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Testing the Functional Equivalence of Retention Intervals and Sample-Stimulus Disparity in Conditional Discrimination

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TESTING THE FUNCTIONAL EQUIVALENCE OF RETENTION INTERVALS AND

SAMPLE-STIMULUS DISPARITY IN CONDITIONAL DISCRIMINATION

by

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ABSTRACT

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by

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    Memory-trace theories of remembering suggest that performance in delayed

matching-to-sample (DMTS) procedures depends on a memory trace that degrades with

time. By contrast, the theory of direct remembering suggests that increasing the delay

between sample and comparison stimuli in DMTS procedures is functionally equivalent

to decreasing the disparity between sample stimuli. The present dissertation tested this

assumption by assessing the degree to which changes in the frequency of reinforcement

for correct choices biased the distribution of choice responses in a conditional-

discrimination procedure. Seven pigeons responded under a temporal-discrimination

procedure in which temporal sample-stimuli were categorized as being of either short or

long duration by a response to a corresponding comparison key. In the sample-stimulus

disparity condition, the disparity between the sample stimuli (difference between the

short and long samples) was manipulated. In the retention-interval condition, the delay

between sample offset and presentation of the comparison stimuli was manipulated.

Importantly, the same general procedure was used across conditions, facilitating conclusions regarding functional equivalence of the two manipulations. The theory of direct remembering suggests that the relation between sensitivity of behavior to changes in reinforcer frequency and discriminability (accuracy) should be similar in the sample-stimulus disparity and retention-interval condition. The results showed that discriminability decreased with both the sample-stimulus disparity and retention-interval manipulations. Overall estimates of sensitivity were similar to those obtained previously. There was, however, no difference in the estimates of sensitivity as a function of discriminability during either the sample-stimulus disparity or retention-interval conditions; sensitivity was independent of discriminability. These results are in contrast to most previous reports, and are interpreted in terms of the use of temporal-sample stimuli in the current experiment. Further analyses of the choice-response data showed that the effects of variation in reinforcer ratios differed across conditions as a function of trial type and trial difficulty. These results suggest the need for careful consideration of behavioral outcomes at several levels of analysis when assessing functional equivalence of experimental manipulations. The potential benefits and hindrances of characterization of behavioral outcomes in terms of functional equivalence are discussed.

(104 pages)

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Ryan D. Ward

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INTRODUCTION

Accurate discrimination of environmental stimuli is important. For example, birds must be able to distinguish between subtle color variations of poisonous and edible berries and insects. For humans, failure to accurately discriminate the color of a stoplight and respond appropriately can have serious consequences. Accordingly, considerable laboratory research has focused on the basic processes underlying discrimination of environmental stimuli. In the most common procedure used with nonhumans, termed conditional discrimination, subjects are presented with a sample stimulus. Following sample termination, choice comparisons are presented. Choice responses to the comparison that matches the presented sample stimulus produce food (see Davison & Nevin, 1999, for a review). In delayed matching-to-sample (DMTS; Blough, 1959) procedures, a delay (retention) interval occurs between presentation of the sample and comparison stimuli. Delayed matching-to-sample procedures have been widely used to study variables that influence remembering.

While traditional accounts of memory in nonhumans conceptualize remembering as a complex cognitive process (e.g., Grant, 1981), recent theoretical treatments suggest that performance in DMTS experiments can be conceptualized as discriminative behavior under delayed stimulus control (White, 1985, 1991). This theory, known as *direct remembering*, does not postulate a memorial representation that mediates accuracy of choice responding at a given retention interval. Rather, performance at one retention interval is suggested to be independent of performance at other retention intervals. Such independence has been empirically demonstrated (White, 2001; White & Cooney, 1996).

A theory of direct remembering suggests that remembering is the same as other discriminative behavior. Because of this conceptualization, manipulations that affect discrimination performance, such as varying retention intervals in DMTS (increasing the difficulty of remembering) or manipulating sample-stimulus disparity in 0-s delay conditional discrimination (making the stimuli more difficult to tell apart), are suggested to be functionally equivalent (see White, 1991). Such functional equivalence, however, has not been empirically demonstrated.

One point of comparison between the effects of manipulating retention intervals and sample-stimulus disparity comes from studies that have varied aspects of the reinforcement for correct choices. Extant quantitative models of conditional discrimination provide methods to assess the sensitivity of changes in comparison-choice responding to changes in the frequency or magnitude of reinforcers arranged for correct choices (see Baum, 1974; Baum & Rachlin, 1969; Davison & Tustin, 1978). According to these models, the ratio of choice responses on either comparison stimulus should approximate the ratio of reinforcer frequencies allocated for these responses. If varying retention intervals and sample-stimulus disparity are functionally equivalent manipulations, sensitivity to variations in the reinforcer frequency ratio should be similar during both manipulations. In studies that have varied the disparity of sample stimuli, however, sensitivity to reinforcer-frequency ratios generally increases with increases in sample-stimulus disparity (e.g., Davison & McCarthy, 1987, 1989; McCarthy & Davison, 1984; Nevin, Cate, & Alsop, 1993; White, 1986; White, Pipe, & McLean, 1985), while studies that have varied retention intervals have reported both increasing (Jones & White, 1992; White & Wixted, 1999) and decreasing (e.g., McCarthy & Davison, 1991;

McCarthy & Voss, 1995) sensitivity to reinforcer-frequency ratios as a function of increasing retention interval.

Before conclusions can be reached with regard to the functional equivalence of manipulating retention intervals and sample-stimulus disparity, reasons for the conflicting results from DMTS procedures must be specified. White and Wixted (1999) interpreted these differences as resulting from proactive interference generated by the short intertrial interval (ITI) durations used in previous experiments. They showed that sensitivity to reinforcer frequency ratios increased with increasing retention interval in a long ITI condition, while in a short ITI condition, the opposite relation was observed.

While some evidence suggests that manipulation of retention intervals and sample-stimulus disparity may be functionally equivalent in their effects on discrimination (Jones & White, 1992; White & Wixted, 1999), these results are not definitive. Multiple differences across procedures that have varied retention intervals and those that have varied sample-stimulus disparity make comparison across studies difficult. Manipulation of both variables within the same general procedure is therefore needed before conclusions can be reached regarding the functional equivalence of both sample-stimulus disparity and retention intervals.

The present experiment tested the functional equivalence of sample-stimulus disparity and retention intervals by assessing sensitivity to variations in reinforcer frequency as a function of both retention intervals and sample-stimulus disparity. Both variables were manipulated within the same procedure to facilitate direct comparison. If varying retention intervals and sample-stimulus disparity are functionally equivalent manipulations, as a theory of direct remembering asserts (e.g., White, 1991), the relation

between sensitivity to reinforcer frequency ratios as a function of both sample-stimulus

disparity and retention interval should be similar. In addition, the present experiment used

temporal-sample stimuli, thus assessing the generality of results reported with sample

stimuli of other dimensions.

REVIEW OF THE LITERATURE

One area of interest in the experimental analysis of behavior is discovering the basic processes involved in accurate discrimination of environmental stimuli. Although various experimental preparations may be employed to this end, the most common is the conditional-discrimination procedure. Conditional-discrimination research is often conducted with pigeons as subjects due to their consistent behavior across experimental conditions, their long experimental life, and the similarities between pigeon and human visual acuity. In addition, studies conducted with a wide variety of species have established the generality of results obtained using pigeons (see White, Ruske, & Columbo, 1996, for discussion).

Conditional Discrimination

In a typical conditional-discrimination experiment, pigeons are placed in an experimental chamber equipped with 3 plastic response keys that can be illuminated from behind with various stimuli. In one common variant of this procedure, matching-to-sample (MTS), one of two sample stimuli (S_1 or S_2) is presented on the center key. Following a specified amount of time or number of responses, the sample is extinguished. The side keys are then lit, each key with a different stimulus (B_1 or B_2). One key is lit with the same stimulus as the sample, while the other key is lit with another stimulus. A peck to the key lit with the stimulus that matches the sample is reinforced (produces food) with some probability and a peck to the other key is not reinforced (does not produce food). Symbolic matching-to-sample (SMTS) procedures are similar to MTS

procedures, with the exception that the sample and comparison stimuli are not identical.

For example, a sample may consist of a key being lit red for a given duration. Following

sample presentation, the side keys may be lit blue and white. If the sample duration is

shorter than a criterion duration (e.g., 6 s), pecks to the blue key are reinforced. If the

sample is longer than 6 s, pecks to the white key are reinforced. Considerable research on

the basic processes involved in discrimination has been conducted using both MTS and

SMTS experimental paradigms (see Davison & Nevin, 1999, for a review).

In addition to lending itself well to exploration of the basic processes involved in

discrimination, the conditional-discrimination procedure can be adapted to study

processes that are involved in memory. Blough (1959) inserted a delay (0, 2, 5, or 10 s)

between sample presentation and presentation of the comparisons. As the delay between

the sample and comparisons increased, accuracy of matching decreased. Since its

introduction, this procedure, termed delayed matching-to-sample (DMTS), has been used

extensively to study variables that influence remembering (see White, 1985, for review).

Remembering is implicated in accurate DMTS performance because to make a correct

choice response when presented with the comparisons, the pigeons must presumably

remember the presented sample (or an encoded instruction) for the duration of the

retention interval. Many studies have shown that variables that are typically thought to

affect memory influence performance in DMTS procedures. For example, increasing the

opportunity for "rehearsal" by increasing the number of times a pigeon is required to

peck the sample stimulus or the number of times the sample is repeated at the beginning

of the trial increases accuracy (e.g., Grant, 1981; Roberts, 1972). In addition, research has

also demonstrated both retroactive (e.g., Cook, 1980) and proactive (e.g., Endhouse &

White, 1988; Grant, 1975) interference effects on DMTS performance. For example, Cook (1980) found decreases in accuracy when he illuminated the houselight during a normally dark retention interval in a DMTS procedure, suggesting a retroactive interference effect of houselight illumination. Proactive interference is evidenced by a decrease in overall accuracy when the ITI is shortened and has been interpreted as resulting from decreased attention to the sample (e.g., Endhouse & White). Thus, the results from a number of studies suggest that performance in DMTS procedures reflects remembering.

Current Theories of Memory in Nonhumans

Many theoretical treatments of memory in nonhumans have been offered. One early theory, proposed by Roberts (1972), suggests that accuracy of performance at a given retention interval in DMTS procedures is dependent on the strength of a memory trace established at the time of sample presentation. Specifically, the theory states that an isomorphic representation (memory trace) of the sample stimulus is formed at sample presentation. The strength of the memory trace increases as a negatively accelerated function of time exposed to the sample. Thus, the longer a sample is presented, or the more times in succession it is presented, the greater the strength of the memory trace. Once the sample presentation is terminated, the strength of the memory trace decays as a negatively accelerated function of time since sample presentation. Thus, according to this theory, the decreasing accuracy as a function of increasing retention interval often seen in DMTS procedures results from the decrease in the strength of the memory trace at progressively longer retention intervals.

