted (see Buckner, Green, & Myerson, 1993; Mazur & Bailey, 1990). For example, if a component arranged that the ratio of reinforcer amounts on the left and right alternatives were 3 to 1, the matching equation predicts that the overall ratio of left to right responses for the component would be approximately 3 to 1. In general, this was found to be the case. An analysis of response ratios between reinforcers, however, revealed that briefly (i.e., 10-15 s) following reinforcer presentation, response ratios heavily favored the most recently reinforced alternative. These were dubbed "preference pulses" and appeared reliably when both reinforcer rate and amounts were manipulated. The size and duration of these pulses, however, depended on the difference between the two alternatives. When each alternative provided food at the same rate or the same amounts, pulses were similar for each alternative. As the alternatives became increasingly different, pulses were more

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extreme and lasted longer for the larger or richer of two alternatives; however, there were clear indications of pulses for the smaller, leaner alternatives. It seems, then, that the size and duration of preference pulses are directly related to the reinforcer ratios arranged for each component.

An additional purpose of the present study was to attempt to reproduce these preference pulses, and then characterize the effects of methamphetamine on choice using Davison and Baum's (2002; 2003) local analysis. To date, no studies have been reported using such analyses to assess the effect of drugs on choice. As one possible behavioral mechanism of methamphetamine's effects is to change the subject's sensitivity to reinforcer amount; methamphetamine may reduce the size and duration of the preference pulses following reinforcer presentations (in the case of a drug-induced decrease in sensitivity), increase the size and duration (in the case of a drug-induced increase in sensitivity), or produce other systematic effects with respect to preference pulse characteristics. In either case such an analysis might reveal more information about the behavioral mechanisms involved in methamphetamine's effects on choice than an analysis in terms of overall response ratios and, thus, might help reveal more fundamental process involved in reinforcement (see Branch, 2006).

Method

Subjects

Four male White Carneau pigeons (*Columba livia*) (405, 1809, 1863, 9337) served as subjects. Two pigeons (1809 and 1863) had previous experience with a two-key concurrent-chains procedure and had previously received several does of methamphetamine (see Pitts and Febbo, 2004); the two remaining pigeons (9337 and

405) were experimentally naïve. All pigeons were maintained at 80% of their free-feeding weight via post-session access to mixed grains (Purina [R]) and housed individually in a colony room under a 12-hr light:dark cycle (lights on at 7:00 a.m.). Water and health grit also were continuously available in home cages.

Apparatus

Two operant-conditioning chambers were used (BRS/LVE, Inc. model SEC-002) each with an internal space of 35.0 cm deep by 30.5 cm wide by 36.0 cm high. One wall of each chamber was constructed of aluminum and contained three response keys arranged in a horizontal line, 26 cm above the chamber floor and 8.5 cm apart (center to center). Each key was 2.5 cm in diameter and required approximately 0.25 N of force to activate its corresponding switch; only the two side keys were used in this study. Each side key was 9.0 cm from its adjacent wall and could be illuminated yellow, red, or green. A 5.0 cm by 6.0 cm rectangular hole, through which food grain was presented, was located 11.0 cm directly below the center key. During grain presentations, all key lights and houselights were extinguished and a white hopper light, located in the hopper, was illuminated. A 1.2-W houselight was located 6.5 cm directly above the center key. Green and red houselights, which were inoperative during this study, were located 5 cm to the left and right of the white houselight, respectively. Each chamber was equipped with an exhaust fan for ventilation, and white noise was present in the room during the session to mask any extraneous sounds. Experimental events were programmed and data recorded in an adjacent room by a Dell Optiplex[R] PC compatible desktop computer using Med Associates 4.0[R] (Georgia, VT) software and interface equipment operating at a 0.01-s resolution.

Behavioral Procedure

Because two pigeons (1809 and 1863) had previous experience with a two-key choice procedure, they required no additional training. For pigeons 9337 and 405, however, adaptation and magazine training occurred over three 20-min sessions. Key pecking was hand-shaped on the center key using the method of successive approximations followed by two brief sessions (50 reinforcers each) of FR 1 reinforcement. Then, for two sessions, side-key pecking was trained using a multiple, left-key FR 1, right-key FR 1 schedule of reinforcement for a total of 40 reinforcers per session. Under this procedure one key was illuminated yellow for a total of 10 reinforcers and then extinguished; at that point the other key was illuminated yellow for 10 reinforcers. Sessions lasted for two cycles in which a cycle includes one of each component. Following initial training, key pecking was reinforced on concurrent variable-interval (conc VI) schedules using the side keys. Each of the side keys were illuminated different colors (red and green, position counterbalanced across subjects). The conc VI values were increased from 2 to 30 s as comparable response rates increased on both keys. Reinforcement during initial training consisted of a single 2.5-s hopper presentation.

Once response rates were deemed stable, the experimental procedure was implemented and remained in effect for the duration of the experiment. This procedure also involved a conc VI 30-s contingency. In addition, the relative reinforcer amount was manipulated within each session. Sessions consisted of five components, each component lasted 12 reinforcer deliveries. Each component began with two "forced-choices," during which only one of the two alternatives was available at a time. For

example, the left key was illuminated (either red or green) and the first response on that key after 5 s (fixed-interval, or FI, 5-s) produced the arranged number of hopper presentations available on that key during the current component. Then that key was extinguished and the other key was lit with an FI 5-s contingency in effect for the arranged reinforcer amount. The order of forced-choice trials within each session was random, with the constraint that one key was illuminated first for three components and the other was illuminated first for the other two components.

Following the forced choices, both side keys were illuminated, one red and one green, and reinforcement was made available according to a single conc VI 30-s schedule (Stubbs & Pliskoff, 1969). For the remaining 10 reinforcers, 5 were arranged for the left and 5 on the right, and each key had 5 intervals (Fleshler & Hoffman, 1962) which were sampled without replacement, and reinforcement was arranged on either key with equal probability. This schedule ensured sampling of both alternatives and held reinforcer rate constant across both alternatives. A 2-s changeover delay (Herrnstein, 1961) was also in effect such that reinforcers were not presented following any responses made within 2 s following a switch from one key to another.

Reinforcer amount was manipulated within session using a procedure similar to that reported by Davison and Baum (2003) and Landon et al. (2003). Reinforcement consisted of an experimentally arranged number of 1.2-s hopper presentations, ranging from one to five. Multiple hopper presentations were separated by 0.5 s. During hopper presentation, the hopper light was illuminated and all other lights in the chamber were extinguished; in between multiple hopper presentations all lights were off. During this phase, each component was associated with a different reinforcer amount ratio (A_L/A_R:

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1/5, 2/4, 3/3, 4/2, 5/1) where A_L and A_R were the number of hopper presentations presented following responses on the left and right keys, respectively. The order of the amount ratios within each session was determined randomly by selecting from the list without replacement. The sum of both alternatives in each component equaled 6 to hold total reinforcer amount constant across components. Components were separated by a 30-s blackout period during which responses had no programmed consequences. The different components were not explicitly signaled. Experiment 1 lasted for approximately 80 sessions (79, 78, 70, and 78 sessions for pigeons 9337, 1809, 1863, and 405, respectively); sessions lasted for approximately 40 min.

Data Analysis

For each component the number of responses and the amount of time spent responding on each alternative were collected. Data from forced-choice trials were collected but were excluded from the present analysis. Time allocation was obtained by starting a timer following the first response on one side key which ran until a switch is made to the other side or a reinforcer is delivered. Ratios of responses (and time spent) on the left key to responses (and time spent) on the right key (B_L/B_R and T_L/T_R) were calculated for each component. The average response and time ratios were then computed for each amount ratio (A_L/A_R) and analyzed using the following equation,

$$\log (B_L/B_R) \text{ or } \log (T_L/T_R) = S_A \log (A_L/A_R) + \log k \qquad (11),$$

where B represents responses on the left and right keys, and A is the amount. Sensitivity (S_A) of response and time allocation was then derived by taking the slope of the line while a measure of bias, k, was derived by taking the y-intercept. For all pigeons, across most components, response and time allocation closely resembled one another, and,

therefore, time allocation data will not be presented, except where noted. For a within component analysis of responding, response ratios were calculated for each successive fifth of each component (i.e., successive pair of inter-reinforcer intervals). This was done summing up all left and right responses during each fifth and calculating the ratio.

For local preference analyses, which were similar to those employed by Davison and Baum (2003), each event during the session was time-stamped and coded as either a left- or right-key response, or a reinforcer delivery. Then, for each component the number of left- and right-key responses made at each location in the response sequence following a reinforcer (e.g., the first, second, third, etc. response following a reinforcer) were summed and a ratio of left to right responses was then calculated. Only data from an inter-reinforcer interval beginning with a "choice" reinforcer were included in this analysis, and data were pooled across the last 20 sessions of the experiment.

Results and Discussion

Plotted in Figure 2 are mean log response (closed circles) and time (open circles) ratios (L/R) as a function of log amount ratios for each pigeon. The data were taken from the last half of each component (i.e., the last five intervals) of the last 20 sessions of the experiment. For all pigeons, response and time ratios were insensitive to the amount manipulation as evidenced by the flat, or near zero, slopes of the regression lines. Sensitivity parameters ranged from -0.016 to 0.052 and -0.012 to 0.029 for response and time allocation, respectively. Bias estimates (k), obtained by taking the y-intercept of the regression lines, ranged from 0.15 to 0.31 and 0.04 to 0.20, respectively for response and time ratios, indicating that all pigeons had a slight bias for the left key.

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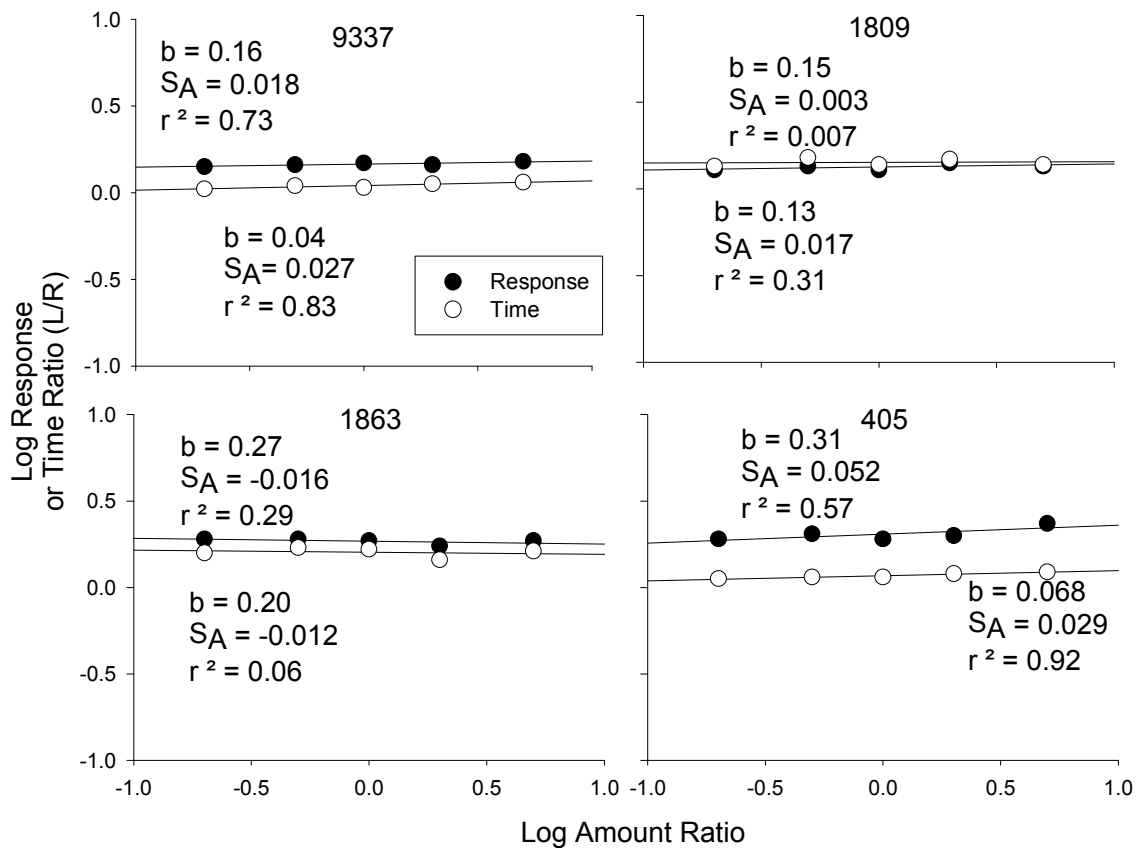
Fig. 2. Experiment 1: Log response and time ratios (L/R) plotted as a function of log amount ratios (L/R). Filled and open circles represent response and time ratios, respectively. The values shown are the y-intercept (b), slope (S_A), and fits (r^2) of the regression lines.

Figure 3 shows mean log response ratios across successive fifths from each component for each pigeon. For all pigeons, response ratios were relatively constant across the component, as indicated by the flat curves, and in favor of the left key, as all values are greater than 0.

Figures 4, 5, 6, and 7 show the results of the preference-pulse analyses for pigeons 9337, 1809, 1863, and 405, respectively. Plotted are response ratios for successive responses following a reinforcer delivery via either the left or right alternative (denoted by filled and open circles, respectively) up to, and including, the sixtieth response. Data points on the far right portion of the x-axis represent the ratio of approximately 90 responses. Note that as the x value increases the number of responses included in the ratio decreases because the likelihood that of an interval timing out increases with time, which necessarily reduced the opportunity for the pigeons to respond. The amount ratio in effect is indicated at the top of each panel.