Throughout the years, the initial iteration of trace-strength theory was revised to include the notions that different stimulus events form separate and independent memory traces, and that the strength of the memory trace for both the correct and incorrect matching comparisons compete with one another in determining the probability of a correct choice response (Roberts & Grant, 1976). Although the theory of trace strength has not survived in its initial form, many current theories have retained the notion that performance in DMTS procedures is mediated by a representation of the sample (or an encoded instruction) that decays as a function of time since sample presentation (see Grant, Spetch, & Kelly, 1997, for discussion).

The Theory of Direct Remembering

In contrast to complex theories of memory, recent theoretical treatments suggest that performance in DMTS procedures reflects discriminative behavior under delayed stimulus control. White (1985, 1991) first proposed this theory of *direct remembering* based on a number of empirical results showing that the initial level of discriminability (accuracy at a 0-s delay) and the rate of forgetting, (slope of the retention function) appeared to be separable aspects of DMTS performance. In contrast to other current theoretical conceptualizations of memory in nonhumans, in which accurate performance at a given retention interval in DMTS experiments is dependent on the strength of a memorial representation of the presented sample stimulus, the theory of direct remembering suggests that performance at any given retention interval is, in effect, a separate discrimination. According to this interpretation, retention intervals do not degrade the strength of a memory trace or representation (such memory traces are not

postulated). Instead, each retention interval becomes part of the stimulus context for the discrimination at that retention interval.

Because performance at each retention interval is considered a separate discrimination, a theory of direct remembering suggests that variables that influence performance at a given retention interval will not necessarily influence performance at other retention intervals, a concept known as temporal independence. Several experiments have demonstrated such independence. For example, White (2001) trained pigeons on a DMTS procedure. Across conditions, reinforcers for correct choices at one retention interval were eliminated, but correct choices at all other retention intervals were reinforced. For example, in one condition all reinforcers for correct choice responses at the 2-s retention interval were eliminated, but correct choices at the 0.1-, 4-, and 16-s retention intervals were reinforced. In this condition, accuracy at the 2-s retention interval decreased, but accuracy at other retention intervals was unaffected. This result held across conditions when reinforcers for correct choices at other retention intervals were eliminated. In another experiment, White and Cooney (1996) varied the ratio of reinforcers for correct red and green color matches at one retention interval, while keeping this ratio constant at another retention interval. Choice responses were biased by the reinforcer differential only at the retention interval at which the reinforcer ratio was varied. In both of these experiments, performance at one retention interval was independent of factors that affected performance at another retention interval, supporting a theory of direct remembering.

These results suggest that remembering may be conceptualized as any other discrimination. Accordingly, the theory suggests that the diminution in accuracy as a

function of increasing retention interval in DMTS procedures does not reflect the

decay of a memory trace or the decreasing strength of a representation. Rather, increased

temporal distance of the comparison stimuli from sample presentation is thought to

decrease performance in the same way as increasing the spatial distance between the

subject and the sample. This conceptualization, then, suggests that decreases in accuracy

in conditional-discrimination procedures, whether they are produced by increasing

retention intervals in DMTS or decreasing the physical disparity of sample stimuli in a

0-s delay discrimination, reflect decreased discriminative control. Thus, according to the

theory, manipulation of retention interval and manipulation of sample-stimulus disparity

should have functionally equivalent effects on discrimination performance (see White,

1991).

Although functional equivalence of retention intervals and sample-stimulus

disparity is a principal tenet of a theory of direct remembering, to date, there have been

no studies that have directly assessed such functional equivalence. The majority of

relevant studies were conducted to test the assumptions of several quantitative models of

conditional discrimination. The most influential of these models was proposed by

Davison and Tustin (1978). Because the theoretical assumptions and quantitative

predictions of this model are central to the design of the proposed research, the model

will be discussed in some detail.

The Davison-Tustin Model of Conditional Discrimination

Davison and Tustin (1978) proposed a model of conditional-discrimination

performance in which the ratio of choice responses following different sample stimuli is

governed jointly by which sample stimulus (S_1 or S_2) is presented on a given trial and

by the ratio of reinforcers obtained for correct comparison-choice responses following

presentation of each sample stimulus. The ratio of choice responses is influenced by the ratio

of reinforcers for correct choice responses following both samples according to the

generalized matching law.

The Matching Law

The matching law (Herrnstein, 1961, 1970) was formulated to describe the

distribution of behavior during concurrent schedules of reinforcement. During a

concurrent schedule of reinforcement, two response options are available. Responses to

each option are reinforced according to a separate schedule of reinforcement. For

example, responses to the left key might be reinforced on a variable interval (VI) 1-min

schedule, while responses to the right key are reinforced on a VI 3-min schedule. Across

conditions, the schedules associated with the two choice options can be varied (e.g., VI 1-

min on both keys, etc.). By varying the rate of reinforcement associated with each key

over several conditions, one can determine the steady-state response ratio associated with

each pair of concurrent schedule values. The general finding is that, once performance is

stable, the ratio of responses on each option matches the ratio of reinforcers obtained for

responding on those options according to Equation 1,

$$\frac{B_1}{B_2} = \frac{R_1}{R_2} \tag{1}$$

where B_1 and B_2 are the number of responses on each respective choice option and R_1 and

R_2 are the number of reinforcers obtained for those responses. Baum (1974) formulated

the *generalized matching law* to account for systematic deviations from matching as

described by Equation 1 in the empirical literature. The generalized matching law

states that the ratio of behavior allocated to each response option is a power function of

the reinforcer ratio obtained for responding on those options according to Equation 2,

$$\frac{B_1}{B_2} = c\left(\frac{R_1}{R_2}\right)^a \qquad (2)$$

where $B_1, B_2, R_1,$ and R_2 are as defined above. The relation between the behavior ratio and

the reinforcer ratio can be modified by a bias toward one choice option over the other (c),

possibly resulting from unprogrammed asymmetries in the response requirements (e.g.,

more force required to close the switch on the left key than on the right key), and by the

degree to which changes in the reinforcer ratio produce concomitant changes in the

behavior ratio, termed sensitivity (a).

Estimates of the c and a parameters are generally obtained by plotting obtained

behavior ratios as a function of obtained reinforcer ratios and fitting the logarithmic form

of Equation 2,

$$\log\left(\frac{B_1}{B_2}\right) = a \log\left(\frac{R_1}{R_2}\right) + \log c \qquad (3)$$

where all notation is as above. The logarithmic transformation is preferred because it

yields a straight line when fitted. Bias ($\log c$) is estimated as the intercept of the straight

line, while sensitivity (a) is estimated by the slope of the line relating the behavior ratio

to the reinforcer ratio. The left panel of Figure 1 shows matching. The function is a line

with an intercept of 0 and a slope of 1. Matching occurs when there is no bias toward

either respective alternative, meaning the value of $\log c$ is 0, and changes in the reinforcer

ratio produce equal changes in the behavior ratio, meaning the value of a is 1. In this
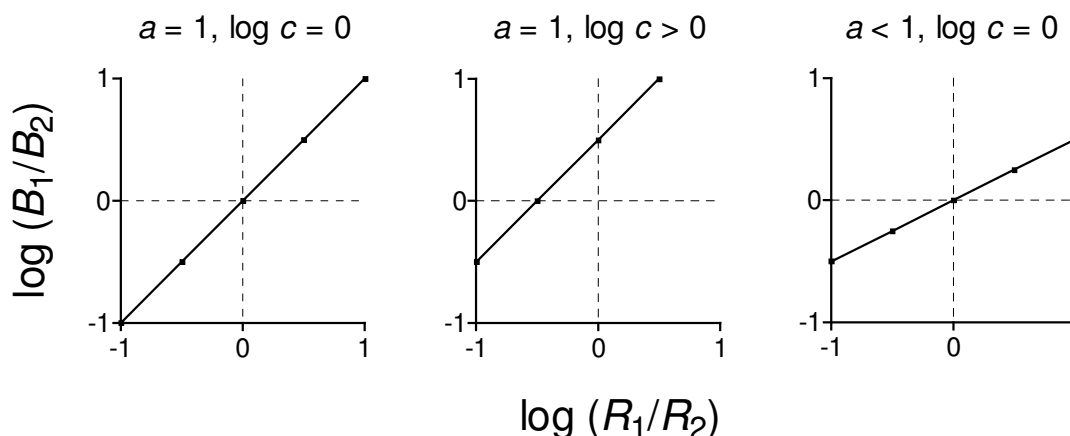
Figure 1. Hypothetical data showing matching (left panel), and the effects of changes in bias (center panel), and sensitivity (right panel) on the form of the matching function.

case, Equation 2 reduces to Equation 1. If responding is biased toward one or the other choice alternative, but there is a one-to-one correspondence between the behavior ratio and the reinforcer ratio, as shown in the center panel of Figure 1, the intercept of the line is shifted in the direction of that alternative, but the slope remains 1. Finally, if changes in the behavior ratio are not as extreme as the variation in the reinforcer ratio, as is usually the case, and there is no bias, the intercept of the line will not change but the slope will be less than 1, as shown in the right panel of Figure 1. Different values of both the *a* and log *c* parameters result in varying slopes and intercepts of the matching function.

The Generalized Matching Law Applied to Conditional Discrimination

The model of conditional discrimination proposed by Davison and Tustin (1978) treats the choice point (presentation of the comparison stimuli) in conditional-discrimination procedures as two concurrent reinforcement-extinction schedules each signaled by a different stimulus. The schedule associated with each comparison stimulus

Responses

	B_1	B_2
S_1	**W** (correct)	**X** (incorrect)
S_2	**y** (incorrect)	**z** (correct)

Figure 2. Possible sample-stimulus presentations, choice-response combinations (*w*, *x*, *y*, *z*), and outcomes in a conditional-discrimination procedure.

depends on which sample stimulus (S_1 or S_2) is presented at the beginning of the trial.

The possible combinations of the events in a given conditional-discrimination procedure

are presented in Figure 2. On trials in which S_1 is presented, responses to B_1 are

reinforced (*w*) and responses to B_2 are not reinforced (*x*). On trials in which S_2 is Thus,

according to the model, the ratio of responses to each comparison stimulus is governed

by the reinforcer ratio according to the generalized matching law (Equation 3).

According to Equation 3, the ratio of responses to B_1 and B_2 should equal the ratio

of reinforcers (R_1/R_2) obtained for responding on those alternatives, modified according

to the parameters log *c* and *a*. An additional consideration in conditional-discrimination

experiments is the degree to which the sample stimuli are discriminable from one

another. For example, a procedure in which S_1 is green and S_2 is red will result in more

differential responding than a procedure in which S_1 is green and S_2 is blue. This

differential responding results from the greater difference in wavelength between green

and red as opposed to green and blue. The degree of discriminability between the

sample stimuli is reflected in the parameter log d of the Davison-Tustin model. This

parameter is essentially a biasing term in the same way as log c. However, whereas log c

reflects inherent bias, log d reflects the biasing effect of the presented sample stimulus.

On trials in which S_1 is presented, behavior will be biased toward B_1, and vice versa. The

more discriminable S_1 is from S_2, the greater will be the bias to choose B_1 or B_2 when the

comparisons are presented. Thus, the response ratio following S_1 presentations is

governed by the reinforcer ratio according to

$$\log\left(\frac{B_w}{B_x}\right) = a\log\left(\frac{R_w}{R_z}\right) + \log c + \log d \, , \qquad (4a)$$

and the relation between response and reinforcer ratios following S_2 presentations is

described by

$$\log\left(\frac{B_y}{B_z}\right) = a\log\left(\frac{R_w}{R_z}\right) + \log c - \log d \qquad (4b)$$

where w, x, y, and z are the cells in the matrix depicted in Figure 2, and other terms are as

above. Note that because the numerators in both Equations 4a and 4b are B_1 responses,

log d is positive in Equation 4a and negative in Equation 4b. These two equations show

that the ratio of choice responses following each stimulus presentation is a function of the

ratio of reinforcers for those responses modified according to the sensitivity to variations

in reinforcer ratios (a), bias for one choice comparison over the other (log c), and the

biasing effect of the presented sample stimulus (log d). Parameter estimates of a, log c,

and log d are obtained by plotting the obtained choice response ratios as a function of the

obtained reinforcer ratios following both S_1 and S_2 presentations and fitting Equations 4a

(for S_1 presentations) and 4b (for S_2 presentations) to these data. The estimates of a and

log c are the slope and intercept of the straight lines, respectively, and an estimate of

stimulus discriminability (log d) can be obtained by multiplying the difference between

the intercepts of Equations 4a and 4b by 0.5.

Point Estimates of Discriminability and Bias

Accuracy in conditional-discrimination experiments has traditionally been

characterized by calculating the proportion of correct responses (correct/(correct +

incorrect)). There are several properties of the proportion correct measure, however, that

make its use problematic. First, the measure is bounded by 0.5 (chance accuracy) and 1.0

(perfect accuracy). Because of this restricted range, changes in accuracy at the lower and

upper bounds of proportion correct are constrained by ceiling and floor effects and are

therefore less sensitive to changes in discrimination performance. Second, the calculation

of proportion correct does not take into account bias for one comparison stimulus over

the other, making conclusions as to the reasons for poor discrimination performance

difficult. For example, the same value of .5 would result if choice responding was

completely undifferentiated or if one choice comparison was responded to exclusively,

perhaps as a result of a color or side bias. For these reasons, proportion correct is not a

sufficient measure of discrimination performance in some cases.

A bias free measure of accuracy can be obtained from the Davison-Tustin model

by subtracting Equation 4b from Equation 4a. With some rearrangement, this gives

$$\log d = 0.5 \ \log \left(\frac{B_w B_z}{B_x B_y} \right) \tag{5}$$

where all notation is as above. Log d (discriminability) is a measure of accuracy that reflects the discriminability between S_1 and S_2 and is free of bias for one comparison stimulus over the other or for any biasing effects of the reinforcer differential. This measure is equivalent to the discriminability index proposed by Luce (1963) and has similar properties as d' from classic detection theory (Green & Swets, 1966). Because it is a bias free measure, log d is preferred over proportion correct in some situations. In addition, log d is not bounded by .5 and 1, rather it has a range of 0 (no discrimination) to infinity (perfect accuracy on an infinitely large number of trials). Representative values of log d, and corresponding estimates of proportion correct are presented in Table 1.

An estimate of bias can be calculated by adding Equation 4b to Equation 4a. With some rearrangement, this gives

$$\log b = 0.5 \; \log\left(\frac{B_w B_y}{B_x B_z}\right) = a \log\left(\frac{R_w}{R_z}\right) + \log c \tag{6}$$

where all notation is as above. Thus, log b (overall response bias) is a function of the

Table 1

Representative Values of Proportion Correct and Corresponding Values of log d

S_1 Corr	S_1 Incorr	S_2 Corr	S_2 Incorr	Prop Corr	log d
995	5	995	5	.99	2.30
950	50	950	50	.90	1.28
800	200	800	200	.80	0.60
700	300	700	300	.70	0.37
600	400	600	400	.60	0.18
500	500	500	500	.50	0.00

Note. All calculations are based on 1000 trials with each sample stimulus (S_1 and S_2).

reinforcer differential and inherent bias. Equation 6 can be applied to conditional-discrimination data in the same way as Equation 3 is applied to concurrent-schedule data. The left side of Equation 6 is independent of the discriminability of the sample stimuli (log d). Equation 5 and the left side of Equation 6 are point estimates, and do not require the parametric variation of reinforcer ratios required to obtain estimates of discriminability and bias when using Equations 4a and 4b.

<div align="center">

Sensitivity to Variation of Reinforcer Frequency

in Conditional Discrimination

</div>

In the theoretical treatment of conditional discrimination above, Equations 4a and 4b suggest that the effects of changes in the reinforcer-frequency ratio (R_w/R_z) and changes in the discriminability of the sample stimuli (log d) are additive and therefore, independent. This independence suggests that sensitivity to variations in the reinforcer-frequency ratio (a) should not be affected by changes in discriminability (log d). Empirical tests of this independence were supported at first. For example, McCarthy and Davison (1980) arranged a temporal-discrimination procedure with a relatively easy (5 s vs. 30 s) and a relatively difficult (20 s vs. 30 s) condition. They then varied the reinforcer frequency for correct choice responses during both conditions to obtain estimates of sensitivity. They found that discriminability (log d) was lower during the difficult-discrimination condition. In addition, in accordance with the Davison-Tustin formulation, the estimates of sensitivity were independent of the level of discriminability, indicated by no significant differences in the slopes of the functions (Equations 4a and 4b) relating the ratio of choice responses to the ratio of reinforcers.

Although initial experiments reported independence of sensitivity and discriminability (e.g., McCarthy & Davison, 1979, 1980), subsequent experiments did not confirm such independence. For example Davison and McCarthy (1987) employed a complex temporal-discrimination procedure in which trials consisted of presentation of either a fixed or variable stimulus duration. The fixed duration remained the same throughout each experimental condition, but was varied across two conditions (5 s vs. 20 s). The variable stimulus duration was varied within session across 12 values, ranging from 2.5 to 57.5 s. Responses to one key were reinforced following the fixed duration and responses to the other key were reinforced following other durations. The reinforcer frequency for correct responses was varied during both conditions. Discriminability was highest when the disparity (difference between the fixed and variable duration stimuli) was greatest, similar to the results of McCarthy and Davison (1980). Contrary to the results of McCarthy and Davison, sensitivity to variations in the reinforcer-frequency ratio increased with decreases in discriminability, indicating that these two parameters were not independent. This inverse relation between stimulus discriminability and sensitivity to reinforcer frequency has been confirmed when sample-stimulus disparity has been varied across conditions (McCarthy & Davison, 1984; White, 1986), as well as when a range of color (Davison & McCarthy, 1989), and line orientation (White et al., 1985) sample stimuli varying in disparity were presented within session.

Several investigations have assessed sensitivity to reinforcer-frequency ratios as a function of increasing retention interval in DMTS experiments. Similar to the results of studies that have varied sample-stimulus disparity, increasing the retention interval in DMTS experiments decreases discriminability as measured by log d (see White, 1985, for

review). Initial research suggested independence of sensitivity and discriminability.

For example, Harnett, McCarthy, and Davison (1984; Experiment 2) varied the duration

of the retention interval from 0.06 s to 10.36 s across three conditions in a DMTS

procedure. During each condition, they varied the reinforcer frequency ratio for correct S_1

and S_2 responses. Similar to the results from studies that varied sample-stimulus disparity,

discriminability (log d) decreased with increasing retention interval. In addition,

sensitivity to changes in the reinforcer-frequency ratio remained similar across the three

retention interval conditions, thus demonstrating independence of sensitivity and

discriminability in accordance with the Davison-Tustin model.

Although the results of Harnett and colleagues suggested independence of

sensitivity and discriminability in DMTS, later studies reported conflicting results. For

example, McCarthy and Davison (1991) varied retention-interval duration from 0.5 s to

30 s across conditions in a delayed symbolic matching-to-sample procedure. Within each

condition, they varied the relative frequency of reinforcers for correct responses.

Discriminability decreased as a function of increasing retention interval, consistent with

the results of previous studies. Sensitivity to variations in the reinforcer-frequency ratio,

however, also decreased with increasing retention interval, rather than remaining similar

across retention intervals as reported by Harnett and colleagues. Yet another result was

reported by Jones and White (1992). They varied retention-interval duration across four

values (0.01-, 1-, 4-, 12-s) within session and varied relative reinforcer frequency across

conditions. Discriminability decreased with increasing retention interval, as previous

studies had reported. Sensitivity to reinforcer-frequency ratios, however, increased with

decreasing discriminability, contrary to the results of Harnett and colleagues and

McCarthy and Davison (see also White & Wixted, 1999). Jones and White suggested

that the different results between studies might have been due to varying retention

intervals within session instead of across conditions, as well as to the development of

extreme side biases in the McCarthy and Davison study. This interpretation was tested by

McCarthy and Voss (1995). They varied retention intervals within session and reinforcer

frequency across conditions, similarly to the procedure used by Jones and White.

Discriminability decreased with increasing retention interval. In addition, sensitivity to

reinforcer-frequency ratios also decreased with decreasing discriminability, consistent

with the results of McCarthy and Davison. Thus, variation of retention intervals within

session vs. across conditions cannot account for the different results. Moreover, the

different results cannot be due to the development of extreme side biases, as no

systematic biases were evident in the McCarthy and Voss data.

Although the specific reasons for the different results from procedures that have

varied retention intervals and reinforcer frequency are unclear, McCarthy and Voss

(1995) noted one potentially important difference between procedures. To date, the

studies that have reported decreasing sensitivity to reinforcer-frequency ratios with

increasing retention intervals have reported much lower levels of discriminability ($\log d$)

than those that have reported increasing sensitivity as a function of increasing retention

interval. Although discriminability typically drops to low levels at longer retention

intervals in all DMTS studies, there are large differences in discriminability at shorter

retention intervals between studies. McCarthy and Davison (1991) generally reported 0-s

delay $\log d$ values of less than 1.2, and McCarthy and Voss reported average 0.5-s delay

$\log d$ values of less than 1.0. By contrast, Jones and White (1992) reported 0.01-s delay

log *d* values of around 2.0 and White and Wixted (1999) reported 0.2-s delay log *d*

values of around 2.0 as well. Thus, the different results reported across studies are

confounded by the overall level of discriminability generated by the procedure.

White and Wixted (1999) conducted a study that directly assessed the role of

overall discriminability in sensitivity to reinforcer-frequency ratios in DMTS procedures.

In Experiment 2, overall discriminability was varied by manipulating the sample-stimulus

response requirement from fixed ratio (FR) 5 to FR1 across two conditions. The relative

reinforcer frequency for correct choices was varied during both conditions.