A similar pattern of responding emerged among all pigeons: immediately following reinforcer delivery, responding was heavily biased towards one alternative then shifted towards the other alternative by approximately the tenth response, and the response ratios continued to oscillate about indifference (i.e., where $\log (B_L/B_R) = 0$) through the sixtieth response. The first 10 responses after a reinforcer were biased toward the left key for three pigeons (9337, 1809, and 1863) and toward the right key for 405. For Pigeons 9337 and 405, the oscillations of preference were more extreme than
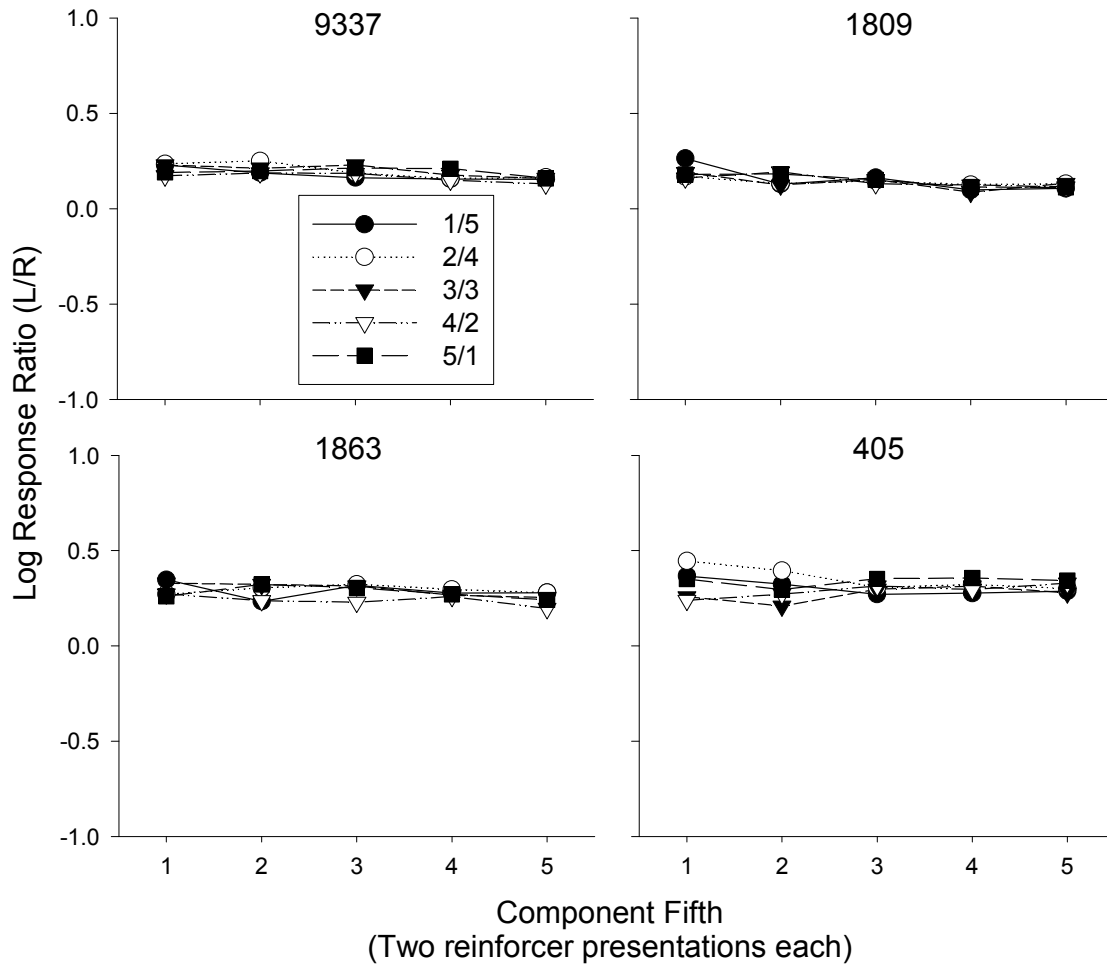
Fig. 3. Experiment 1: Log response ratios plotted for each successive component fifths (pairs of intervals) for each amount ratio.
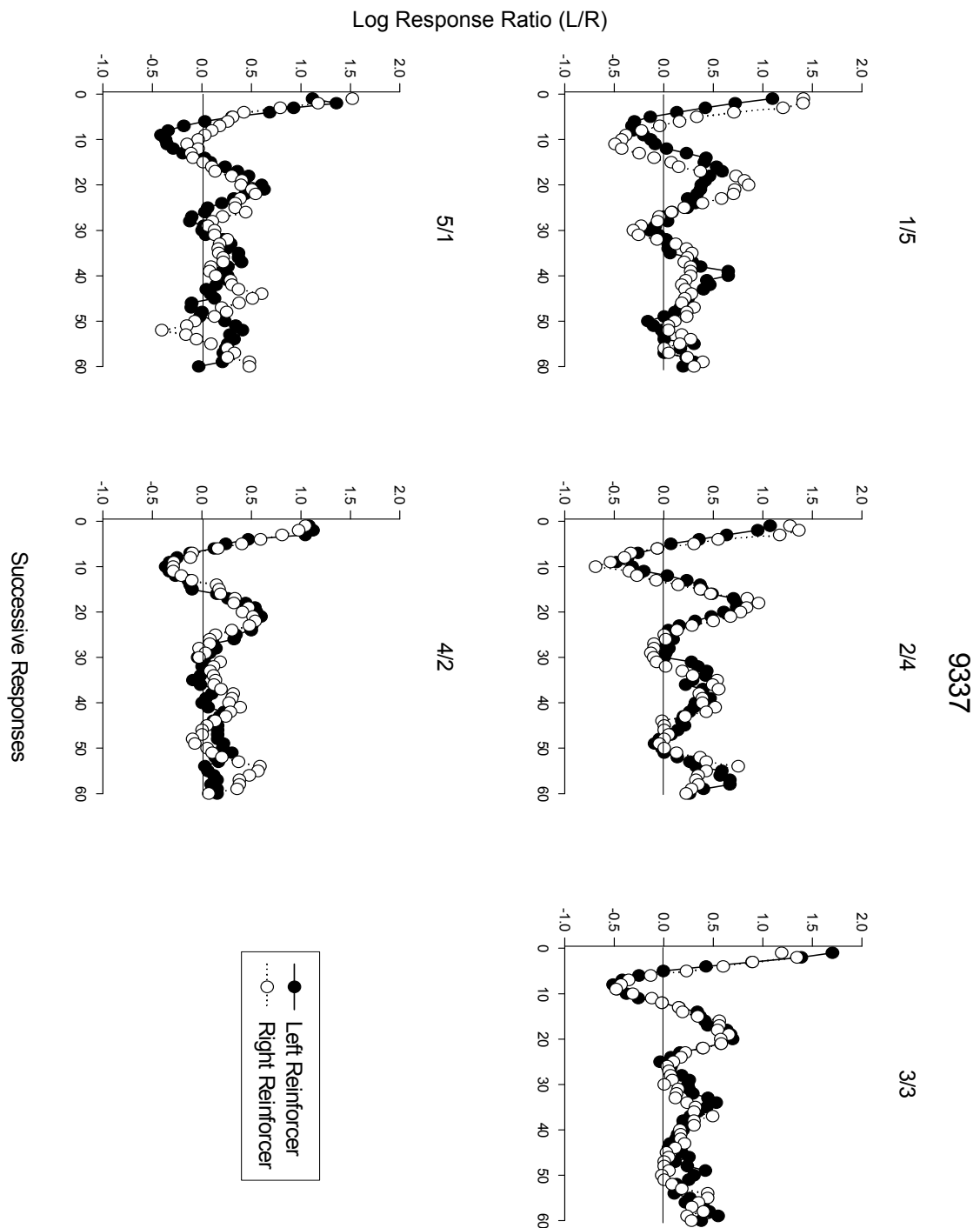
Fig. 4. Experiment 1: (Pigeon 9337) Log response ratios of successive responses following a reinforcer delivered via the left (filled circles) and right (open circles) alternatives.
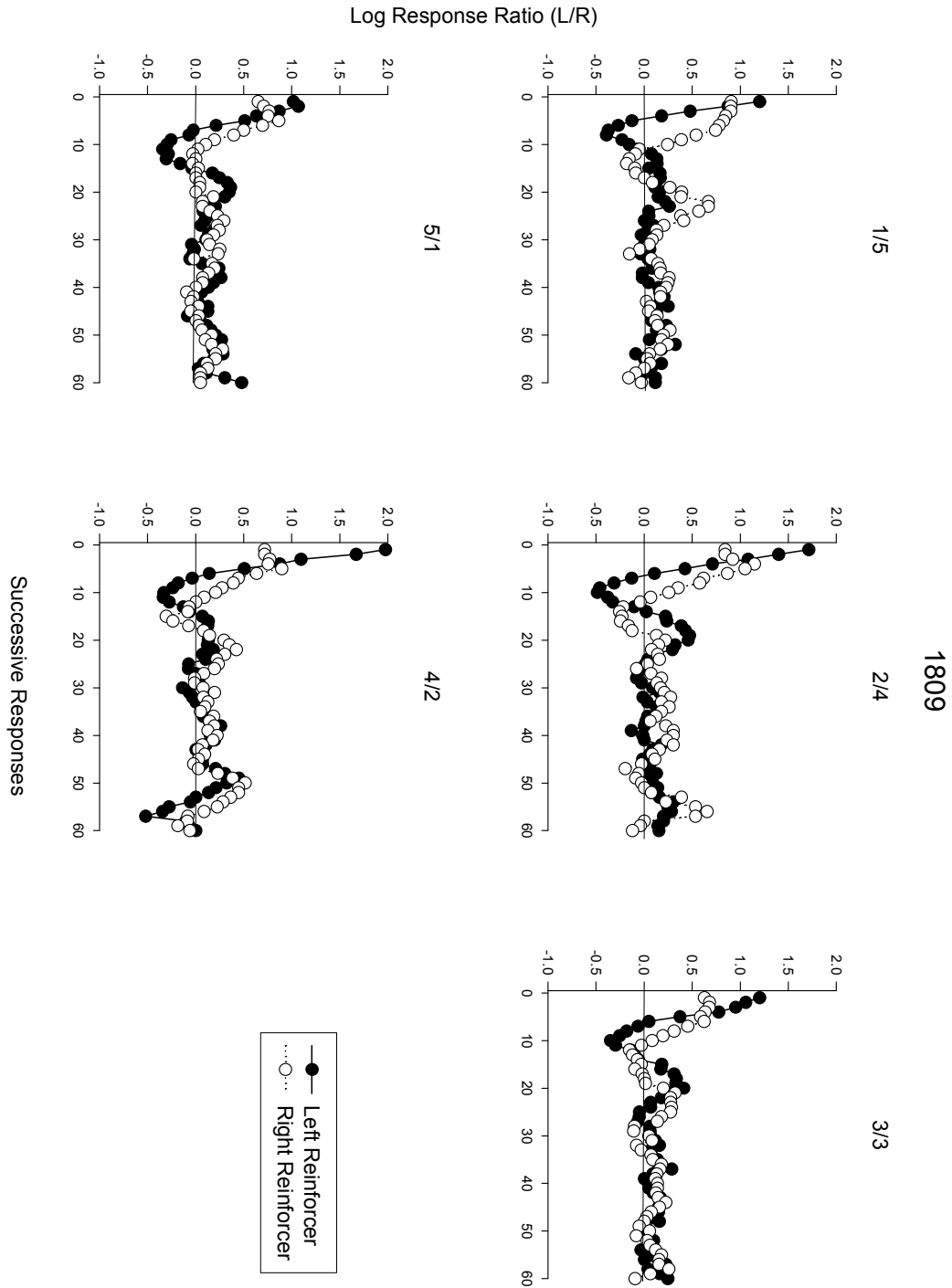
Fig. 5. Experiment 1: (Pigeon 1809) Log response ratios of successive responses following a reinforcer delivered via the left (filled circles) and right (open circles) alternatives.
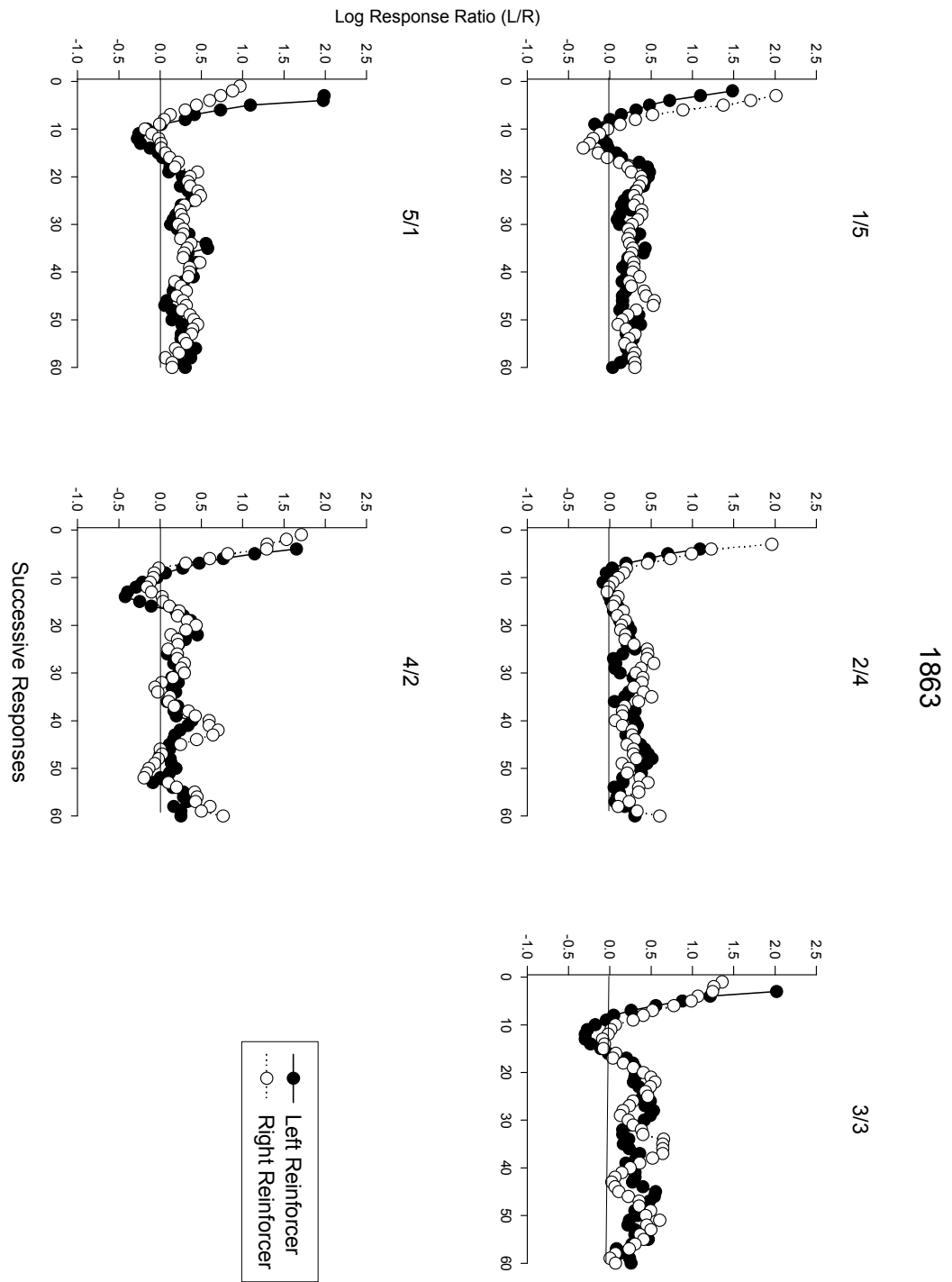
Fig. 6. Experiment 1: Pigeon (1863) Log response ratios of successive responses following a reinforcer delivered via the left (filled circles) and right (open circles) alternatives.