Discriminability (log *d*) was higher during the FR5 condition than during the FR1

condition. Sensitivity to reinforcer-frequency ratios increased as a function of retention

interval in both conditions, although overall sensitivity was higher during the FR1

condition. In Experiment 3 the duration of the ITI was manipulated. Short ITI durations

have been shown to decrease discriminability in conditional-discrimination procedures

(e.g., Endhouse & White, 1988; Roberts, 1972; White, 1985), and the experiments by

McCarthy and Davison (1991) and McCarthy and Voss (1995) employed extremely short

ITI durations (0-5 s). Within each condition, White and Wixted varied the reinforcer

frequency for correct choices. They found that during the 15-s ITI condition,

discriminability was overall higher than during the 1-s ITI condition. In addition,

sensitivity to reinforcer-frequency ratios (*a*) increased with increasing retention interval

during the 15-s ITI condition and decreased with increasing retention interval during the

1-s ITI condition. Given the results of Experiment 2, in which the FR requirement was

varied, these results do not appear to be accounted for by the overall level of

discriminability. White and Wixted suggested that short ITI durations may increase the

proactive effect of previously reinforced responses, thus resulting in higher sensitivities at short retention intervals, and decreasing sensitivity at longer retention intervals. Thus, according to White and Wixted, decreasing sensitivity to relative reinforcer ratios as a function of increasing retention interval may be due to short ITI durations.

The results of Jones and White (1992) and White and Wixted (1999) suggest that manipulation of sample-stimulus disparity and retention intervals may be functionally equivalent. Specifically, these studies, in which retention intervals were varied in a DMTS procedure, found similar relations between discriminability and sensitivity to reinforcer-frequency ratios as studies that have varied sample-stimulus disparity: sensitivity increased as discriminability decreased. Definitive conclusions as to the functional equivalence of both manipulations, however, are not possible, as procedural differences across studies that have varied sample-stimulus disparity and retention intervals make direct comparison difficult. Table 2 summarizes the studies conducted to date that have assessed the relation between sensitivity to reinforcer frequency and discriminability. Examination of the table shows that in addition to ITI duration, other differences, such as type of procedure used, the manner in which reinforcers are scheduled for correct choices (more on this below; see Methods), whether disparity or delay was varied within session or across conditions, among others, have varied between studies. Thus, it is necessary to manipulate both retention interval and sample-stimulus disparity within the same general procedure if meaningful comparisons are to be made. The present study accomplished this goal.

Table 2

Summary of Previous Investigations of the Relation Between Sensitivity and Discriminability in Conditional Discrimination

Study	Manipulation	# of delays or disparities arranged	Varied within session or across conditions	SR scheduling	Procedure	ITI duration	Sensitivity as a function of decreasing discriminability
McCarthy & Davison (1980)	disparity	2	across	uncontrolled	SMTS	3 s	independent
Harnett, McCarthy, & Davison (1984)	delay	3	across	controlled	SMTS	0 s	independent
McCarthy & Davison (1984)	disparity	5	across	both	SMTS	0 s	independent and increase
White, Pipe, & McLean (1985)	disparity	5	within	controlled	Multiple schedule	NA	increase
White (1986)	disparity	2	within	uncontrolled	Multiple schedule	NA	increase
Davison & McCarthy (1987)	disparity	13	within	controlled	SMTS	3 s	increase
Davison & McCarthy (1989)	disparity	8	within	controlled	SMTS	5 s	increase
Alsop & Davison (1991)	disparity	7	across	controlled	SMTS	3 s	inverted U shape
McCarthy & Davison (1991)	delay	13	across	controlled	SMTS	3 s	decrease
Jones & White (1992)	delay	4	within	uncontrolled	MTS	10 s	increase
Nevin, Cate, & Alsop (1993)	disparity	2	across	controlled	SMTS	6 s	increase
McCarthy & Voss (1995)	delay	4	within	controlled	MTS	5 s	decrease
White & Wixted (1999)	delay	4	within	uncontrolled	MTS	1, 15 s	increase and decrease
Sargisson & White (2007)	delay	5	within	uncontrolled	MTS	15 s	increase

STATEMENT OF THE PROBLEM

Although contemporary behavioral theories of remembering in nonhumans suggest that degrading discriminability by manipulating retention-interval duration is functionally equivalent to degrading discriminability by decreasing sample-stimulus disparity, such functional equivalence has not been conclusively demonstrated. Studies that have manipulated sample-stimulus disparity have generally reported an inverse relation between sensitivity discriminability, while those that have manipulated retention-interval duration have reported varying relations. Procedural differences between experiments make comparison of the results of studies that have manipulated sample-stimulus disparity and those that have manipulated retention-interval duration difficult. Therefore, the present experiment assessed sensitivity of conditional-discrimination performance to variations in relative reinforcer frequency as a function of discriminability in both a retention-interval and a sample-stimulus disparity condition. Both variables were manipulated across conditions within the same general procedure to facilitate direct comparison. In addition, the present experiment used temporal-sample stimuli, thus assessing the generality of previous results obtained using sample stimuli from other dimensions

METHOD

Design

This experiment used a small-N "single-subject" design in which each animal experiences all experimental conditions. The animal's behavior in one condition serves as the control or comparison for its behavior under other conditions (Sidman, 1960). Large quantities of data are gathered from a relatively small number of animals and conditions are run for extended periods of time. Multiple replications are performed, minimizing the number of animals used and intersubject variability. Judgments about stability of data are typically made by visual inspection and descriptive, rather than inferential, statistics.

Subjects

Eight experimentally naïve adult pigeons served as subjects. One pigeon stopped key-pecking for unknown reasons during the initial condition of the experiment and data from this pigeon are not included. Pigeons were maintained at 80% (+/- 15g) of free-feeding weights by postsession feeding as needed. Between sessions, pigeons were individually housed in a temperature-controlled colony under 12:12 hr light/dark cycle and had free access to water and digestive grit. This experiment was approved by the Utah State University Institutional Animal Care and Use Committee.

Apparatus

Four BRS/LVE sound-attenuating chambers were used. Chambers were constructed of painted metal with aluminum front panels. The chambers measured 35 cm

across, 30.7 cm deep, and 35.8 cm high. Each front panel had three translucent plastic

keys that could be lit from behind with white, green, red, and blue light and required a

force of at least 0.10 N to record a response. Keys were 2.6 cm in diameter and 24.6 cm

from the floor. A lamp (28 V 1.1 W) mounted 4.4 cm above the center key served as a

houselight. A rectangular opening 9 cm below the center key provided access to a

solenoid-operated hopper filled with pelleted pigeon chow. During hopper presentations,

the opening was lit with white light and the houselight and keylight were extinguished.

Extraneous noise was masked by white noise and chamber ventilation fans.

Contingencies were programmed and data collected by a microcomputer using Med

Associates® interfacing and software.

<div align="center">Procedure</div>

Pretraining

The pigeons were exposed to an autoshaping procedure (e.g., Brown & Jenkins,

1968) in which key colors were paired with food delivery. During this procedure, all key

colors were presented in the key locations in which they would appear during the

experiment. Once pigeons reliably pecked all key colors in all locations, the experiment

began.

The experiment was conducted in two conditions, a sample-stimulus disparity

condition and a retention-interval condition. Within each condition, sensitivity to

variations in the reinforcer frequency ratio (*a* in Equation 6) was assessed. The order of

conditions was counterbalanced across subjects to minimize the influence of any order

effects. Pigeons 373, 597, 46, and 49876 experienced the sample-stimulus disparity

condition first, while pigeons 289, 49807, and 49864 experienced the retention-interval condition first. Sessions were conducted 7 days per week at approximately the same time.

Sample-Stimulus Disparity Condition

During this condition, sensitivity to variations in reinforcer ratios was assessed as a function of sample-stimulus disparity. The final procedure consisted of a temporal-discrimination procedure in which samples of varying duration were presented within session. The retention interval was fixed at 0.1 s for the duration of the condition. Trials began with the illumination of the houselight and center key green. This key served as a trial-ready stimulus to ensure that the pigeon was attending to the sample. A peck to the center key extinguished it and lit the center key red for the sample duration. For the purposes of this experiment, durations shorter than 6 s were considered short (S_1), and those longer than 6 s were considered long (S_2). Sample durations of 1 and 11 s were considered easy and sample durations of 5 and 7 s were considered difficult.

Sample durations were randomly selected each trial with the constraint that each sample duration was presented an equal number of times during the session and that each sample duration was presented twice in each block of eight trials. Following sample presentation, the left and right keys were lit blue and white. The location of each color (left or right key) was randomly determined from trial to trial (e.g., Stubbs, 1968). A peck to the key lit one color following short sample durations and to the key lit the other color following long sample durations sometimes (see below) resulted in 2.5 s access to food. Key colors corresponding to short and long sample durations were counterbalanced. Nonreinforced correct choices and incorrect choice responses resulted in a 2.5 s blackout.

There was a limited hold on the trial-ready and comparison stimuli, such that if a response was not made after 20 s, the stimuli were extinguished and the next experimental event took place (sample presentation or blackout). Trials were separated by a 20-s ITI during which all keylights and the houselight were extinguished. Sessions ended after 80 trials. Thus, each sample duration was presented 20 times per session.

During initial training, only sample durations of 1 and 11 s were presented, the probability of reinforcement for correct choices was 1.0, and sessions lasted for 40 trials. For the first 5 sessions, a correction procedure was implemented. During this procedure, incorrect choice responses extinguished the comparison keys and produced a 2.5 s blackout. Following the blackout, the entire trial was repeated, with the same sample duration and comparison colors in the same key locations. This process continued until a correct choice response terminated the trial in food. Once accuracy appeared stable (21-30 sessions, across pigeons) difficult samples were introduced and the number of trials per session was increased to 80.

Initially, difficult samples of 5 and 7 s were introduced. In some cases, accuracy with these sample durations was extremely low. Thus, the samples were adjusted to be more discriminable (e.g., to 4 and 8 s) until accuracy appeared stable. Sample duration was titrated on an individual pigeon basis until stable performance was established with samples of 5 and 7 s. Once accuracy with easy and difficult samples was established within the criterion ranges (see description below), the probability of reinforcement for correct choice responses was decreased from 1.0 to .5 across several consecutive sessions (6-8 sessions, across pigeons).

Retention-Interval Condition

During this condition, sensitivity to variations in reinforcer frequency ratios was assessed as a function of retention interval duration. The final procedure used in this condition was identical to that used in the sample-stimulus disparity condition except that sample-stimulus disparity was fixed and the duration of the retention interval was varied. Retention intervals of two durations were presented within session. Trials began with the illumination of the houselight and center key green. This key served as a trial-ready stimulus to ensure that the pigeon was attending to the sample. A single peck on the center key extinguished it and lit the key red for the duration of the presented sample. Sample durations used during this condition were 1 (S_1) and 11 (S_2) s. Following sample presentation, the center key was extinguished and a retention-interval was initiated. The duration of the retention interval was randomly selected on each trial with the constraint that each retention interval occurred an equal number of times throughout the session and that each retention interval was presented twice following each sample duration in each block of four trials. Following the retention interval, the side keys were lit, one blue, one white. As in the disparity condition, the location of each color was randomized across trials. A peck to the key lit one color following a 1-s sample duration and to the key lit the other color following a 11-s sample duration sometimes resulted in 2.5 s access to food. Key colors corresponding to short and long samples were counterbalanced. Nonreinforced correct choices and incorrect choices resulted in a 2.5 s blackout. The 20-s limited hold described above was in place during this condition. Trials were separated by a 20-s ITI during which all key lights and the houselight were extinguished. Sessions

ended after 80 trials. Thus, each retention interval was presented 20 times following both S_1 and S_2 presentations.

Initial training was identical to that of the sample-stimulus disparity condition described above. Midway during initial training, however, the pigeons that experienced this condition first were switched to different experimental chambers (for reasons not relevant to this study). This move necessitated several more sessions of correction in the new chambers before accuracy with the short delay stabilized and the long delay was introduced.

Similarly to the sample-stimulus disparity condition, retention intervals were titrated on an individual pigeon basis until accuracy was stable and within the criterion ranges (described below). This individual titration resulted in terminal retention intervals differing between pigeons (4 to 10 s, across pigeons). Once accuracy was stable on both short- and long-retention interval trials, the probability of reinforcement for correct choice responses was decreased from 1.0 to .5 (a reinforcer ratio of 1:1, see Table 3 below). This took 7-11 sessions, across pigeons.

Scheduling of Reinforcers

During both conditions, reinforcement for correct choices was scheduled as follows. At session onset and following each reinforcer presentation, the next reinforcer was assigned to a correct S_1 or S_2 response with a fixed probability. No other reinforcers were arranged until the scheduled reinforcer was collected. This way of scheduling reinforcers is a controlled reinforcer ratio procedure and ensures that the programmed

Table 3

Conditions, Reinforcer-Frequency Ratios, and Reinforcer Probabilities

During All Experimental Conditions

Condition	Frequency ratio	Reinforcer probability	
		S_1	S_2
Sample-stimulus disparity			
1	1:1	0.5	0.5
2	1:9	0.9	0.1
3	9:1	0.1	0.9
4	1:3	0.25	0.75
Retention interval			
1	1:1	0.5	0.5
2	1:9	0.9	0.1
3	9:1	0.1	0.9
4	1:3	0.25	0.75

Note. Within each condition, the 1:9 and 9:1 reinforcer ratio conditions were counterbalanced across pigeons.

reinforcer ratios are similar to the obtained reinforcer ratios (e.g., McCarthy & Davison, 1991).

Equating Disparity and Delay

The goal of the present research was to test the functional equivalence of manipulating sample-stimulus disparity and retention intervals. As demonstrated by White and Wixted (1999), the level of discriminability can affect the relation between sensitivity to variations in reinforcer frequency and discriminability. It is therefore important that discriminability across the sample-stimulus disparity and retention interval conditions be equated. To this end, two overall levels of baseline discriminability were established in each condition. Values of log *d* greater than 1.5 comprised the high discriminability range, and values below 1.5 comprised the low discriminability range.

The sample durations used in the sample-stimulus disparity condition were 1 and 11 s

(high discriminability), and 5 and 7 s (low discriminability). These sample durations were

chosen based on several months of preliminary exploration with the procedure, and

produced values of log d within the criterion ranges. In the retention-interval condition,

the duration of the short retention interval was 0.1 s and the duration of the long retention

interval was adjusted on an individual pigeon basis to produce the criterion

discriminability ranges (4-10 s, across pigeons). In this way, discriminability was roughly

equated before reinforcer frequency was varied, thus strengthening conclusions regarding

functional equivalence of sample-stimulus disparity and retention intervals.

Discriminability was equated at the beginning of the sample-stimulus disparity and

retention interval conditions (1:1 reinforcer ratio), but was allowed to vary during

conditions in which reinforcer frequency was varied.

Data Collection

During both conditions, the data collected were the number of correct and

incorrect choice responses on the blue and white keys, and the number of reinforcers

collected from the blue and white keys. In addition, the number of responses to and the

number of reinforcers collected from the left and right keys was collected to assess any

side biases.

Measures

Data from the last 10 sessions of each condition were pooled. To obtain measures

of discriminability, accuracy was calculated both as proportion correct and as log d

(Equation 5). Log d is incalculable if the subject does not make at least one error

following each sample during the session. Even pooled over 10 sessions, such

discrimination performance is not uncommon (see Alsop, 2004). Thus, it is customary to

add a small number (in this case 0.25; cf. Odum, Shahan, & Nevin, 2005; see Brown &

White, 2005 for discussion) to each of the cells in the log d equation. With this correction

in place, the maximum value of log d at each stimulus-disparity pair in the sample-

stimulus disparity condition was 2.90. Likewise, the maximum value of log d at each

delay in the retention-interval condition was also 2.90. Log b (left side of Equation 6)

was calculated to obtain a measure of overall response bias.

Assessing Sensitivity to Variations in the
Reinforcer-Frequency Ratio

By changing the probability of reinforcement for correct S_1 and S_2 responses, the

reinforcer frequency ratio was varied across three or four ratios. Each reinforcer ratio was

fixed for at least 25 sessions and until the estimates of log d and log b appeared stable as

judged by visual inspection (no unusual variability or trends over the last several

sessions). The conditions, reinforcer-frequency ratios and probability of reinforcement

for correct S_1 and S_2 choices are presented in Table 3. The number of sessions in each

experimental condition for all pigeons is presented in the Appendix.

Sensitivity to variations in the reinforcer ratio was assessed by plotting the

measure of response bias (log b) as a function of the log reinforcer ratio and fitting

Equation 6 to these data. As discussed above, sensitivity to variations in the reinforcer-

frequency ratio is estimated as the slope of the fitted lines. The slope estimates were

plotted as a function of discriminability during both the sample stimulus disparity and

retention interval conditions to assess the relation between discriminability and sensitivity

to reinforcer ratios. Separate regressions were conducted for easy and difficult trials during the sample-stimulus disparity and retention interval conditions. The biasing effects of the reinforcer differential on S_1 and S_2 trials was assessed by plotting the obtained short/long response ratio as a function of the obtained short/long reinforcer ratio following both S_1 and S_2 presentations and fitting Equations 4a and 4b to these data.

Statistical Analysis

Paired-samples *t* tests were used to assess differences in accuracy between the high and low discriminability ranges. Paired-samples *t* tests were also used to assess changes in sensitivity as a function of discriminability during both the retention interval and sample-stimulus disparity conditions and to compare estimates of sensitivity and accuracy across conditions.

RESULTS

Because the goal of the present experiment was to assess sensitivity to variations in reinforcer frequency as a function of discriminability, it is important to demonstrate that different levels of discriminability were established by the sample-stimulus disparity and retention interval manipulations before reinforcer ratios were varied. Figure 3 shows accuracy calculated as both proportion correct and log d (Equation 5) from the sample-stimulus disparity and retention-interval conditions for all pigeons. The data are from the 1:1 reinforcer ratio condition (before reinforcer ratios were varied).

The upper panels show that proportion correct was high during easy trials in both the sample-stimulus disparity and retention-interval conditions and decreased during difficult trials in both conditions. The mean estimates of accuracy (standard error in parenthesis) on easy and difficult trials during the sample-stimulus disparity condition were 0.98 (0.00) and 0.76 (0.03), respectively. During the retention interval condition, the mean accuracy on easy and difficult trials was 0.99 (0.00) and 0.91 (0.01). The differences between easy and difficult trial accuracy were significant when assessed by paired-samples t tests during both the sample-stimulus disparity, $t(6) = 7.90$; $p = 0.0002$, and retention-interval, $t(6) = 8.58$; $p = 0.0001$, conditions. In addition, the difference in accuracy during easy trials in the sample-stimulus disparity and retention-interval conditions was not significant, $t(6) = 1.12$; $p = 0.31$. The difference between accuracy during difficult trials across the two conditions was statistically significant, $t(6) = 4.46$; $p = 0.0043$.
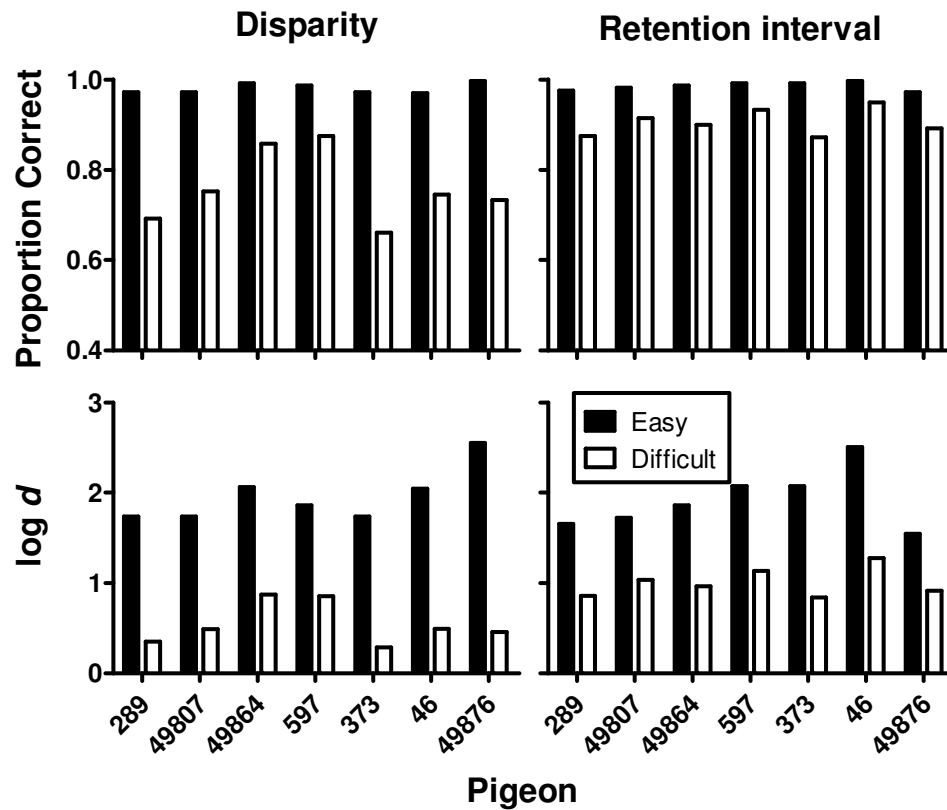
Figure 3. Estimates of accuracy on easy and difficult trials, calculated both as proportion correct (upper panels) and log *d* (lower panels; Equation 5) obtained from the 1:1 reinforcer ratio condition (before reinforcer ratios were varied) for all pigeons. The left panels show accuracy during the sample-stimulus disparity condition. The right panels show accuracy during the retention-interval condition.