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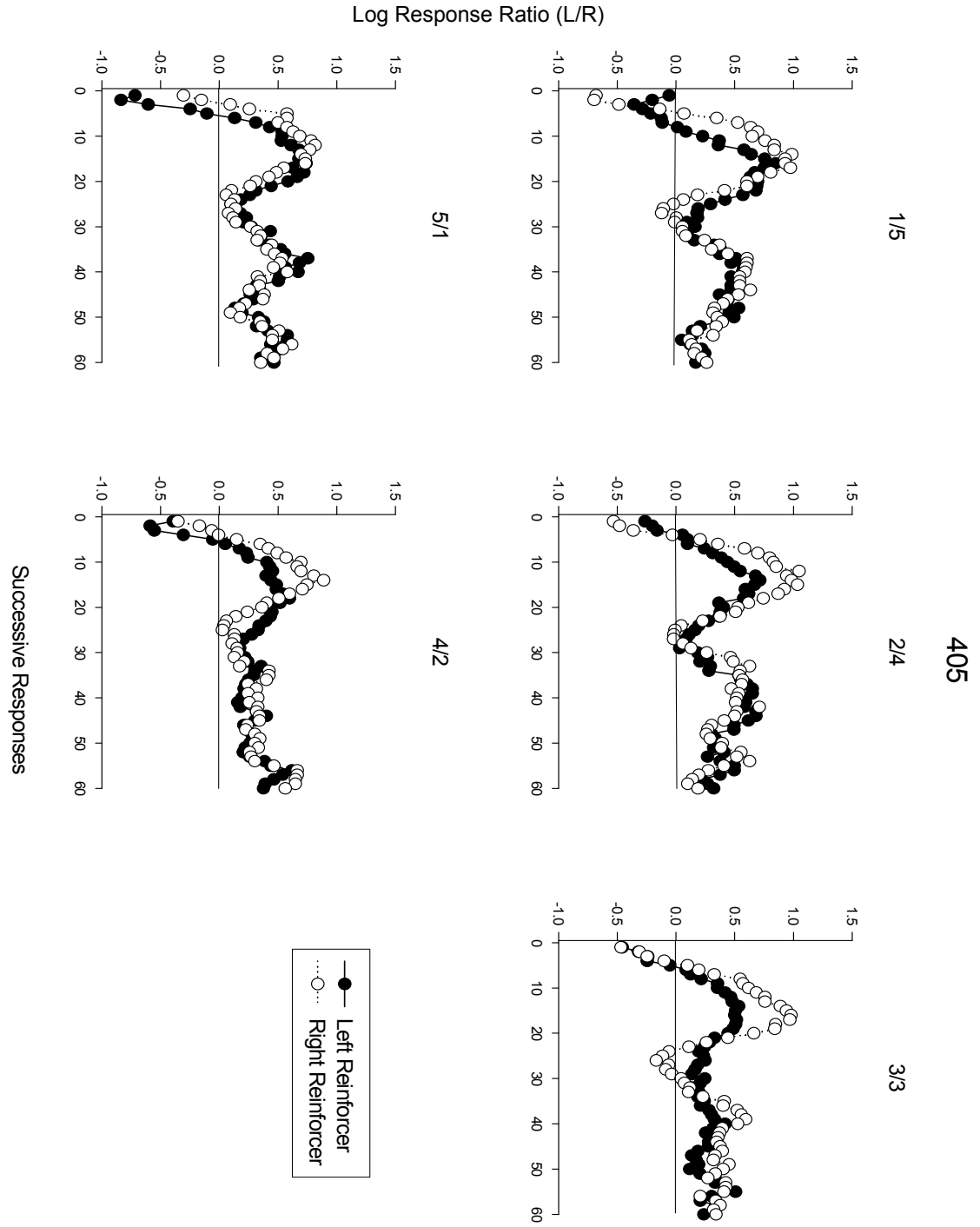
Fig. 7. Experiment 1: (Pigeon 405) Log response ratios of successive responses following a reinforcer delivered via the left (filled circles) and right (open circles) alternatives.

those for Pigeons 1809 and 1863. Note, also, that while all pigeons initially tended to alternate quite frequently, this alternation generally decreased in frequency and amplitude as time passed. The particular alternative response that produced the immediately preceding reinforcer did not affect the direction of the bias (left vs. right key); however, it did appear to modulate the size of the bias (see below and Figure 8). Generally, reinforcers following left-key responses resulted in larger pulses than those following right-key responses, although there were a few exceptions with Pigeons 9337 and 405. In addition, for all pigeons, responding by the 16th response tended to cease oscillating and showed consistent evidence of the left-key bias (consistent with the data presented in Figures 2 and 3).

For a more quantified characterization of the effects of reinforcer amount on preference pulses, Figures 8 and 9 show pulse size and length, respectively, as a function of reinforcer amount. Previous reports have shown that these measures varied directly with relative reinforcer amount (Davison & Baum, 2003; Landon, Davison, & Elliffe, 2003); that is, the presentation of the larger reinforcer resulted in larger and longer duration pulses. Figure 8 shows pulse size (i.e., the log response ratios of the first response immediately following a reinforcer) following left (closed circles) and right (open circles) reinforcers for each component. In most cases reinforcer amount did not appear to affect pulse size systematically; that is, there is no evidence of a monotonic increase in pulse size with respect to amount. For example, pigeons 9337, 1809, and 1863 tended to show the same pattern: following left reinforcers, at all amounts, they showed a relatively constant preference for the left alternative. In fact, pigeon 1863 never responded on the right alternative immediately after a left reinforcer
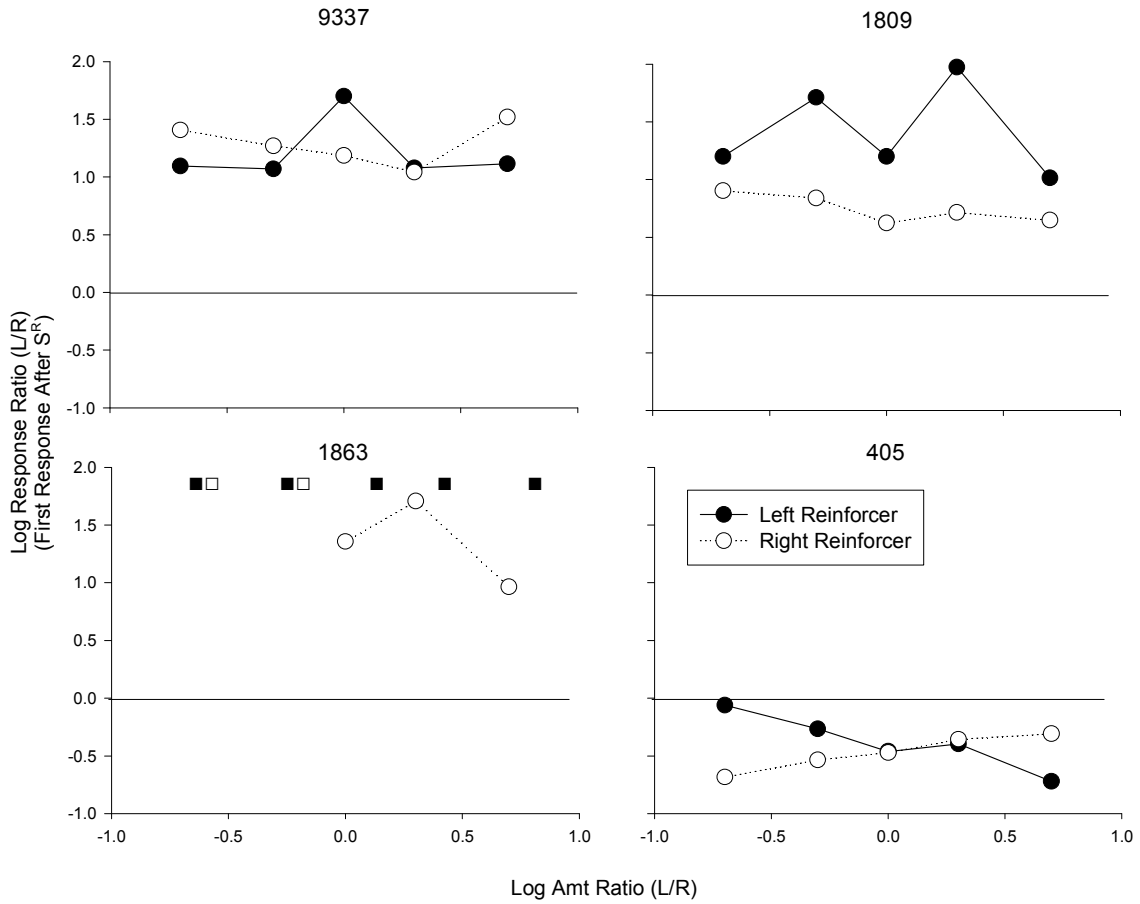
Fig. 8. Experiment 1: Pulse size (i.e., the log response ratio of the first response after reinforcer delivery) as a function of amount ratios following reinforcers from the left (filled circles) and right (open circles) alternatives. Note that squares represent infinite response ratios in favor of the left alternative following left (closed) and right (open) reinforcers.

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and rarely did so following a large-right reinforcer. Note that in the bottom left panel (1863) squares indicate an infinite ratio in favor of the left alternative following reinforcers produced by left key pecks (filled squares) and right key pecks (open squares). Pigeon 405 showed similar effects, but toward the opposite direction relative to the other pigeons. Contrary to the other pigeons, pulse size did vary somewhat with magnitude. Two general effects were present: first, the right "bias" pulse following a left reinforcer decreased as a function of the L/R amount ratio (as the left reinforcer amount increased and the right reinforcer amount decreased); second, the right bias pulse following a right reinforcer increased as a function of the (L/R) amount ratio.

Figure 9 shows pulse length following left (closed circles) and right (open circles) reinforcers for each component. Pulse length is defined as the number of responses before a crossover; that is, the number of responses before preference switches (i.e., the sign of the log response ratio changes) to the opposite alternative for the first time following a reinforcer. For all pigeons there were slight effects of amount on pulse length. For Pigeons 9337 and 1809, pulse length following a left-alternative reinforcer increased with amount. Likewise, for Pigeons 1863 and 405, pulse length following a right-alternative reinforcer also increased with amount.

Contrary to previous findings (Davison & Baum, 2003) responding maintained by the "variable-environment" procedure during the current experiment did not appear to be sensitive to relative reinforcer amount. Whereas sensitivity developed rather early in components (i.e., after three reinforcer presentations) in their studies, sensitivity never developed in the present experiment. Sensitivity parameters obtained from traditional-style "matching" plots (Figure 2) revealed no effect of reinforcer amount at the

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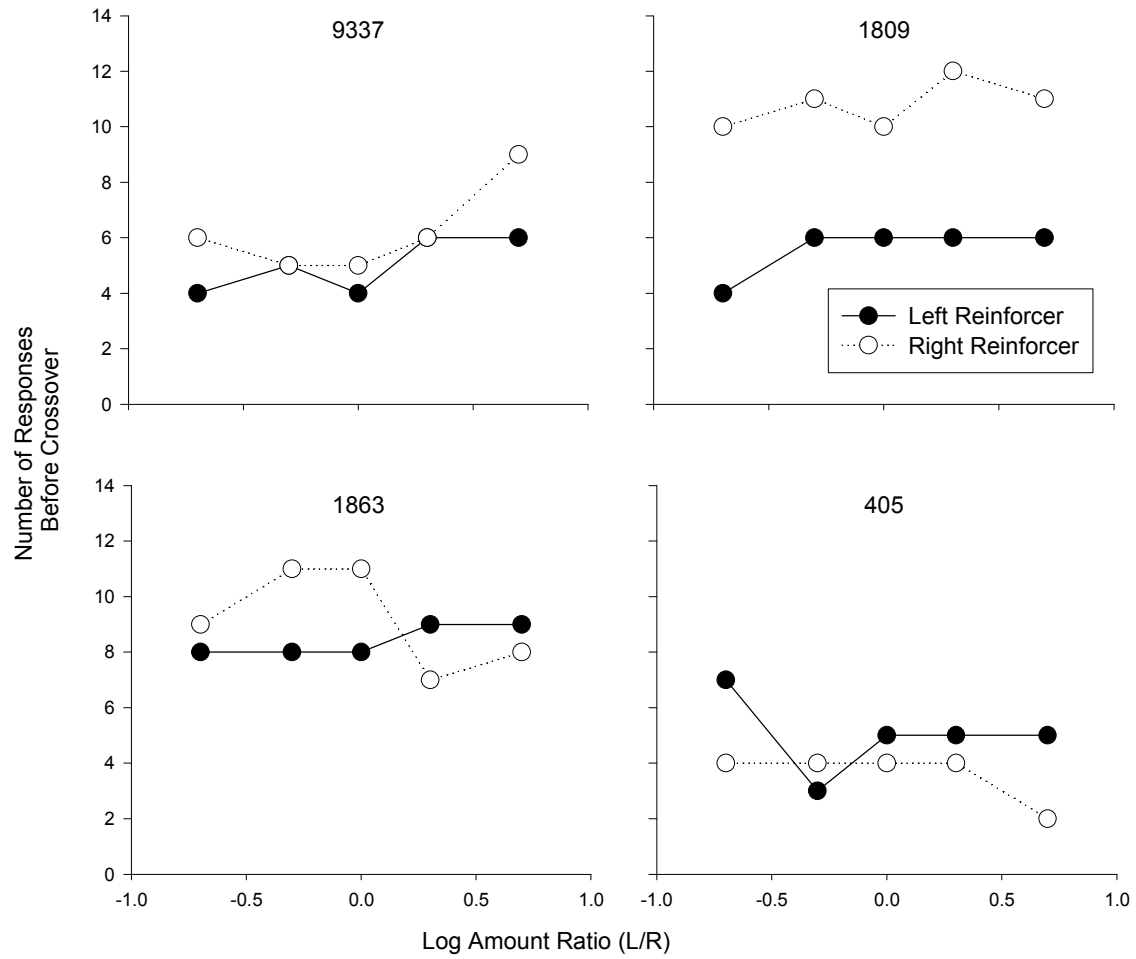
Fig. 9. Experiment 1: Pulse duration (i.e., number of responses before the first oscillation) as a function of amount ratios following reinforcers from the left (filled circles) and right (open circles) alternatives.

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component by component level. Response ratios plotted across each component (Figure 3) also revealed no effect of reinforcer amount at the within component level; that is, there was no evidence that differential responding (i.e., preference) developed at any point during the component.

In addition, local analyses (Figures 4 through 9) revealed very little control by reinforcer amount, contrary to previous reports (Davison & Baum, 2003; Landon, Davison, & Elliffe, 2003) or even control by the particular side from which the most recent reinforcer was delivered. First, neither pulse size nor length varied reliably with reinforcer amount; however, for pigeon 405 the right bias following a left reinforcer decreased as a function of left amount, and right bias following a right reinforcer increased with right amount and, necessarily, decreased with left amount.

A number of procedural and subject differences may account for lack of correspondence between the present results and those previously reported (Davison & Baum, 2003). The present procedure had characteristics that differed somewhat from the previously used Davison and Baum procedure. First, the current procedure included forced-choice trials at the beginning of each component (presumably signaling the amount ratio in effect during the current component) whereas, the original procedure had none and began each component with the choice trials. Forced-choice trials were included based on the assumption that these trials may help facilitate "learning" (i.e., the development of sensitivity) within each component. Forced-choice trials have been used previously in choice procedures, presumably as a way to signal the contingencies currently in effect (see Mazur, 1987). Although it seems unlikely that they would hinder

the development of sensitivity, the present data suggest the effects of this variable warrant further study.

Second, under the current procedure, each of the two keylights were illuminated a different color (red and green) whereas under previous procedures (e.g., Davison & Baum, 2003) both keys were illuminated yellow. The purpose of arranging these conditions as such in the current experiment was that different color keys might have enhanced discriminative control, signaling the amounts in effect for the current component, and facilitate development of sensitivity. This characteristic, however, may have hindered the development of sensitivity to reinforcer amount in at least two ways. For each pigeon, one key color was always located on one particular side, and another color on the other side, so during each session, each color was presented with each reinforcer amount. This could have, effectively, reduced the discriminative control of the reinforcer amount itself and increased control by color. In the studies by Davison, Baum, and colleagues, only one key color was used for both keys and all components, which may have maximized the discriminative control by amount and reduced control by color. A related argument could be made, although this would probably be true of other procedures as well, that because each key color was associated with all reinforcer amounts equally within each session, responding on each key was under the control of the overall reinforcer rate associated with each key color. Throughout the experiment, responses on each side produced reinforcement at an average rate of one per minute. It may be the case that equal overall reinforcer rates gained primary control over responding. Indeed, previous research suggested that responding maintained in similar

situations is more sensitive to relative reinforcer rate than amount (see Davison, 1987; Davison & Baum, 2003, Todorov, 1973).

Another account of the lack of sensitivity to amount in the current study could be derived from behavioral momentum theory (Nevin & Grace, 2000; Nevin, 1974). Behavioral momentum theory suggests that response strength (i.e., the likelihood of responding to persist in the face of a challenge) is a function of the reinforcer rate maintaining responding. That is, responding maintained by higher rates of reinforcement may be considered to have more strength and are relatively more likely to persist longer, or be less affected, by typical response disrupting events such as prefeeding or response-independent food presentation. For example, when responding maintained by two different reinforcer rates (e.g., a VI 30-s schedule and a VI 300-s schedule) each paired with different discriminative stimuli (perhaps in a multiple VI 30-s, VI 300-s schedule of food presentation) is challenged by prefeeding, responding in the presence of the stimulus previously paired with the higher reinforcer rate (i.e., the VI 30-s schedule) will be stronger (i.e., less disrupted) than responding during the stimulus previously paired with the lower reinforcer rate (see Nevin, 1974). Therefore, Nevin and Grace suggested that response strength is a function of the Pavlovian relationship between discriminative stimuli and their correlated rates of reinforcement. The same relationship exists by responding associated with different reinforcer amounts: responding which results in relatively larger reinforcers can be considered stronger, and more resistant, than responding maintained by relatively smaller reinforcers (see Nevin, 1974, Experiment 3).

Nevin and Grace (2000) argued that behavioral momentum theory also may apply to concurrent schedules. They suggested that preference for an alternative in concurrent

schedules is indicative of the strength of that response. In a situation where multiple operants are available, the preferred alternative may be considered to have more strength (e.g., Grace & Nevin, 1997). In the current experiment, whereas each side was, briefly during the session, associated with different reinforcer amounts, the overall amount of the reinforcers (165 brief hopper presentations per side per session) obtained from each alternative, and thus each key color, was equal. Therefore, the strength of responding maintained by each alternative was equal which would predict no preference within the session and would suggest that the more molar contingencies (i.e., average reinforcer amount across the session paired with a side or color) controlled responding rather than component by component changes in relative amounts. Although this explanation could account for the current results, it does not offer an explanation for the results of the numerous other studies that reported the development of differential responding with respect to amount. In other studies, both side keys were also paired with overall equal reinforcer amounts and rates, yet responding favored higher rates and larger amounts differentially across the session. Nor does this explanation account for the failure to acquire more strength with in a component. Presumably as a component progresses, local reinforcer amount densities across the two alternatives, in components that arrange different reinforcer amounts, would differ with respect to side and key color and so should preference, as a behavioral momentum account suggests. Perhaps the duration of exposure to the amount ratio in effect (12 reinforcers per component) was too short for these contingencies to take effect (but see Davison & Baum, 2000; 2003).

Of course, another procedural difference could also account for the failure of this group of pigeons' responding to develop sensitivity to amount. That is, the pigeons in the

present study were relatively inexperienced at responding under this procedure during which conditions changed quite frequently (i.e., every 12 reinforcers and randomly from component to component). Two pigeons (9337 and 405) had minimal training under any behavioral procedure before being placed on the current procedure whereas the other two pigeons (1809 and 1863) had extensive training; however, they responded under a concurrent-chains procedure during which the relative immediacy of reinforcement was manipulated rather than amount (see Pitts & Febbo, 2004). It could be argued that the training each pigeon received before implementation of the current procedure was insufficient to produce response allocation sensitive to the procedure. For example, none of the pigeons in the present study had experience with the reinforcer amount manipulation. During preliminary training for all pigeons, reinforcement was delivered via one continuous hopper presentation of a given duration (2.5 s). In the current experiment amount was manipulated by presenting a number of brief hopper presentations. Perhaps exposing each pigeon to the multiple-hopper-presentation reinforcer would have facilitated sensitivity. In addition, no measure was taken of the pigeons' actual eating behavior (e.g., whether or not the pigeon withdrew its head from the hopper between hopper presentations during reinforcement), and, thus, it is unknown exactly how each pigeon came in contact with the arranged reinforcer amount. Perhaps the addition of a tandem FR 1 requirement, which requires a single response to produce each individual presentation of the hopper during reinforcement (cf. Pitts & Malagodi, 1996), may have increased salience of the amounts of reinforcement in effect and subsequently control by the relative amounts.

Because of the lack of sensitivity resulting from the present experiment, methamphetamine was never administered, and thus, the focus of the remainder of the present study was then directed toward investigating the conditions under which sensitivity of responding to reinforcer amount might develop. Any of the variables discussed above may have played a role in the lack of sensitivity development in Experiment 1. Experiment 2 was designed to determine whether responding in this group of pigeons was sensitive to reinforcer amount at all.

EXPERIMENT 2

Due to the lack of sensitivity of both response and time allocation to within session changes in amount ratios noted for all subjects in Experiment 1, the purpose of Experiment 2 was to investigate sensitivity to reinforcer amount using a "steady-state" procedure previously used in choice studies (see de Villiers, 1977). In other words, the following experiment served as a manipulation check to test whether or not responding in our pigeons was sensitive at all to different reinforcer amounts. During Experiment 2, only two different amount ratios were presented (i.e., 1/7 and 7/1). The pigeons were exposed to a single amount ratio both within and across sessions until preference shifted towards the larger alternative, at which point the amounts associated with each alternative were switched until preference adjusted accordingly. The basic choice procedure used in Experiment 2 was similar to that used in Experiment 1 (e.g., a conc VI 30-s schedule); however, sessions differed in a number of ways: forced-choice trials were removed, each session lasted for 30 reinforcer presentations with a single reinforcer amount ratio in effect, and only one key color was used (both keys were illuminated yellow).

Method

Subjects and Apparatus.

The subjects and apparatus were the same as those used in Experiment 1.

Behavioral Procedure.

Experiment 2 began immediately following Experiment 1.   At the beginning of

each session, both side keys were illuminated yellow, and reinforcement was made

available according to a single, conc VI 30-s schedule (Stubbs & Pliskoff, 1969).

Sessions ended after the 30th reinforcer presentation. Separate lists of 15 interval values

were arranged for each alternative (Flesher & Hoffman, 1962). At the beginning of each

session and immediately following each reinforcer presentation, one of the side keys was

selected (with a 0.5 probability for each key), and an interval was selected from that

side's list without replacement. A 2-s COD was in effect. Reinforcement consisted of the

experimentally arranged number of 1.2 s hopper presentations, as in Experiment 1. The

reinforcer amount available from the larger alternative was increased to seven hopper

presentations whereas the amount available from the smaller alternative was one hopper

presentation (i.e., the ratios were either 7/1 or 1/7).

At the beginning of the experiment the 7/1 (L/R) ratio was in effect for all

subjects and remained in effect within and across sessions until stable response ratios

emerged, as determined by visual inspection of the data. At that time (after

approximately 10 sessions) the absolute amounts arranged on each alternative were

switched with that of the other alternative (i.e., a ratio of 1/7 was then in effect) until

stable response ratios emerged. For two pigeons (9337 and 405) stable responding

emerged much sooner (after approximately 10 sessions) than the other two, so the amount

ratio was then switched back to the previous value (i.e., 7/1). The ratio remained 1/7 for

pigeons 1809 and 1863 through the completion of the experiment.   Experiment 2 lasted

approximately 40 sessions (41, 41, 35, and 40 sessions for 9337, 1809, 1863, and 405

respectively).

Data Analysis.

For each session, the number of responses and the amount of time spent responding on

each alternative were collected. Ratios of responses (and time spent) on the left key to

responses (and time spent) on the right key (B_L/B_R and T_L/T_R) were calculated for each

component. The data from the last five sessions of each condition were used for analysis.

For all pigeons response and time allocation closely resembled one another, and,

therefore, time allocation data will not be presented, except where noted. Preference

pulse analyses were also conducted for session in each condition as described in the Data

Analysis section of Experiment 1.

Results and Discussion

Plotted in Figure 10 are log response and amount ratios for each session during

Experiment 2. Filled circles represent log response ratios over the entire session, open

circles represent log response ratios over the last half of the session, and the small filled

triangles show the amount ratio in effect during that particular session. At the beginning

of the experiment, responding in all pigeons closely approximated indifference (1809

began with a left-side bias), and preference shifted appreciably toward the left alternative

by the seventh or eighth session. For all pigeons response ratios closely approximated

the amount ratio in effect. When the amounts available from each alternative were

reversed (i.e., the large reinforcer was available from the right alternative), preference
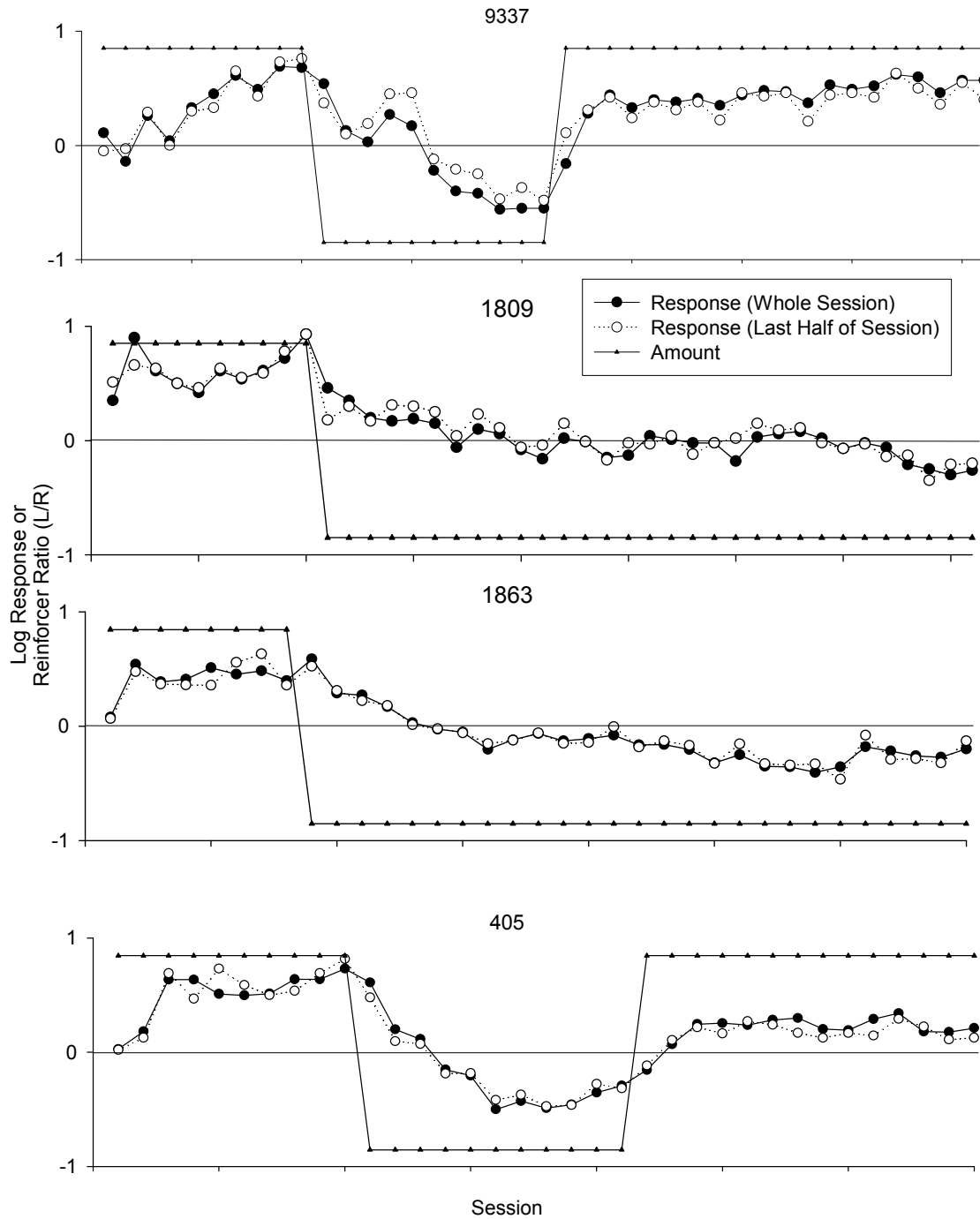
Fig. 10. Experiment 2: Log response or amount ratios plotted for each session. Closed circles represent data taken from the entire session where as open circles represent data taken from the last half of the session. Triangles represent the amount ratio in effect for that session

shifted toward the right alternative. For all pigeons, preference shifted rather

dramatically over the first two to five sessions; however, two distinct patterns emerged:

for pigeons 9337 and 405, preference shifted quickly and reached asymptotic log

response ratios, ranging from -0.21 to -0.48, across the last five sessions for both pigeons.

For pigeons 1809 and 1863, preference also shifted within the first 5 sessions; however,

asymptotic response ratios were not as extreme, and they took longer to achieve, than

those for the other two pigeons. For example, with Pigeon 1863, preference shifted

quickly from the left side toward indifference; this pigeon responded at indifference for

approximately 12 sessions and then showed a slight right-key preference for the last 12

sessions. Responding in 1809 also shifted rather quickly from a left-side preference

toward indifference, but responding remained at indifference for approximately 20

sessions. For this pigeon, a slight preference for the right alternative developed over the

last four sessions of the experiment. For two pigeons (9337 and 405) the amounts

arranged across the two alternatives were reversed again for the remainder of the

experiment and a ratio of 7/1 was, again, in effect. Following the switch in amounts,

preference for each pigeon shifted toward the left alternative. For 9337, response ratios

reached levels comparable to those reached during the first phase of the experiment (i.e.,

when the amount ratio was initially 7/1). For 405, response ratios shifted in favor of the

left alternative; however, asymptotic ratios were much lower than those during the first

phase of the experiment. Responding in both pigeons remained in favor of the left

alternative throughout the remainder of the experiment.