The lower left panel shows that during the sample-stimulus disparity condition, log *d* for all pigeons was higher during easy sample (1 and 11 s) trials than during difficult sample (5 and 7 s) trials. The mean estimates of log *d* on easy and difficult trials (standard error in parenthesis) were 2.00 (0.11) and 0.60 (0.09), respectively. This difference was statistically significant when compared using paired samples *t* tests, $t(6) = 10.88$; $p < 0.0001$. The lower right panel shows that estimates of log *d* for all pigeons were higher during easy (short retention interval) trials than on difficult (long retention interval) trials, with mean accuracy estimates (standard error in parenthesis) of 1.92 (0.12) and 1.0 (0.06) during easy and difficult trials, respectively. These differences were statistically significant when compared using paired samples *t* tests, $t(6) = 10.05$; $p < 0.0001$. In addition, the difference between accuracy on easy trials across the sample-stimulus disparity and retention interval conditions was not significant, $t(6) = 0.24$; $p = 0.82$, while the difference between accuracy on difficult trials across conditions was significant, $t(6) = 3.51$; $p = 0.01$. These results show that the sample-stimulus disparity and retention-interval manipulations were successful in producing different accuracy ranges in both the sample-stimulus disparity and retention-interval conditions (as measured both by proportion correct and log *d*). In addition, there were not differences in accuracy levels as a function of which condition was experienced first (pigeons 289, 48807, and 49864 experienced the retention-interval condition first, while pigeons 373, 597, 46, and 49876 experienced the sample-stimulus disparity condition first).

Figures 4 and 5 show accuracy (calculated as proportion correct) plotted as a function of the log reinforcer ratio (which was manipulated across conditions) for all pigeons during easy and difficult trials during both the sample-stimulus disparity and
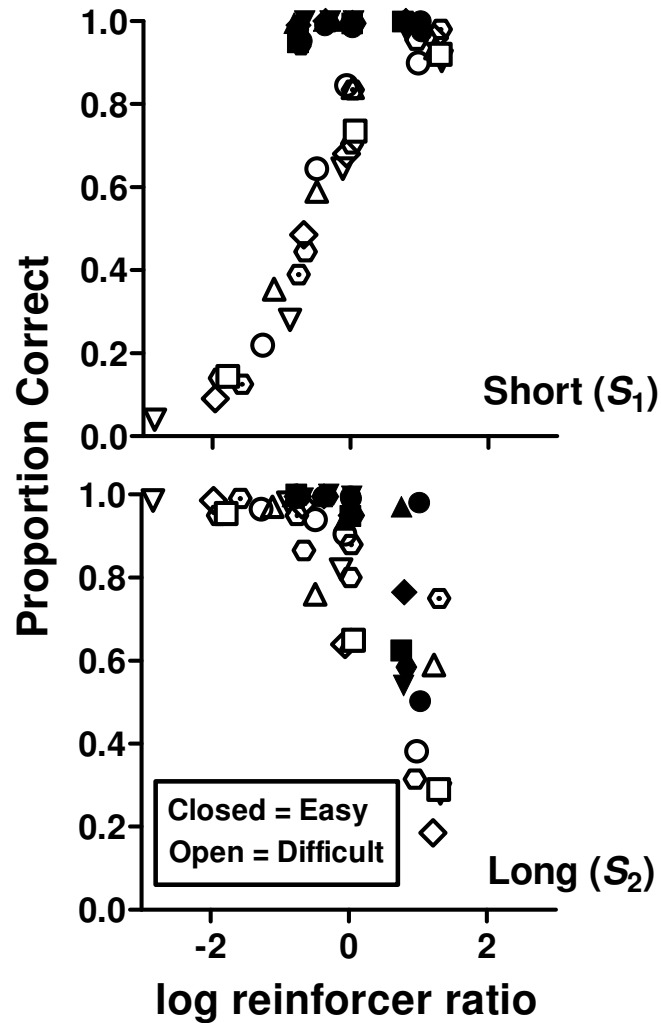
Figure 4. Proportion correct as a function of the log reinforcer ratio for all pigeons during the sample-stimulus disparity condition for both easy (closed symbols) and difficult (open symbols) trial types. Different symbols indicate data from different pigeons. The top panel shows data from short-sample trials and the bottom panel shows data from long sample trials.
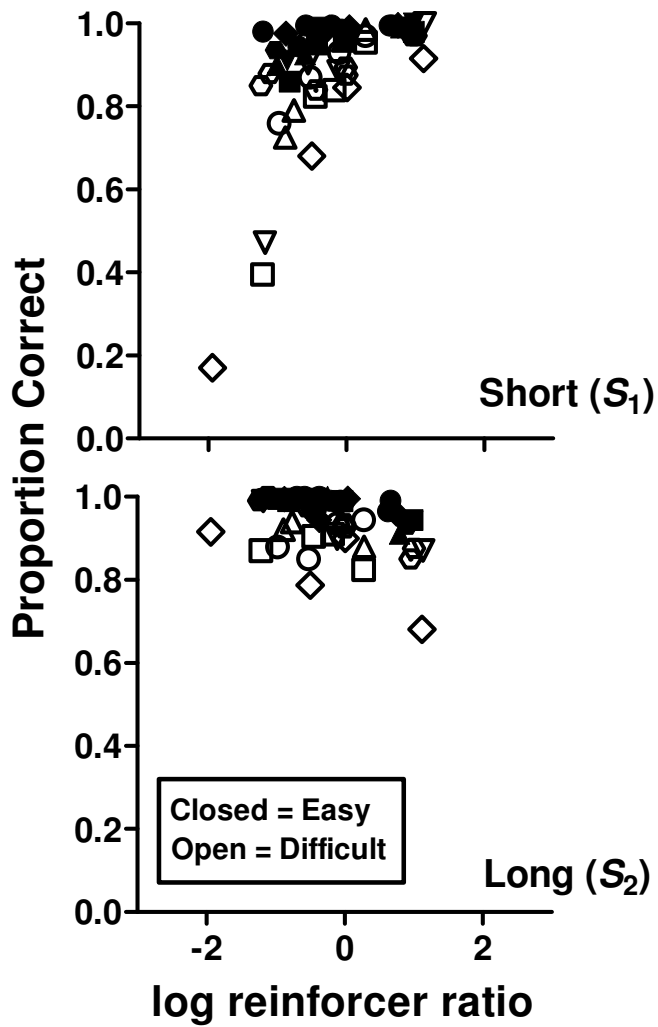
Figure 5. Proportion correct as a function of the log reinforcer ratio for all pigeons during the retention-interval condition. Other details as in Figure 4.

retention-interval conditions of the experiment. Proportion correct on both short (S_1)

and long (S_2) sample trials was calculated separately. Figure 4 shows the results from the

sample-stimulus disparity condition. The top panel shows that proportion correct for short

samples during easy trials was high across all reinforcer ratios (0.95-1.0, across pigeons).

During difficult trials, proportion correct was an increasing function of the

reinforcer ratio. When the reinforcer ratio was negative, indicating a probability of

reinforcement favoring correct long (S_2) choices, proportion correct was low (note that

because accuracy at the low end of proportion correct is bounded at .5, values less than .5

indicate bias for the comparison option corresponding to the long sample duration). As

the reinforcer ratio increased, proportion correct also increased. The bottom panel shows

the results from long (S_2) sample-trials. In general the results were similar to those from

S_1 trials, although there was somewhat more variability in proportion correct across

reinforcer ratios during easy trials (particularly during the 9:1 reinforcer ratio). During

difficult trials, as the reinforcer ratio increased (from negative to positive, indicating

increasing probability of reinforcement for correct short choices), proportion correct for

long samples decreased.

Figure 5 shows the analysis conducted on the data from the retention-interval

condition. The upper panel shows that during easy trials proportion correct for short

samples was high across reinforcer ratios (although not as high as during the sample

stimulus disparity condition; 0.84-1.0 across pigeons). During difficult trials, proportion

correct was somewhat lower for a few birds (particularly at the more extreme negative

reinforcer ratios), but aside from these pigeons, overall, proportion correct appeared

similar to that observed during easy trials. Performance during long-sample trials (bottom

panel) appeared similar for the most part during easy and difficult trials, with the

exception of a decrease in proportion correct for some pigeons. Together, these results

indicate that variation in reinforcer ratios had less of an effect on proportion correct

during the retention-interval condition than during the sample-stimulus disparity

condition. In addition, during both conditions, variation in reinforcer ratios had effects

only during difficult sample trials; proportion correct during easy trials was relatively

unaffected by variations in the reinforcer ratio.

The next two figures show accuracy across reinforcer ratios calculated as log *d*

(Equation 5) for easy and difficult trials. Note that because of the equation used to

calculate log *d*, data from short and long trials cannot be considered separately. Figure 6

shows the data from the sample-stimulus disparity condition. There are two notable

features of the data displayed in this figure. First, the range of the data points along the

x-axis in the lower panel (difficult trials) is somewhat greater than in the upper panel

(easy trials), mostly so for 2 pigeons. This result indicates that, for these pigeons, the log

reinforcer ratio was more extreme during difficult trials than during easy trials. This

result will be discussed in more detail below. The second notable feature of these data is

that across pigeons and trial types, log *d* did not change systematically across reinforcer

ratios.

Figure 7 shows that during the retention interval condition, in general, the range

of the data points along the *x*-axis was more similar during easy (0.1 s retention interval;

upper panel) and difficult (4-10 s retention interval; lower panel) trials, although for some

pigeons (373 in particular) the spread of the difficult-trial data points was greater than the

spread of the easy-trial data points (this result is revisited below). Similarly to the results
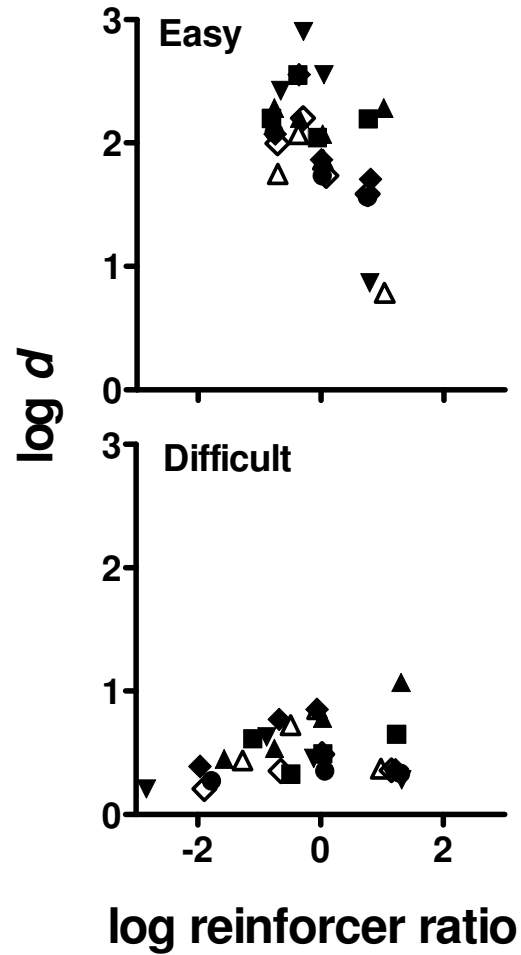
Figure 6. Estimates of log *d* (Equation 5) as a function of the log reinforcer ratio for all pigeons during the sample-stimulus disparity condition of the experiment. Data in the upper and lower panels are log *d* estimates calculated during easy and difficult trials, respectively (see text for details).
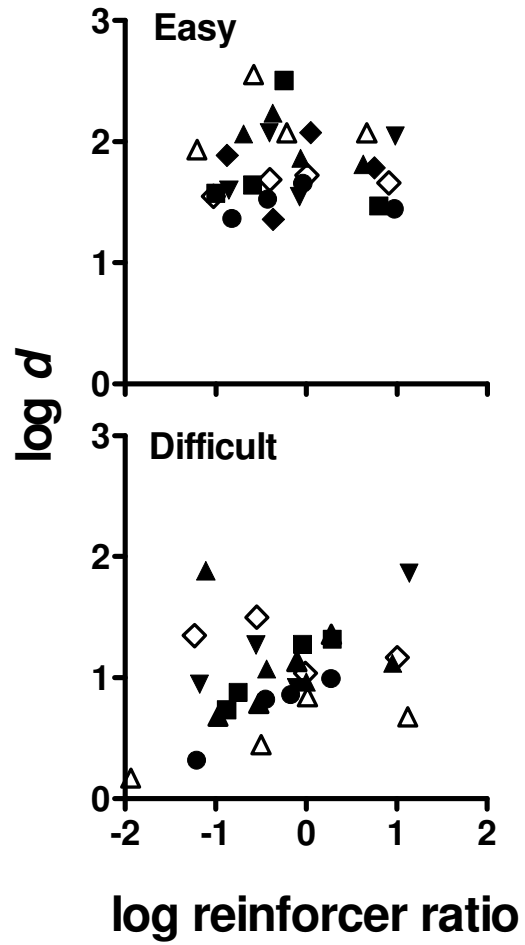
Figure 7. Estimates of log *d* (Equation 5) as a function of the log reinforcer ratio for all pigeons during the retention-interval condition of the experiment. Other details as in Figure 6.

from the disparity condition, across pigeons and conditions, there was no systematic

relation between accuracy and the reinforcer ratio.

To more clearly display the relation between accuracy and trial difficulty, Figure

8 plots log d (averaged across reinforcer ratios) during both the sample-stimulus disparity

(upper panel) and retention-interval (lower panel) conditions for all pigeons on both easy

and difficult trials. Log d was lower during difficult trials than during easy trials for all

pigeons in both conditions of the experiment (see also Figures 6 and 7), although the

difference between log d during difficult and easy trials was somewhat less for some

pigeons during the retention-interval condition than during the sample-stimulus disparity

condition. The mean estimates of log d (standard error in parenthesis) for easy and

difficult trials during the sample-stimulus disparity condition were 2.00 (0.09) and 0.50

(0.06), respectively. This difference was statistically significant when compared using

paired-samples t tests, $t(6) = 16.00$; $p < 0.0001$. The mean estimates of log d (standard

error in parenthesis) for easy and difficult trials during the retention interval condition

were 1.81 (0.08) and 1.01 (0.11), respectively. This difference was statistically significant

when compared using paired samples t tests, $t(6) = 6.91$; $p = 0.0005$. Taken together,

these results indicate that, across reinforcer ratios, accuracy was higher during easy trials

than during difficult trials in both the disparity and retention-interval conditions. Thus,

the differences in accuracy established at the beginning of the experiment were

maintained across variation of reinforcer ratios.

Figures 9 and 10 show estimates of response bias (log b; left side of Equation 6)

plotted as a function of the log reinforcer-frequency ratio during easy and difficult trials

during both the sample-stimulus disparity and retention-interval conditions, respectively.
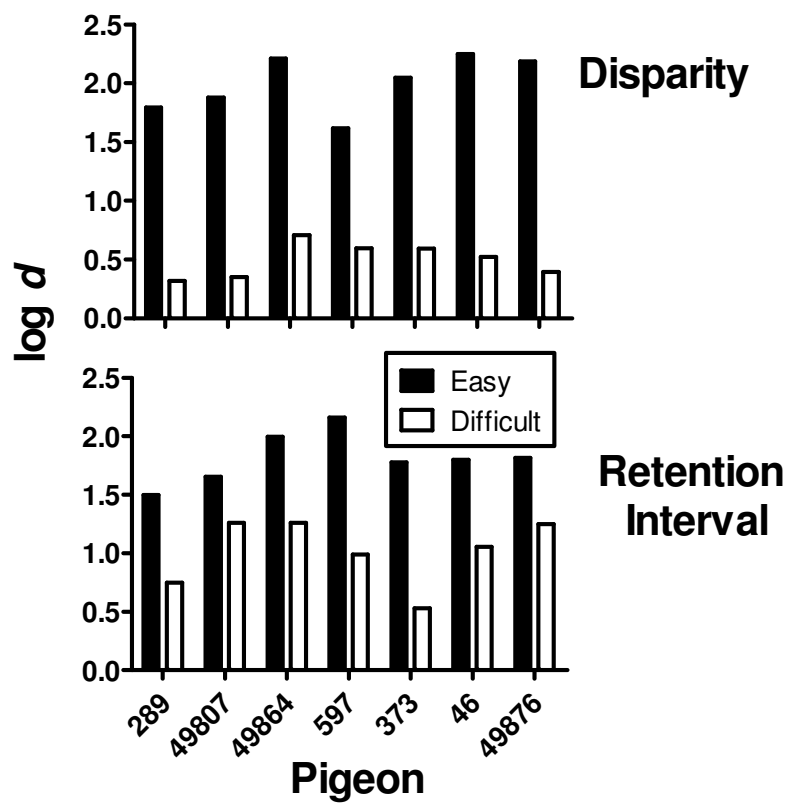
Figure 8. Estimates of log *d* (averaged across reinforcer ratios) for all pigeons during easy and difficult trials during the sample-stimulus disparity (upper panel) and retention-interval conditions (lower panel).
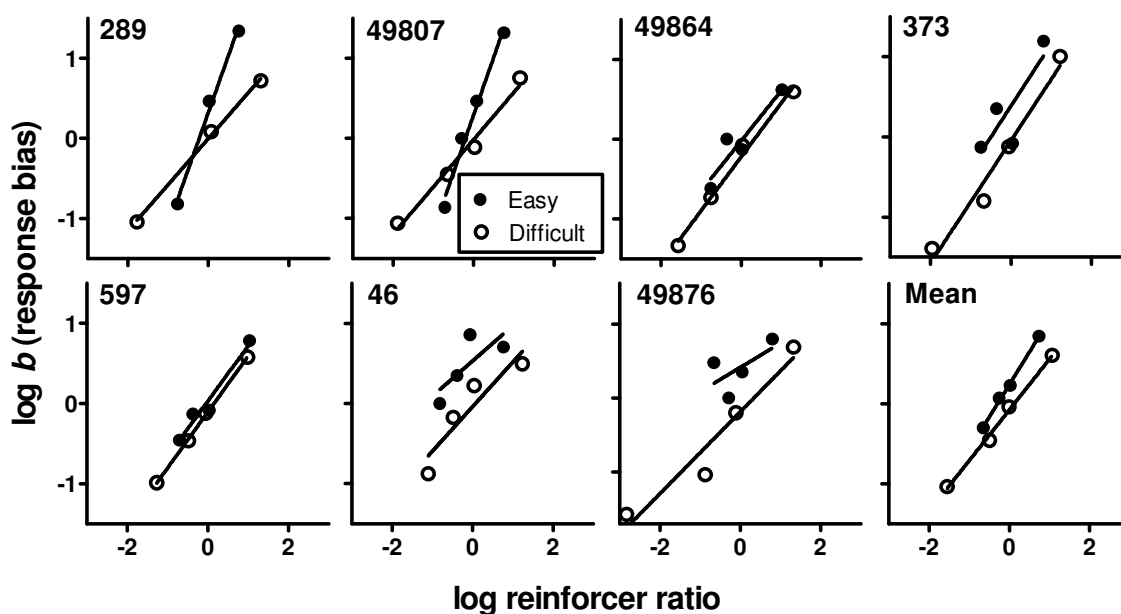
Figure 9. Estimates of response bias (log *b*; left side of Equation 6) as a function of the log reinforcer ratio for all pigeons during easy (filled data points) and difficult (unfilled data points) trials during the sample-stimulus disparity condition. Straight lines through the data points show the best fits of Equation 6 to the data (see Appendix for individual parameter estimates).
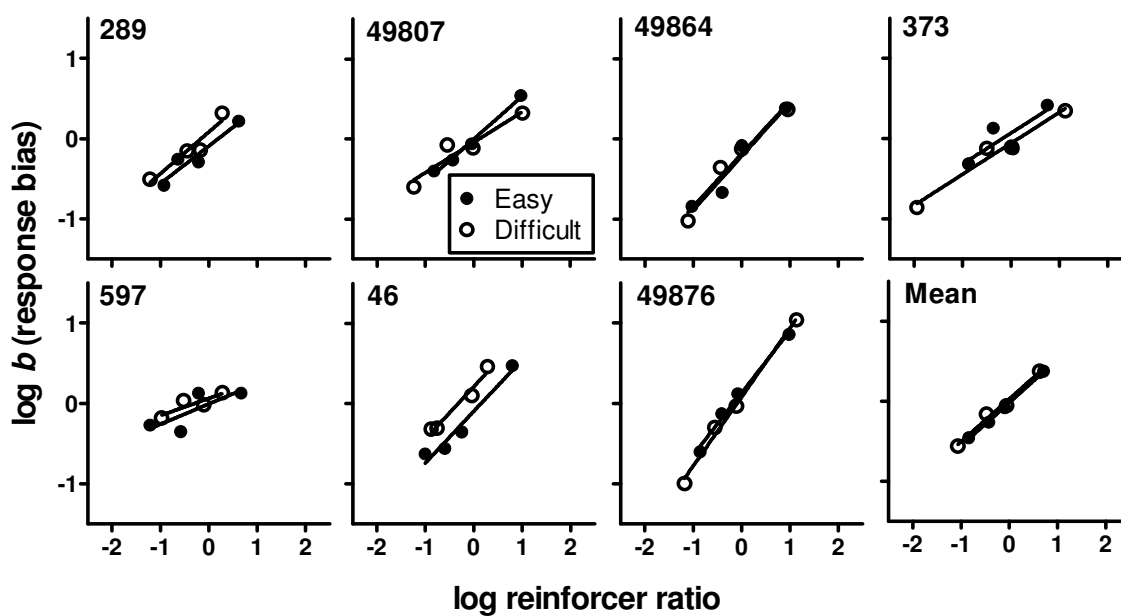
Figure 10. Estimates of response bias (log *b*; left side of Equation 6) as a function of the log reinforcer ratio for all pigeons during the retention-interval condition. Other details as in Figure 9.

The straight lines through the data points show the best fitting regressions of Equation 6 (parameter estimates and variance accounted for are presented in the Appendix). First, it should be noted that for some pigeons, the spread of the bias functions (distance along the *x*-axis) during difficult trials was greater (and in some cases, much greater) than during easy trials (as noted above), indicating more extreme obtained reinforcer ratios during difficult trials than during easy trials. In all cases where this result is apparent, the extremity occurs in the 1:9 reinforcer-ratio condition (left most data point on the bias function).