Displayed in Figure 11 are log response (closed circles) and time (open circles)

ratios from the last five sessions of each condition plotted as a function of log reinforcer
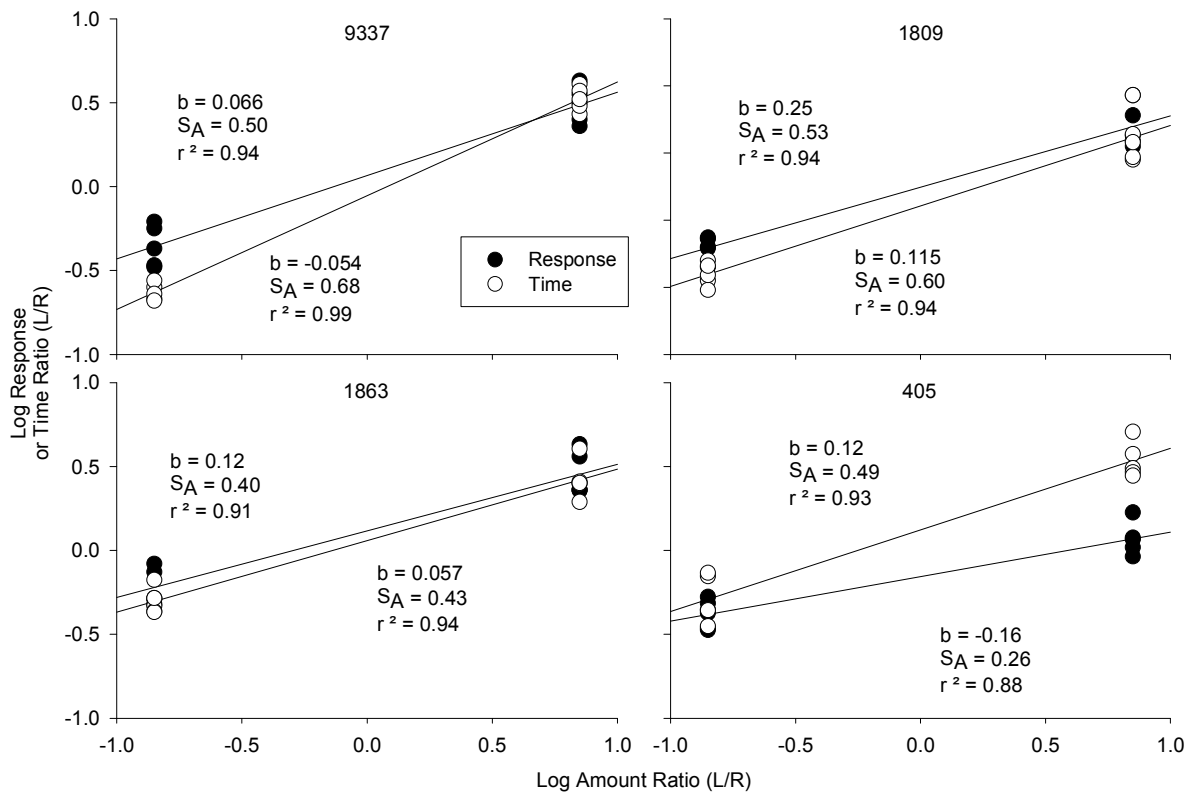
Fig. 11. Experiment 2: Log response and time ratios (L/R) plotted as a function of log amount ratios (L/R). Filled and open circles represent response and time ratios, respectively. The values shown are the y-intercept (b), slope (S_A), and fits (r^2) of the regression lines.

amount ratio for each pigeon. The data presented are taken from the last half the session (i.e., the last 15 intervals). For all pigeons the response and time ratios were relatively sensitive to the amount ratios in effect as evidenced by the positive slopes of the regression lines. Sensitivity parameters ranged from 0.40 to 0.53 and 0.43 to 0.68 for response and time ratios, respectively. Bias estimates (k) ranged from -0.16 to 0.25 and -0.054 to 0.12 for response and time ratios, respectively.

Within-session analyses also revealed sensitivity of responding to relative reinforcer amount. Figure 12 shows mean response ratios for each successive sixth of each session (i.e., successive groups of five intervals). Generally, for all pigeons, response ratios remained constant across the session, as indicated by the flat curves, with one exception: during sessions in which the larger reinforcer is available from the right alternative (i.e., a ratio of 1/7), 9337 tended to began sessions with an extreme right-key preference which then shifted towards indifference across the session. Each subject showed a consistent preference for the larger alternative during each condition. Pigeons 1809 and 1863 showed evidence of the left-key bias as both curves are shifted up, asymmetrically about the indifference line, whereas 405 showed evidence of a right key bias, as both curves are shifted downward.

Figure 13 shows the results of the preference-pulse analysis for all pigeons, presented in a similar style as in Figures 4 through 7. The data presented are taken from the last 5 sessions of each condition, and from all intervals during the session beginning with a reinforcer delivery (29 per session); For Pigeons 9337 and 405, these data were taken from the second exposure to the 7/1 ratio. Data points on the far right portion of
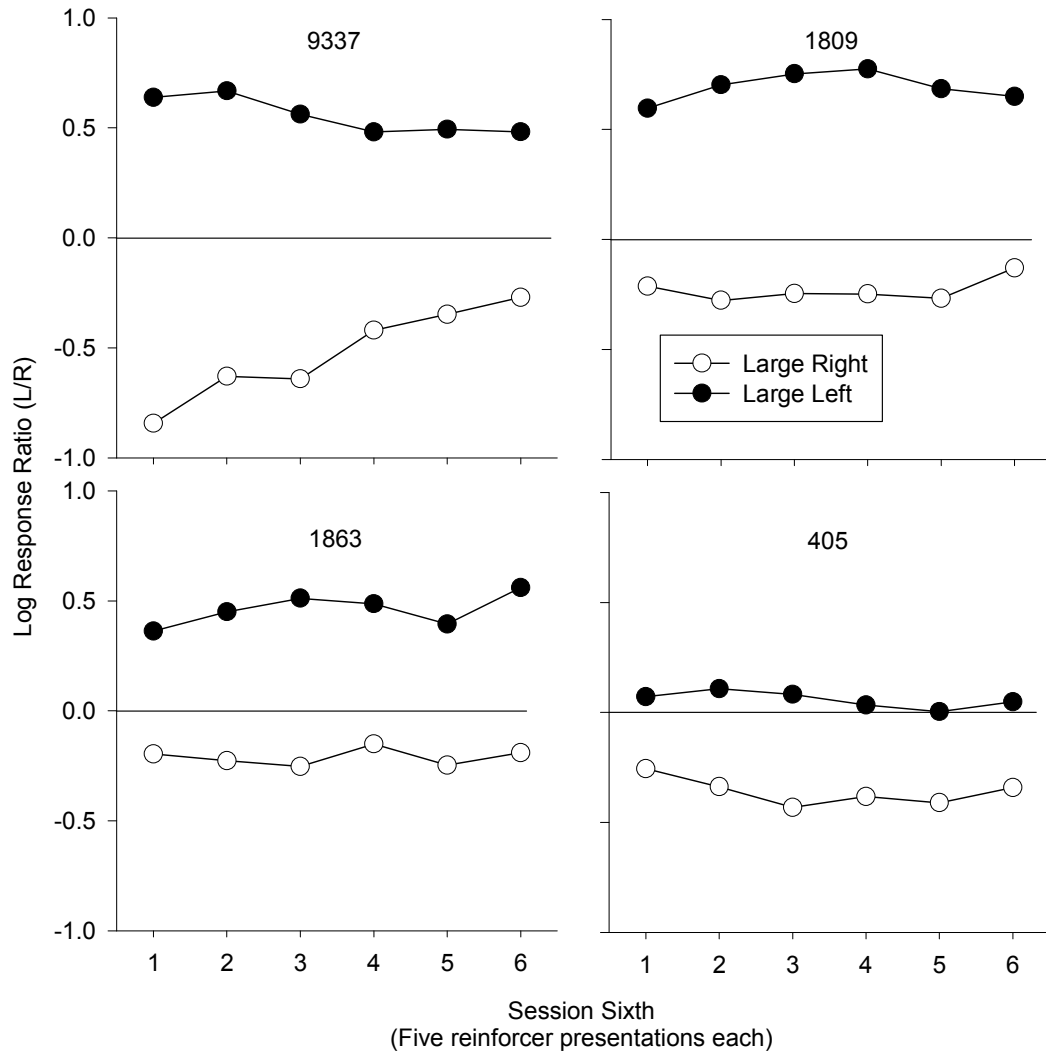
Fig. 12. Experiment 2: Log response ratios plotted for each successive sessions sixth (five intervals each) for sessions in which the larger reinforcer was on the left (filled circles) or on the right (open circles).
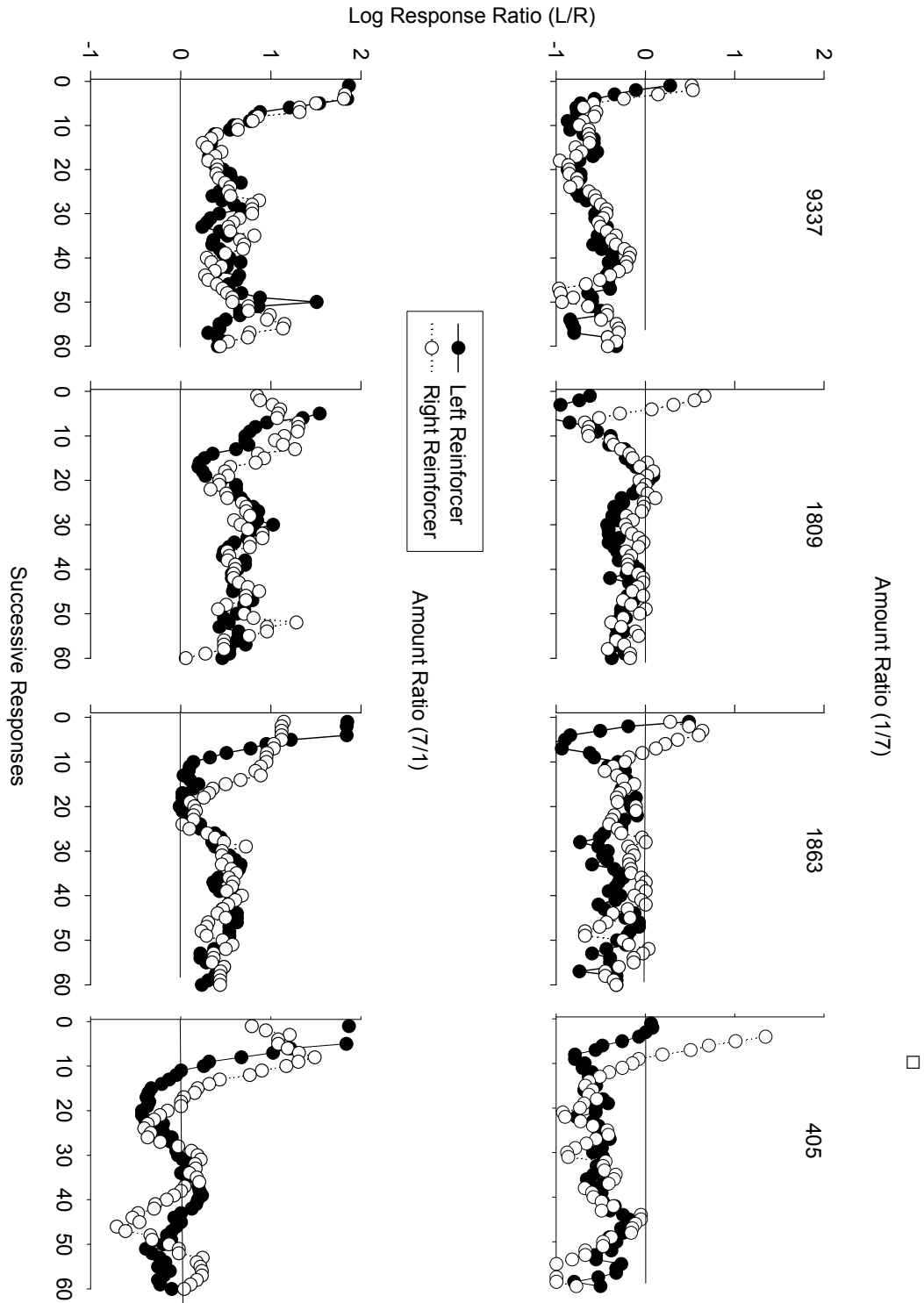
Fig. 13. Experiment 2: Log response ratios of successive responses following a reinforcer delivered via the left (filled circles) and right (open circles) alternatives for each subject. The top panels are data from sessions during which the amount ratio was 1/7 whereas the bottom panels are from sessions during which the amount ratio was 7/1.

the *x*-axis represent the ratio of approximately 145 responses. Note that as the *x* value increases the number of responses included in the ratio decreases because the likelihood of an interval timing out increases with time, which necessarily reduced the opportunity for the pigeons to respond.

Plotted in the top panels of Figure 13 are the data from the 1/7 condition. For all pigeons, the delivery of a large-right reinforcer resulted in a moderate pulse toward the left alternative (note that 405 never responded on the right alternative immediately after a right reinforcer, as indicated by the open square) followed by a switch to the right side where responding settled in favor of the right alternative, around a log response ratio of approximately -0.5. The delivery of a small-left reinforcer resulted in a somewhat smaller pulse toward the left alternative (for 9337, 1863, and 405) also followed by a switch to the right alternative. For 1809, however, the small-left reinforcer resulted in a sizeable pulse to the right alternative followed by a switch to less extreme preference for the right side (comparable to other subjects). For all pigeons, pulse duration appeared to be longer following the large-right reinforcer.

Plotted in the bottom panels of Figure 13 are the data from the 7/1 condition. The delivery of a large-left reinforcer, for all pigeons, resulted in a rather large (sometimes infinite; see 1809) pulse in favor of the left alternative. For three pigeons (1809, 1963, and 405) small-right reinforcers resulted in a reduced pulse toward the left alternative, whereas for 9337, they produced a left-key pulse equally as large as the pulse produced by large-left reinforcers. For three pigeons (9337, 1809, and 1863) responding after the pulse settled in favor of the left key, whereas for 405, responding settled around indifference.

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The results from Experiment 2 suggested that subjects were relatively sensitive to the reinforcer amount manipulation, at least under the steady-state procedure in effect. Compared to the procedure used in Experiment 1, the amount ratios were larger (more discrepant), and subjects were exposed to each ratio for longer durations per session (30 reinforcer presentations at each ratio versus 10 presentations) and, ratios were presented in a much more predictable fashion (repeatedly across consecutive sessions). Sensitivity parameters obtained from the matching plots (Figure 11) were comparable to those obtained in previous studies employing similar procedures which manipulated relative reinforcer amount (Catania, 1963, Todorov, 1973, Todorov et al., 1984). Within session response ratio plots confirmed that a constant preference had developed for the larger alternative (Figure 12); at the beginning of the session, all pigeons began responding on the alternative producing the larger alternative, presumably due to the predictability of the condition. Responding at a more local level, however, does not appear to show much systematic control by amount. Local analyses (Figure 13) failed to show consistent evidence of control by amount at the just-after-reinforcement level as has be demonstrated previously (Davison and Baum, 2003; Landon, Davison, & Elliffe, 2003). In fact, the effects noted here were systematically opposite of those reported by Davison, Baum, and colleagues. For example, during the 1/7 condition, when the right reinforcer was large, a right-reinforcer delivery typically resulted in a pulse toward the left key, whereas a small-left reinforcer delivery resulted in a much smaller preference for the left (see 9337, 1863, and 405) or preference for the right (see 405). During the 7/1 condition a qualitatively similar yet more extreme pattern emerged: large-left reinforcers resulted in a rather extreme preference for the left whereas a small-right reinforcer typically resulted

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in a less extreme left side preference. This general effect could be characterized as an interaction among reinforcer amount and a side bias: in most cases a large-reinforcer delivery resulted in preference for the left alternative and small-reinforcer deliveries resulted in an reduced preference for the left alternative. Although it appears that amount controls the final level of responding following the pulse (i.e., after the 20th or 30th response following a reinforcer delivery), pulse direction did not vary systematically with reinforcer amount. In fact, it appears that amount modulated the degree of left key bias which appears in responding of all subjects.

In the current experiment, responding generally was sensitive to reinforcer amount. That is, differential responding developed and remained in favor of the larger of two reinforcers, as would be expected based upon a wealth of previous findings (see Davison & McCarthy, 1988; deVillers, 1977, for reviews). Although the reinforcer rate associated with both alternatives were equated (as in Experiment 1) a rather sizable preference did develop in all pigeons for the larger reinforcer. On the basis of these results it appeared that the pigeons' preferences were, in fact, sensitive to the reinforcer amount manipulation, at least under steady-state conditions. One possible factor involved in the development of preference noted here but not in Experiment 1 could be the less rapid shift in amount ratio (or predictability of the environment). For all sessions (except for a couple following a transition), the amount ratios in effect were the same as the previous, and thus, preference developed albeit gradually. Experiment 3 was conducted to see if preference could come under control of reinforcer amount under conditions that changed more rapidly than those arranged in Experiment 2.

EXPERIMENT 3

The results of Experiment 2 suggested that the pigeons' responding was, in fact, sensitive to reinforcer amount manipulations (at least under steady-state conditions). The purpose of Experiment 3 was to assess sensitivity to reinforcer amount under conditions in which the reinforcer amount arranged for each alternative changed more rapidly than in Experiment 2. Rather than using a within-session procedure similar to that used by Davison and Baum (2003), another procedure was implemented during which reinforcer amount ratios changed unpredictably. In Experiment 3, amount ratio alternated between two values (1/7 and 7/1) from session to session, rather than from component to component. The current procedure was very similar procedures used to investigate sensitivity of responding to both reinforcer rate (Hunter & Davison, 1985; Schofield & Davison, 1997) and reinforcer delay (Grace, Bragason, & McLean, 2003; Grace & McLean, 2006) during which the ratio of reinforcer rates or delays were varied pseudorandomly from session to session. In these studies, two reinforcer parameters varied unpredictably across sessions according to a pseudorandom binary sequence (PRBS; see Hunter & Davison, 1985).

Method

Subjects and Apparatus.

The subjects and apparatus were the same as those used in Experiments 1 and 2.

Behavioral Procedure.

Experiment 3 began immediately following Experiment 2. During Experiment 3, all stimulus and reinforcer conditions were identical to those in effect during Experiment 2; however, the amount ratio which was in effect for each session (either 1/7 or 7/1) was

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determined according to a 31-step PRBS. Each session served as a separate step in the

sequence (which is shown by the triangles in Figure 14). The PRBS was presented three

times, and the experiment, therefore, lasted 93 sessions. Sessions ended after the 30th

reinforcer presentation.

Data Analysis.

For each session the number of responses and time spent responding on each

alternative were collected. Ratios of responses on the left key to responses on the right

key (B_L/B_R) were calculated for each session (and for the first and last halves of each

session). Sensitivity of responding to amount was assessed using the following modified

version of the generalized matching equation (Baum, 1974), which provided estimates of

the sensitivity of responding to the amount ratio in effect during the current session as

well as to the ratio in effect during each of the three previous sessions (cf. Davison and

McCarthy, 1988; Grace et al., 2003; Schofield and Davison, 1997):

$$\log (B_{Ln}/B_{Rn}) = S_0 \log(R_{Ln}/R_{Rn}) + S_1 \log(R_{L(n-1)}/R_{R(n-1)}) + S_2 \log(R_{L(n-2)}/R_{R(n-2)})$$

$$+ \ S_3 \log (R_{L(n-3)}/R_{R(n-3)}) + \log k \tag{12},$$

where B and R represent response and reinforcer characteristics, respectively, available

from each alternative (*L* or *R*); *n* represents the current session, *n-1* the previous session,

and so on; and S_X represents the sensitivity of responding in the current session to the

reinforcer ratio in effect for the current session (i.e., when $x = 0$; Lag 0) or to ratios in

effect during previous sessions (i.e., when $x = 1$ to 3; Lag 1 to Lag 3). Lag 1 refers to the

immediately preceding session, Lag 2 the session before that, and so on; *k* refers to bias.

This analysis will be referred to as the lag-regression analysis. For the lag-regression

analysis, response ratios collected during the current session (starting with the fourth

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session of Sequence 1 and continuing through all sessions of the remaining sequences) and the amount ratios in effect during the current and previous three sessions were entered into the Equation 1 and analyzed using a linear multiple regression (SPSS$^{®}$) which produced sensitivity and bias estimates. A separate analysis was conducted for response ratios obtained during each of the three sequences; also, ratios from the whole session, first half of the session, and last half of the session were analyzed separately.

Results and Discussion

Figure 14 displays log response and amount ratios for individual pigeons for each session across the three exposures to the PRBS. Log response ratios from the first and the last half of a session and amount ratio in effect during the session are represented by filled circles, open circles, and filled triangles, respectively. Sequence presentations are separated by breaks in the lines; note, however, that Sequences 2 and 3 began immediately after their respective preceding sequence. At the beginning of the experiment, responding for all pigeons appeared to be relatively insensitive to changes in amount ratios; that is, shifts in responding across sessions did not appear to track changes in amount. All pigeons showed evidence of a bias toward one of the keys. By the end of Sequence 1, responding for Pigeons 9337 and 405 reliably tracked changes in amount; that is, a shift in the response ratio reliably followed a shift in the amount ratio. In contrast, responding for Pigeons 1809 and 1863 remained relatively insensitive to changes in amount and was biased toward the left key; for these two pigeons, responding began to track changes in amount by the end of Sequence 2. By the end of Sequence 3, responding in all pigeons showed considerable sensitivity to the amount ratio. Although
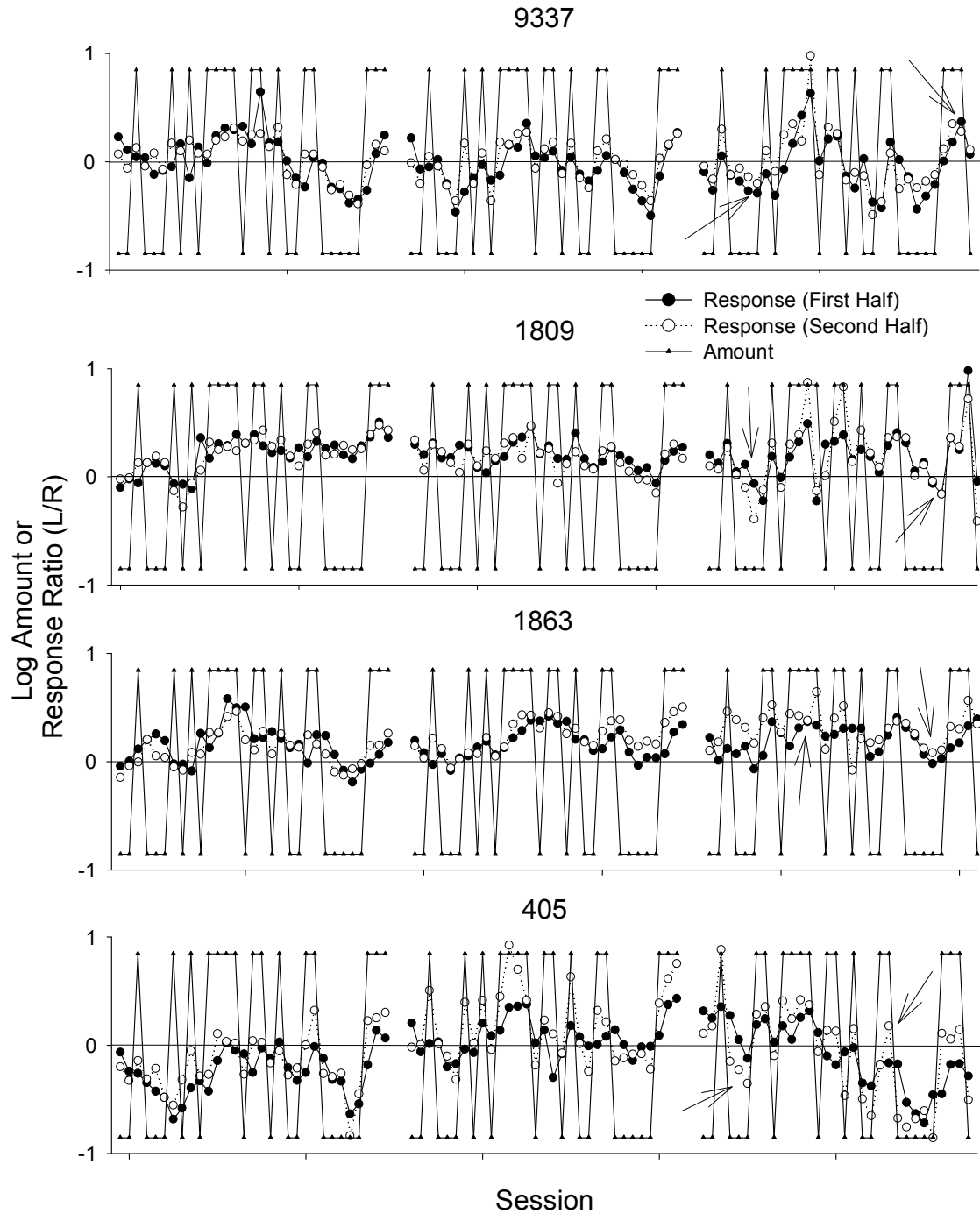
Fig. 14. Experiment 3: Log response or amount ratios plotted for each session across the three exposures of the PRBS. Closed and open circles represent data from the first and last half of the session, respectively, and triangles represent the amount ratio in effect for that session. Arrows indicate examples of instances in which response ratios typically shifted toward the alternative associated with the large reinforcer across consecutive sessions that arranged the same amount ratio.

biases were still present, responding in all pigeons reliably shifted with shifts in relative reinforcer amount. Two additional features of these data should be noted. First, for most pigeons (particularly Pigeon 405), response ratios during the second half of the session tended to be more extreme than to those during the first half of the session, suggesting that shifts in preference occurred within sessions. Second, response ratios typically shifted toward the alternative associated with the large reinforcer across consecutive sessions that arranged the same amount ratio. This effect was evident to some extent for all pigeons, even during the third PRBS (indicated by the arrows in Figure 14).

Figure 15 shows the mean response ratios across session sixths (blocks of 5 reinforcers); the means include all data taken from all sessions in Sequence 3 (31 sessions, 14 large-left sessions and 17 large-right). Generally, all pigeons demonstrated differential responding with respect to relative amount ratios; however, they did so in different ways. For example, responding in Pigeons 1809 and 1863 was heavily biased toward the left key such that responding in favor of the right alternative (i.e., log ratios less than 0) rarely developed. Instead, preference for the left alternative was attenuated in sessions when the amount ratio was 1/7. That is, while responding rarely favored the right key when the large reinforcers followed right-key responses, it was less extreme and more closely approximated indifference relative to responding when the larger reinforcer followed left-key responses. In contrast, Pigeon 9337 began sessions with slight right-key bias and either shifted to the left alternative (during sessions when the larger reinforcer followed left-key responses) or stayed on the right (during sessions when the larger reinforcer followed right-key responses). For Pigeons 9337, 1809, and 1863, when responding did shift, it typically occurred early in the session (i.e., during the first two

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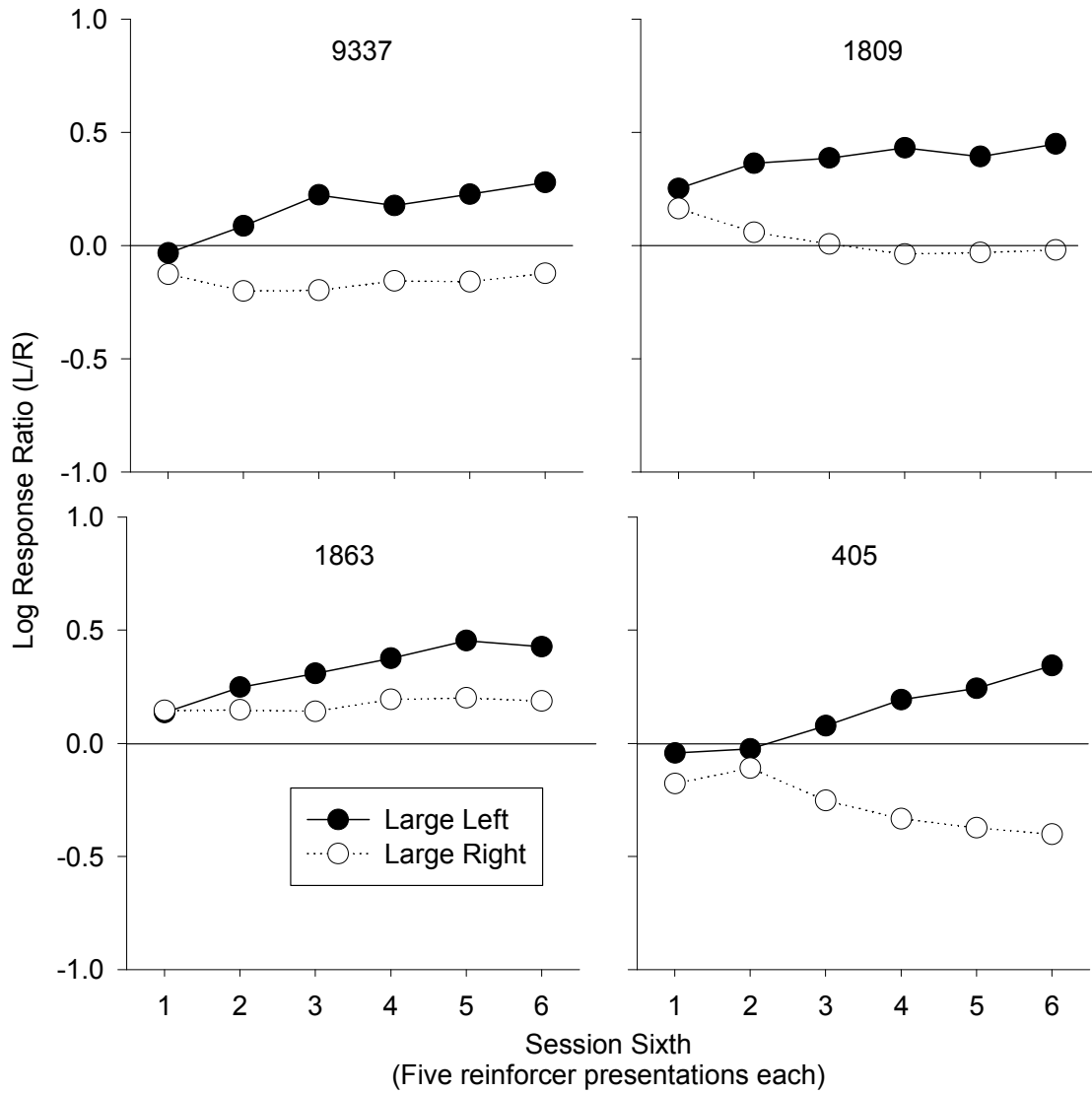
Fig. 15. Experiment 3: Log response ratios plotted for each successive sessions sixth (five intervals each) for sessions in which the larger reinforcer was on the left (filled circles) or on the right (open circles).

sixths of the session or 10 reinforcer deliveries). Pigeon 405 also began sessions with a slight right-key bias, and responding shifted during the third or fourth sixth (i.e., after about 15 reinforcer deliveries). By the end of the session, this pigeon developed a more extreme, and less biased, preference than the other pigeons.

Figure 16 shows the results of the lag-regression analyses for individual pigeons for response ratios from the whole session (left panels), first half of the session (center panels), and last half of the session (right panels) and across the first (squares), second (triangles), and third (circles) sequence presentations up to Lag 3 (including data from the current and previous 3 sessions). The data from each sequence were analyzed separately to characterize acquisition of sensitivity to reinforcer amount throughout the experiment and across session halves to characterize acquisition of sensitivity within the session. Sensitivity parameters for each lag, as well as overall bias estimates for each sequence (located above B on the x-axis) are presented. Symbols containing dots within them indicate instances in which sensitivity coefficients were significantly different from 0 ($p < 0.05$).

For the data taken from the whole session, a similar pattern emerged for all subjects across all three sequences. First, highest sensitivity estimates were obtained at Lag 0 (except for Pigeon 9337 during the first sequence and Pigeon 1863 during the first two sequences); indeed, in each instance (except for Pigeon 1809 during the first sequence), Lag-0 sensitivity was significantly greater than zero (indicated by dotted symbols). Second, in most cases, Lag-1 and Lag-2 sensitivities were positive (20 of 24 sensitivity estimates were significantly greater than zero). Third, by Lag 3, sensitivity
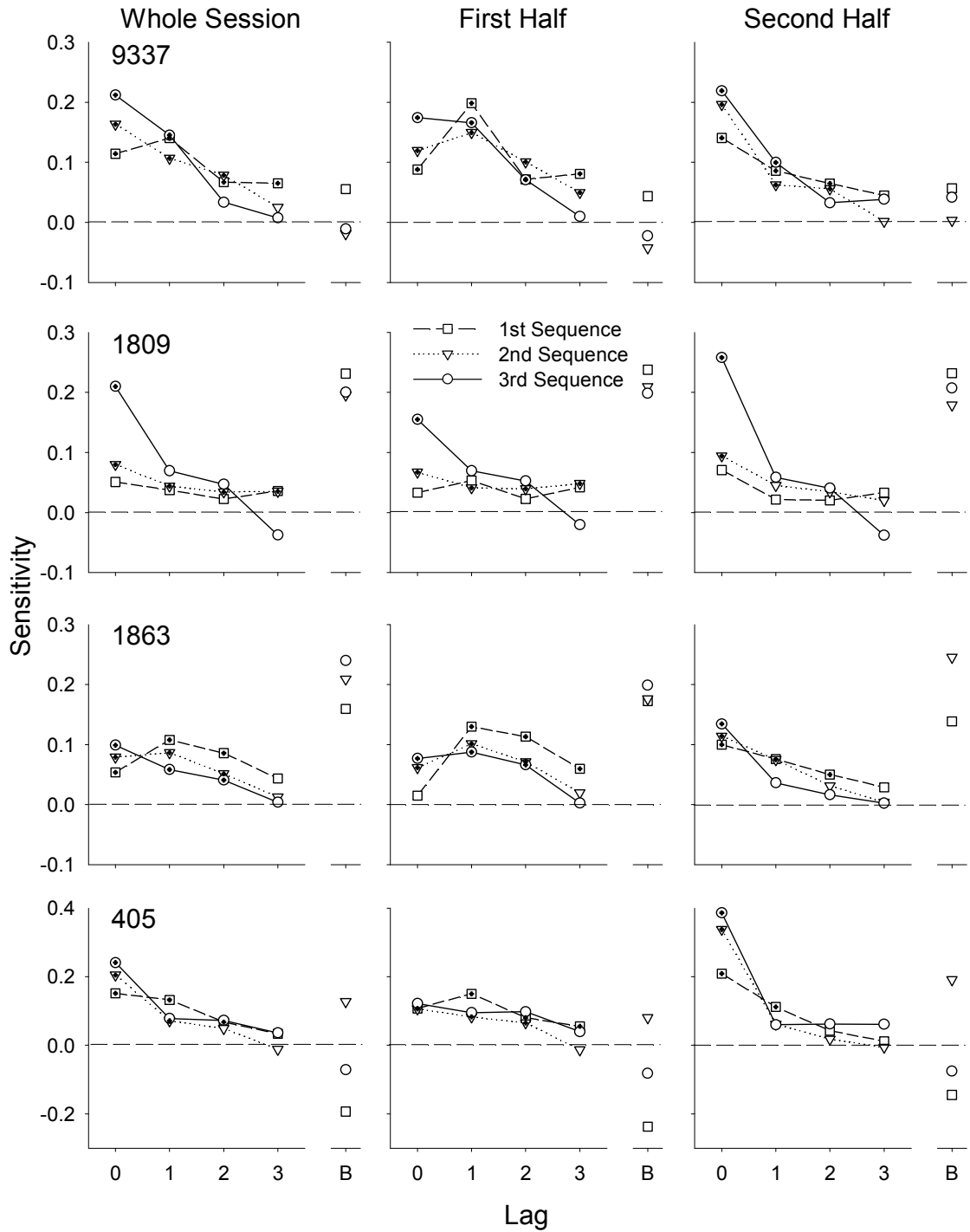
Fig. 16. Experiment 3: Sensitivity estimates obtained from the results of lag-regression analyses on data obtained during the whole session (left panels), first half of the session (center panels), and second half of the session (right panels) are plotted as a function of Lag for the first (squares), second (triangles), and third (circles) PRBS (see Data Analysis for a description). Bias estimates are located above B. Dotted symbols indicate instances in which sensitivity parameters that are significantly greater than zero. Note the different *y*-axis scale for Pigeon 405 (bottom panels).

was near 0 (only 2 of 12 sensitivity estimates were significant.). Finally, across sequences, sensitivity at Lag 0 increased for all pigeons (from 0.15 to 0.21 for 405, from 0.05 to 0.21 for Pigeon 1809, from 0.11 to 021 for Pigeon 9337, and from 0.05 to 0.10 for 1863). For the higher lags there was no systematic trends across birds, except that Lag-3 sensitivities tended to decrease across sequences.

Figure 16 (left panels) also shows that three pigeons' (1809, 1983, and 405) responding was biased toward one of the keys. For Pigeons 1809 and 1863 the considerable left-key bias did not change systematically across sequences, whereas for Pigeon 405, there was a right-key bias during Sequence 1, a left-key bias during Sequence 2, and a right-key bias during Sequence 3. For Pigeon 9337 there was a slight left-key bias during the first sequence and no systematic bias in subsequent sequences.

The center and right panels of Figure 16 show the results of lag-regression analyses of data from the first and second halves of the session, respectively, for individual pigeons. Comparison of the center and right panels reveals three general patterns. First, Lag-0 sensitivities during the second half of the session were greater (range: 0.07 to 0.39) than those obtained in the first half (range: 0.02 to 0.17) for each pigeon and across all sequences. Second, Lag 1 and Lag 2 sensitivities were generally lower in the second half of the session than in the first. During the first half, 18 of 24 sensitivity estimates were significantly greater than zero, whereas during the second half only 9 of 24 were. Third, all Lag-3 sensitivity estimates dropped to zero, or near zero, in the second half of the session. Bias estimates did not systematically change across session halves.
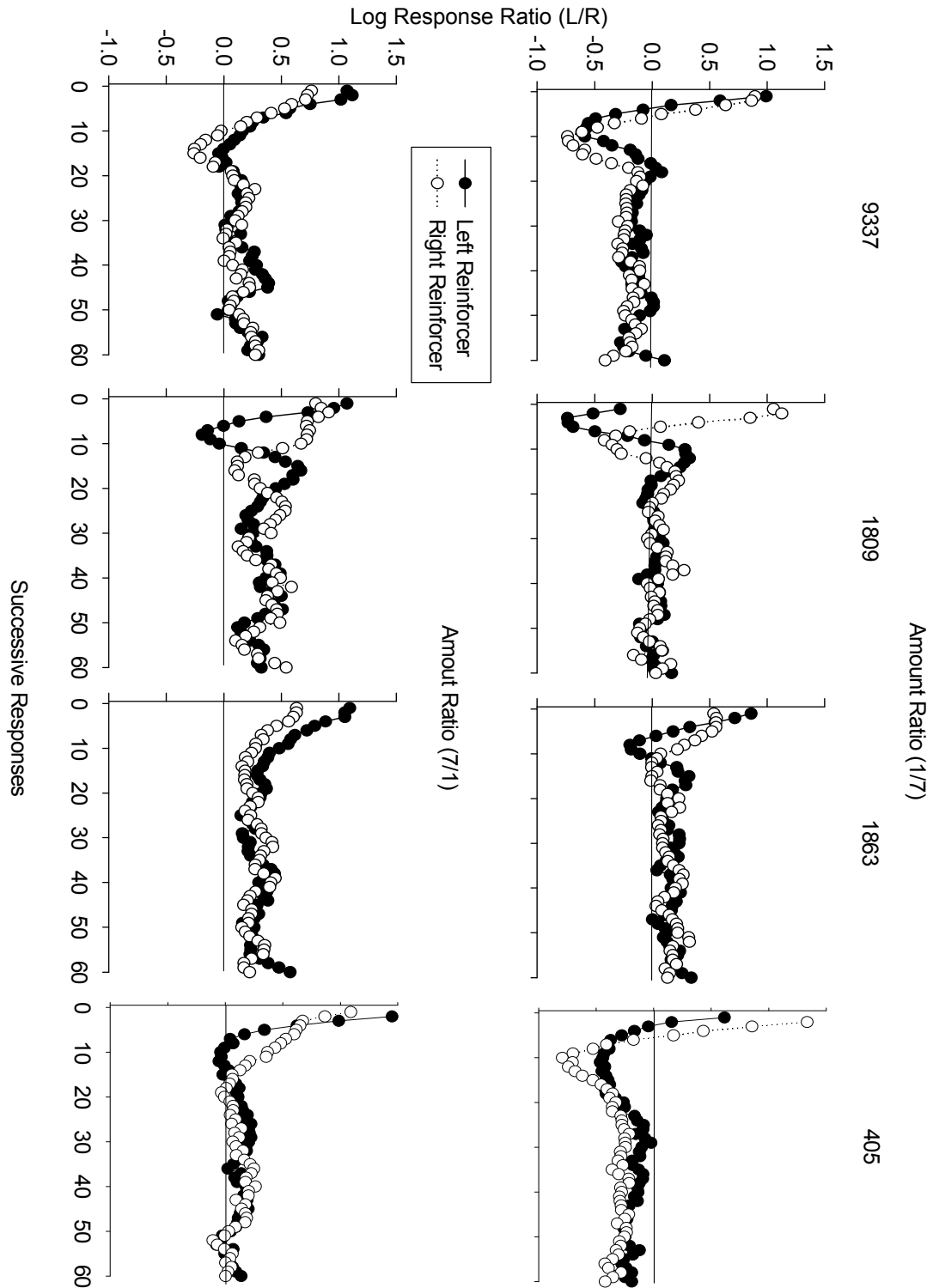
Fig. 17. Experiment 3: Log response ratios of successive responses following a reinforcer delivered via the left (filled circles) and right (open circles) alternatives for each subject. The top panels are data from sessions during which the amount ratio was 1/7 whereas the bottom panels are from sessions during which the amount ratio was 7/1.

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Figure 17 shows the results of the preference pulse analysis for all pigeons, presented in the same style as in Figure 13. The data presented are taken from the last 31 sessions of the experiment (Sequence 3), and from all intervals during the session beginning with a reinforcer delivery (29 per session). Data points on the far right portion of the x-axis represent the ratio of approximately 450 responses. Note that as the x value increases, the number of responses included in the ratio decreases because the likelihood of an interval timing out increases with time, which necessarily reduces the size of the sample. Generally, the pattern of responding for each pigeon in each condition was very similar to the pattern which emerged during Experiment 2. A reinforcer delivery following responses on either side produced a marked pulse toward the left alternative (with an exception, again, for Pigeon 1809 after a small-left reinforcer), and the probability of responding on the left after a reinforcer was attenuated, generally, by a small reinforcer from either alternative.

Responding for all pigeons developed some sensitivity to the reinforcer amount ratio, although at different rates and to different degrees. By the end of the third PRBS, all pigeons' response ratios tracked unpredictable changes in the amount ratio across sessions to some extent. At the beginning of the experiment, responding was heavily biased toward one key and did not track changes in reinforcer amount. As the experiment progressed, responding became more sensitive to the amount ratio, as evidenced by the session to session shifts in responding toward the alternative that produced the larger reinforcer. Two pigeons, 9337 and 405, showed this effect rather dramatically; response ratios shifted in favor of the larger reinforcer in most instances.

These results were somewhat similar to those reported in previous experiments investigating sensitivity to reinforcer rate (Hunter and Davison, 1985; Schofield and Davison, 1997) and immediacy (Grace, et al., 2003; Grace and McLean, 2006) using the same general procedure. In all of these studies, response allocation showed sensitivity to the reinforcer manipulations as early as the end of the first sequence. In the present experiment, sensitivity developed in 2 pigeons at the end of Sequence 1 and, to varying degrees, in all pigeons by the end of Sequence 3. It should be noted that sensitivities for rate (Hunter and Davison, 1985; Schofield and Davison, 1997) and immediacy (Grace, et al., 2003; Grace and McLean, 2006) found in previous studies were much higher than sensitivity to amount in the current experiment. This is consistent with previous reports that responding under concurrent schedules is typically more sensitive to reinforcer rate and immediacy than reinforcer amount under both steady-state and variable-environment procedures (e.g., Davison and Baum, 2003; Landon et al., 2003; Schneider, 1973; Todorov, 1973; Todorov et al., 1984).

In the current experiment, whole-session estimates of sensitivity to amount (0.10-0.24 during Sequence 3) were lower, but approached those obtained from other variable-environment procedures. For example, Davison and Baum (2003), using a mixed, concurrent VI schedule, reported amount sensitivities ranging from 0.22-0.31, and Todorov et al. (1984) reported estimates ranging from 0.23-0.67. The current whole-session estimates also were lower than those reported by Schneider (1973) and Todorov (1973) under steady-state conditions (0.27-0.34) and by Landon et al. (2003) (0.71-0.8) who manipulated reinforcer amount in a manner similar to the one used in the current study. Whole-session sensitivity estimates in the present study were lower still than those

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reported by McLean and Blampied (2001) (0.73-1.04), using a procedure in which a given amount ratio was in effect for a long period as VI schedules were manipulated. Interestingly, in the current study, sensitivity estimates for data in the second half of the session were higher (0.13 to 0.39) than those for the whole session and more closely approximated those previously reported. Taken together, these data suggest that sensitivity to reinforcer amount may depend on the length of exposure to a given amount ratio, both within and across sessions.

For all pigeons in the current experiment, Lag-0 sensitivities for the whole session were higher than those found at other lags and increased across sequences (although early in training Lag 1 sensitivity was higher in a few instances, e.g., Pigeon 1863, Figure 2, left panels). These results are comparable to those reported by Grace et al. (2003) and Schofield and Davison (1997). Generally, this suggests that responding was more sensitive to the reinforcer amount arranged in the current session and that sensitivity to those conditions increased with exposure to the contingencies.

Response ratios in the present study increasingly shifted toward the alternative associated with the larger reinforcer amount across consecutive sessions with the same amount ratio. As a result, sensitivity at Lags 1 and 2 was positive, suggesting that immediately following a switch in the amount ratio, responding is not asymptotically sensitive to the amount ratio in effect within that session and subsequent exposure to the same-amount ratio increases preference for the richer alternative. These results are in accord with the findings of Davison and Hunter (1979). They found that immediately following a change in reinforcer parameters, responding was heavily biased toward the

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previously preferred alternative, but that bias disappeared fully in as little as three sessions, resulting in maximally sensitive responding.

Based on the changes of sensitivity at particular Lag positions (Lag 0 versus all others), it could be argued that the "sensitivity" parameter typically referred to when discussing control by reinforcer characteristics (e.g., rate, immediacy, and amount) is an amalgamation of at least two processes: sensitivity of responding to current conditions and sensitivity of responding to previous conditions (i.e., carryover effects) (see Davison and Baum, 2000; 2002). Presumably, with increased exposure to a particular set of contingencies a shaping process occurs during which sensitivity to current conditions increases and sensitivity to previous conditions decreases. These shifts in sensitivity across Lag position was less pronounced in the current experiment than previous experiments (e.g., Grace et al., 2003; Schofield and Davison, 1997). Given that sensitivity to reinforcer amount typically is lower than to reinforcer rate and immediacy, more exposure to the current procedure may be necessary to increase sensitivity at Lag 0 and decrease sensitivity at the other lags.

Analysis of performance in the first and second half of the sessions suggests another source of control over sensitivity to reinforcer amount. In all pigeons, Lag-0 sensitivity increased substantially from the first to the second half of the session indicating within-session acquisition similar to that reported for immediacy by Grace et al. (2003). Also, for 2 of the 4 pigeons, Lag-1 sensitivity decreased substantially from the first to the second half of the session suggesting that control by the previous session was decreasing across the session. Extending the sessions by presenting more reinforcers would increase exposure to the amount ratios during a session and, thus, might increase

the sensitivity reached during the session. One drawback of this remedy, however, is the possibility of satiation.

In summary, the present experiment demonstrates that sensitivity of responding to reinforcer amount can develop under a rapid-acquisition procedure. The pattern of development of sensitivity to amount closely resembled those reported previously with other reinforcer parameters (e.g., Grace et al., 2003; Grace and McLean, 2006; Hunter and Davison, 1985; Schofield and Davison, 1997). Like previous studies using the PRBS methodology, sensitivity estimates approached, but were slightly lower than, estimates obtained under steady-state procedures. In addition, the estimates obtained in the present study approximated those obtained using other types of variable-environment procedures (e.g., Davison and Baum, 2003).

GENERAL DISCUSSION

The purpose of the present series of experiments was to investigate the conditions under which sensitivity to reinforcer amount would develop using a variable-environment procedure. The results of Experiment 1 suggested that the responding was not sensitive to reinforcer amount under a within-session procedure similar to the one used by Davison and Baum (2003). The data were analyzed at three different levels in search of orderly data with respect to reinforcer amount, and few were found. Generalized matching plots (Equation 4), plotting log response ratios from an entire component or session as a function of the log amount ratio in effect that component or session, previously, have revealed orderly data in the form of a linearly increasing straight line with slope ranging from 0.3 to 1.2 under steady-state type procedures (see Landon, Davison, Elliffe, 2003; McLean and Blampied, 2001; Schneider, 1973; Todorov, 1973). Davison and Baum

(2003) reported sensitivity estimates across subjects that ranged from 0.21 to 0.33. The lower sensitivity estimates, when compared to those of the steady-state procedures, might be expected given the nature of the procedure (e.g., rapidly changing conditions and little exposure). In Experiment 1 of the present study, however, no consistent preference developed in any component; across pigeons, the highest sensitivity estimate obtained was 0.058 (see Figure 2). Furthermore, finer analyses also revealed little control by amount at more local levels. For example, within component analyses, in which response ratios were plotted as a function of component fifths, revealed that no preference developed at any point during any component.

Local analyses failed to reveal the sort of order reported by Davison and Baum (2003). For all pigeons in the present study, reinforcers delivered after responses from either side generally resulted in responding on one particular alternative. For example, Pigeon 1863 tended to respond on the left alternative nearly exclusively following reinforcers produced by responses on either alternative. Therefore, reinforcer delivery tended to produce what could be called a *bias* pulse, rather than a *preference* pulse. In addition, contrary to results reported by Davison and Baum, reinforcer amount did not have a systematic effect on the size or length of these bias pulses; however, for Pigeon 405, larger left reinforcers tended to decrease and larger right reinforcers tended to increase the size of the pulse. Possible reasons for the failure to replicated Davison and Baum's results were outlined in the Results and Discussion in Experiment 1. It is unclear at this point why sensitivity did not develop under the Davison and Baum procedure in Experiment 1. A number of variables are, presumably, important: number of reinforces per component, difference in absolute reinforcer amounts, number of

amount ratios presented. As many of these variables were not systematically manipulated in the current study, further investigations are certainly warranted.

The results from Experiment 2 suggested that the pigeons' responding was sensitive to relative reinforcer amounts, as responding shifted toward the alternative which produces the relatively larger reinforcer under steady-state conditions. In Experiment 2, only two reinforcer ratios were used (1/7 and 7/1), and each reinforcer ratio was in effect for the within and across consecutive sessions until a preference for (or shift toward) the larger reinforcer emerged. Responding in all four pigeons shifted rather quickly upon implementation of the new procedure (the 7/1 ratio was in effect) and overall session response ratios for 3 of 4 pigeons (1809, 1863, and 405) approximated the amount ratio; Pigeon 1809's response ratios did shift in the same direction but not as dramatically. When the amount ratio was then switched (the 1/7 ratio was then in effect), preference in all pigeons then shifted toward the other alternative. Sensitivity estimates under this procedure ranged from 0.40 to 0.53; these values are comparable to those from previous research using similar procedures (see the above discussion). For Pigeons 405 and 9337, preference shifted back following a return to the original amount ratio. Experiment 2 demonstrated that responding in these pigeons was sensitive to reinforcer amount under steady-state conditions. Within-session analyses (Figure 12) indicated a relatively steady preference for the alternative which produced the larger reinforcer. The results of Experiment 2 suggested that responding under typical steady conditions was indeed sensitive to changes in relative reinforcer amount.

The results in Experiment 3 generally were comparable to results obtained using the same type of procedure to investigate the effects of other variables (e.g., rate and

immediacy of reinforcement). That is, sensitivity of responding to reinforcer amount developed with increased exposure to the procedure, as shown by Grace, et al., (2003) and Grace and McLean (2006) with reinforcer immediacy, and by Hunter and Davison (1985) and Schofield and Davison (1997) with reinforcer rate. Also, the sensitivity estimates obtained in the current study (0.13-0.39) were comparable to previous studies studying sensitivity to reinforcer amount under concurrent schedules in both steady-state and variable-environment procedures (but see Landon, Davison, and Elliffe, 2003; McLean and Blampied, 2001).

Compared to previous studies investigating reinforcer rate and immediacy, development of sensitivity to reinforcer amount occurred much more slowly. Such slow development of sensitivity under the PRBS procedure might also account to the inability for sensitivity to form at all under the variable-environment procedure employed in Experiment 1 of the current study (during which reinforcer parameters changes much more often and arranged for smaller absolute differences between the two available food amounts). However, given the large carryover sensitivity, it would be expected for some sensitivity to develop by the end of a component. Indeed, Davison and Baum (2000, 2002, 2003) reported a similar effect explicitly. As the component progress (i.e., food was delivered according to the rate or amount ratio arranged for that component), sensitivity to the current component increased while sensitivity to previous components decreased.

Responding Under PRBS Procedures as a Baseline to Study Drug Effects

As the purpose for this study was to develop a baseline with which to assess the effects of environmental manipulations (e.g., drug administration) on sensitivity of

responding to reinforcer amount, it is important to consider the implications that the baseline procedure and results of Experiment 3 have for such manipulations and the subsequent interpretations of any effects of pharmacological manipulations. Under the PRBS methodology reported in the present study, responding was reasonably sensitive to the reinforcer-amount manipulations. In accord with previous studies, response ratios generally shifted across sessions concomitantly with shifts in amount ratios. By the end of the third sequence, Lag-0 sensitivity estimates in all cases was higher than at all other Lags (as noted in previous studies). Unlike, previous studies, however, Lag-1 and -2 sensitivity estimates remained positive throughout the experiment, suggesting presence of carryover effects from the amount ratios arranged during previous sessions. In the current study, carryover effects were evident in at least one of two ways. First, after a switch in amount ratio, responding was not maximally sensitive, resulting in notable undermatching of response ratios to the amount ratios in effect. Second, response ratios tended to become more extreme when a particular amount ratio was in effect for multiple consecutive sessions.

The pervasive carryover effects throughout the experiment raises some issues for consideration concerning the use of this baseline for assessing the effects of drugs. The first concerns the dosing regimen. Under the current procedure, it is evident that response ratios emitted on any given session is a function of both the amount ratio arranged for the current session as well as those arranged in previous sessions. As such, it is important to consider which sessions should be used for acute drug determinations, which to use as controls for drug sessions, and how many sessions should intervene between drug determinations.

The current investigation was directed toward characterizing the effects of drugs on sensitivity of responding to current reinforcer parameters (rather than effects on carryover sensitivity); therefore, it would be important to administer the drug before sessions when carryover sensitivity is likely to be minimal. According to the current results, carryover sensitivity appears to have been completely dissipated by the third consecutive session of one amount ratio and, thus, it could be argued that acute doses should be administered on those sessions. However, the case could be made that with training, Lags-1 and -2 sensitivities may drop to zero with subsequent exposure to the PRBS (surely this is possible given other studies [Grace et al., 2003; Grace and McLean, 2006; Schofeld and Davison, 1997] who reported near zero estimates) which would then suggest other sessions within the sequence would be reasonable candidates for acute dosing.

A second consideration concerns the analysis of the effects of the drug on sensitivity. That is, what type of analyses would be appropriate to properly characterize changes in sensitivity. When determining acute effects of drugs on responding under choice procedures, it is typical for researchers to use point estimates of sensitivity using within session response ratios to determine acute effects (for example, see Pitts and Febbo, 2004); however, doing so assumes negligible carryover effects. Under the current procedure, point estimates of sensitivity would be an inaccurate characterization of sensitivity to responding on any given session within the PRBS sequence given the nature of the manifestation of carryover sensitivity. For example, when the same amount ratio was arranged for multiple consecutive sessions, response ratios tended to become more extreme with each subsequent session of exposure. In such cases, point estimates of

sensitivity to the current session would be inflated due to the cumulated sensitivity which may have developed across multiple consecutive amount ratio presentations. Conversely, taking point estimates from sessions following a switch in amount ratio would result in deflated estimates of sensitivity, due to similar but opposite effects. In this case, carryover sensitivity would have a subtracting effect on response ratios obtained during the current session. As such, it appears that point estimates given the current state of responding (i.e., significant carryover sensitivity) would be inaccurate for determining acute effects of drugs. As with the dosing regimen, however, the use of such analyses is wholly dependent on the state of responding at the time of drug administration. It could be the case, as previously mentioned, that Lag-1 and greater sensitivities dissipate entirely, and point estimates would be sufficient. In either case, analyses of drug effects under such a procedure depends on the extent to which current and previous experimental conditions exert control over responding at beginning of a dosing regimen.

Sensitivity to Amount and Implications for Behavioral Mechanisms

Although sensitivity to reinforcer amount did develop, it can be argued that under the current preparation that it did so at a slower rate compared to other reinforcer parameters. Indeed, in the other studies investigating other reinforcer parameters under the PRBS methodology (Grace et al., 2003; Grace & McLean, 2006; Hunter & Davison, 1987; Schofield & Davison, 1997) responding became quite sensitive in as little as one sequence presentation, and failed to exhibit high carryover sensitivity. In all cases, Lag-0 sensitivity estimates were higher than all other Lag values from the beginning of the experiment, and Lag-1 and greater estimates approximated zero with little across-sequence decreases (for example, see Grace et al., 2003, Figure 2). In the current study,

however, Lag-1 and -2 sensitivity estimates remained positive throughout the experiment. Note that carryover sensitivity did diminish within session as noted by comparing the center and right panels of Figure 16. The persistence of carryover sensitivity across sequence presentations (along with the gradual decrease within session) suggests that sensitivity to reinforcer amount develops more gradually compared to other dimensions of reinforcement (e.g., rate and delay).

If sensitivity to reinforcer amount does indeed develop more slowly than sensitivity to reinforcer rate or delay, such an interpretation has implications for changes in sensitivity to reinforcer amount as a behavioral mechanism of drug action under self-control procedures. Recall that the use of quantitative analyses to identify behavioral mechanisms (Pitts and Febbo, 2004) revealed that the robust effects of stimulants to increase choice of larger, delayed reinforcers (under some conditions) is largely due to effects on sensitivity to reinforcer delay. That is, stimulants tended to decrease sensitivity to delay shown by a drug-induced decrease in the slope of delay-discounting functions. Decreases in slope were accompanied, in several instances, by a decrease in the y-intercept (interpreted by Pitts and Febbo as either a drug-induced change in sensitivity to reinforcer amount or response bias). In the current study, when sensitivity to reinforcer amount did develop, it did so gradually within and across sessions, but at a much slower rate than would be expected if it were to be implicated as a behavioral mechanism involved in within-session drug-induced shifts in preference under self-control procedures. Note, however, that the changes in y-intercept were, for most pigeons, small changes relative to changes in slope which may reflect smaller changes in sensitivity to amount.

The rate of development of sensitivity under the current conditions may also have implications for the differential effects of stimulants on self-control reported in the literature. As noted above, stimulants generally have been reported to increase choice of larger, delayed reinforcers relative to control performances (e.g., Pietras et al., 2003; Pitts & Febbo, 2004; Pitts & McKinney, 2005; Richards et al., 1999; Wade et al); however, others have reported the exact opposite, that stimulants increased choice of smaller, immediate reinforcers (e.g., Charriet & Thiebot, 1996; Evenden & Ryan, 1996). Although this difference in effects could potentially be explained by procedural differences (i.e., the use of signaled versus unsignaled delays) (see Pitts and Febbo, 2004; Richards et al., 1999 for discussions), it could be the case that differences in the rate of development of sensitivity to amount could also contribute to the seemingly opposite effects. For example, conditions that are not very favorable to rapid development of sensitivity to amount, but are favorable for development of sensitivity to delay (e.g., when the delays are signaled) might be expected to yield increases in self control. In contrast, conditions more favorable to development of sensitivity to amount relative to delay (e.g., when the amount ratios are more extreme and/or delays are not signaled) might allow stimulants to affect sensitivity to amount and, thus, allow the drug to produce an increase in impulsive choices. That is, the drug effect on either sensitivity to amount may depend on the prevailing conditions and the extent to which responding is controlled primarily by either reinforcer delay or amount. If the stimulants do, in fact, reduce sensitivity to amount, which is a plausible interpretation of results reported by Pitts and Febbo or the tendency of stimulants to increase choice of smaller, more immediate reinforcers as demonstrated by Charriet and Thiebot and Evenden and Ryan, the case

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could be made that under certain circumstances the effect on sensitivity to amount will be more dramatic and occur more rapidly (i.e., when delays are unsignaled) compared to circumstances under which effects on sensitivity to delay are more pronounced (i.e., when delays are signaled).

Summary and Conclusions

The purpose of the present study was to develop a baseline with which to study the effects of various environmental variables (e.g., drug administration) on sensitivity of responding to reinforcer amount under concurrent schedules of reinforcement as well as to validate the use of quantitative methods to identify potential behavioral mechanisms of drug action. These results suggest that the rapid-acquisition procedure may be a suitable procedure for investigating sensitivity of responding under concurrent schedules in which reinforcer amount is varied and may provide a suitable baseline for examining effects of other experimental manipulations (e.g., drugs) as well as characterize the acquisition of sensitivity through training. However, the present results suggest that the speed of acquisition of sensitivity to reinforcer amount might preclude it as a primary behavioral mechanism involved in drug-induced shifts in preference under self-control procedures. Further research should focus on this possibility directly.

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