This result may seem puzzling in light of the fact that a controlled reinforcer-ratio procedure was used in the present experiment, and this procedure is used specifically to keep the obtained reinforcer ratios similar to the programmed reinforcer ratios (and therefore similar during easy and difficult trials). Inspection of the choice response and reinforcer data in the Appendix shows that this result was due to the development of extreme biases by some pigeons during difficult trials in the 1:9 reinforcer-ratio condition. Specifically, all pigeons that showed this effect developed an extreme bias for B_2 (long sample) comparison-choice responding regardless of the presented sample duration. Given that the reinforcer ratio in this condition was 1:9 in favor of correct B_2 responding, it is not surprising (and indeed, was expected) that some bias for B_2 would develop. The extreme bias developed by these pigeons, however, resulted in there being no (or very few) reinforcers obtained for correct B_1 choice responses during the last 10 sessions of this condition. Thus, when reinforcer ratios were calculated for these pigeons, the obtained reinforcer ratio under this condition was much more extreme than for pigeons that developed a more moderate bias.

Figure 9 shows that for all pigeons during both easy and difficult trials in the sample-stimulus disparity condition, choice responding was biased by variations in the reinforcer ratio for correct choices (indicated by changes in the measure of response bias across log reinforcer ratios). As discussed above, sensitivity to variations in relative reinforcer frequency is calculated as the slope of the best-fitting regression line. Tests of these slopes indicated they were significantly greater than 0 for both easy, $t(6) = 4.87$; $p = .0028$, and difficult, $t(6) = 19.93$; $p < .001$, trials. In addition, the slopes of the regressions were similar during easy and difficult trials, with the exception of pigeons 289 and 49807 (individual parameter estimates and variance accounted for are presented in the Appendix). Finally, there was no systematic difference in the measure of inherent bias (log c) across pigeons.

Figure 10 shows that for all pigeons during both easy and difficult trials in the retention-interval condition, choice responding was biased by variations in the reinforcer ratio for correct choices, with the biasing effects being smallest for pigeons 373 and 597. Tests of these slopes indicated that they were significantly greater than 0 for both easy, $t(6) = 6.68$; $p = .0005$, and difficult, $t(6) = 6.32$; $p = .0007$, trials. In addition, the slopes of the regressions were similar during easy and difficult trials for all pigeons (more on this result below). Finally, there was no systematic difference in the measure of inherent bias (log c; see Appendix) across pigeons.

To more clearly display differences in sensitivity between easy and difficult trials, Figure 11 shows estimates of sensitivity (slopes) obtained from regression of Equation 6 on the response-bias data in Figures 9 and 10 for each pigeon during easy and difficult trials for both the sample-stimulus disparity and retention-interval condition. The top
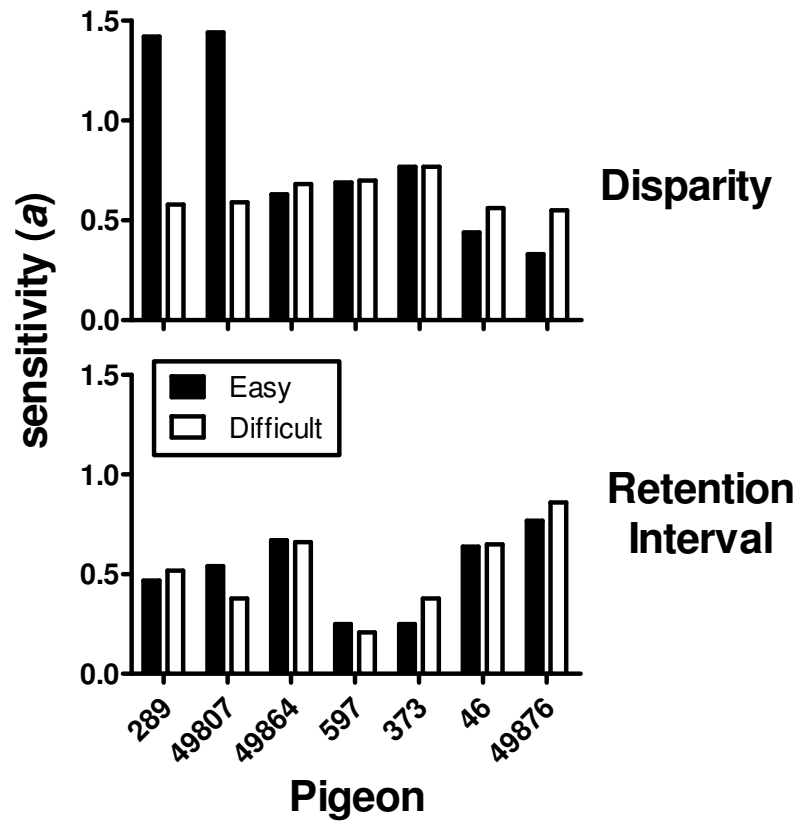
Figure 11. Estimates of sensitivity (slopes of regressions lines in Figures 9 and 10) for all pigeons during easy and difficult trials during the sample-stimulus disparity (upper panel) and retention-interval conditions (lower panel).

panel shows the data from the sample-stimulus disparity condition. Although the

estimates of sensitivity varied somewhat between pigeons, there was no systematic

difference in the estimates of sensitivity during easy and difficult trials across pigeons.

The mean estimate of sensitivity (standard error in parenthesis) during easy and difficult

trials was 0.81 (0.17) and 0.63 (0.03), respectively. Note that the value of sensitivity for

the easy trials is inflated by the high estimates of sensitivity for pigeons 289 and 49807.

The difference in sensitivity between easy and difficult trials was not significant, $t(6) =$

1.07; $p = 0.33$.

The bottom panel (retention-interval condition) shows that although the estimates

of sensitivity varied between pigeons, there was no systematic difference in the estimates

of sensitivity during easy and difficult trials across pigeons. The mean estimate of

sensitivity (standard error in parenthesis) during easy and difficult trials was 0.51 (0.08)

and 0.52 (0.08), respectively. These values were not significantly different, $t(6) = 0.28$;

$p = 0.79$. Together, these results indicate that although estimates of sensitivity were

overall similar to those obtained in previous experiments (see Baum, 1983), they did not

differ during easy and difficult trials during either the sample-stimulus disparity or

retention-interval conditions.

Recent assessments of sensitivity of conditional-discrimination performance to

variations in reinforcer variables have stressed the importance of separately analyzing the

data from S_1 and S_2 trials (Alsop & Porritt, 2006). This separate analysis is required

because in some cases, variations in relative reinforcer frequency may bias choice

responding following one sample stimulus more so than the other. If this is the case,

overall estimates of sensitivity (obtained by regression of Equation 6) will reflect a

disproportionate biasing effect of the reinforcer differential on choice trials of one

type. This is because the overall estimate of sensitivity is essentially an average of the

biasing effects of the reinforcer differential on both S_1 and S_2 trials. For example, Alsop

and Porritt assessed sensitivity to variations in reinforcer magnitude in a conditional-

discrimination procedure. They found that variation of reinforcer magnitude reliably

biased choice responding (as measured by Equation 6). When the data from S_1 and S_2

trials were considered separately, however, they found that the estimates of sensitivity

were almost exclusively due to the biasing effect of reinforcer magnitude on S_2 trials.

Thus, separate analysis of performance on S_1 and S_2 trials allows for a more clear

understanding of the biasing effects of the reinforcer differential.

　　　　To more clearly assess the effects of reinforcer-ratio variation on choice

responding in the present experiment, Figures 12 and 13 plot the log response ratio (a

measure of response bias) as a function of the log reinforcer ratio on both S_1 and S_2 easy

and difficult trials for all pigeons during the sample-stimulus disparity and retention-

interval conditions, respectively. Note that because the log reinforcer ratios against which

the data on easy and difficult trials are plotted are the same as those calculated for the

analyses presented above, the asymmetries apparent in the difficult-sample trial functions

are also apparent here.

　　　　Figure 12 shows the results of the analysis conducted on the data from S_1 and S_2

trials during the sample-stimulus disparity condition. The straight lines through the data

points are the best fitting regressions of Equation 4a for S_1 trials, and 4b for S_2 trials (raw

data are presented in the Appendix). There are several aspects of the data to consider.

First, during easy trials, variation of reinforcer ratios biased responding during S_2 trials
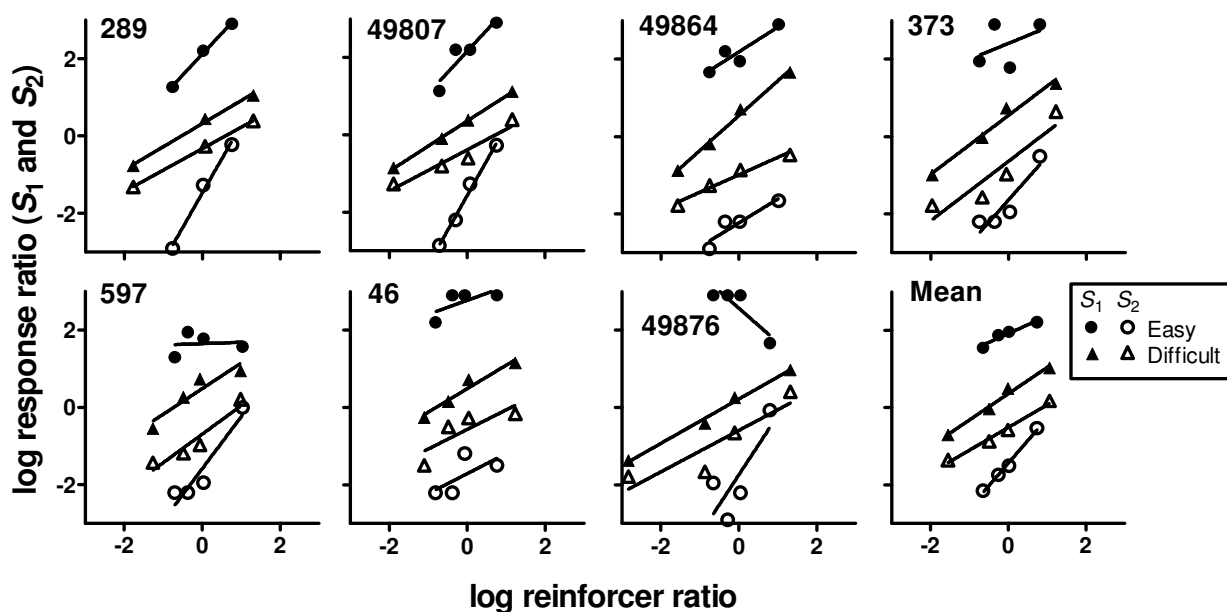
Figure 12. Log response ratios for both S_1 (filled points) and S_2 (open points) trials as a function of the log reinforcer ratio (raw data in Appendix) during easy (circles) and difficult (triangles) trials for all pigeons during the sample-stimulus disparity condition. Straight lines through the data points are the best fitting regressions of Equations 4a and 4b (see text for details).
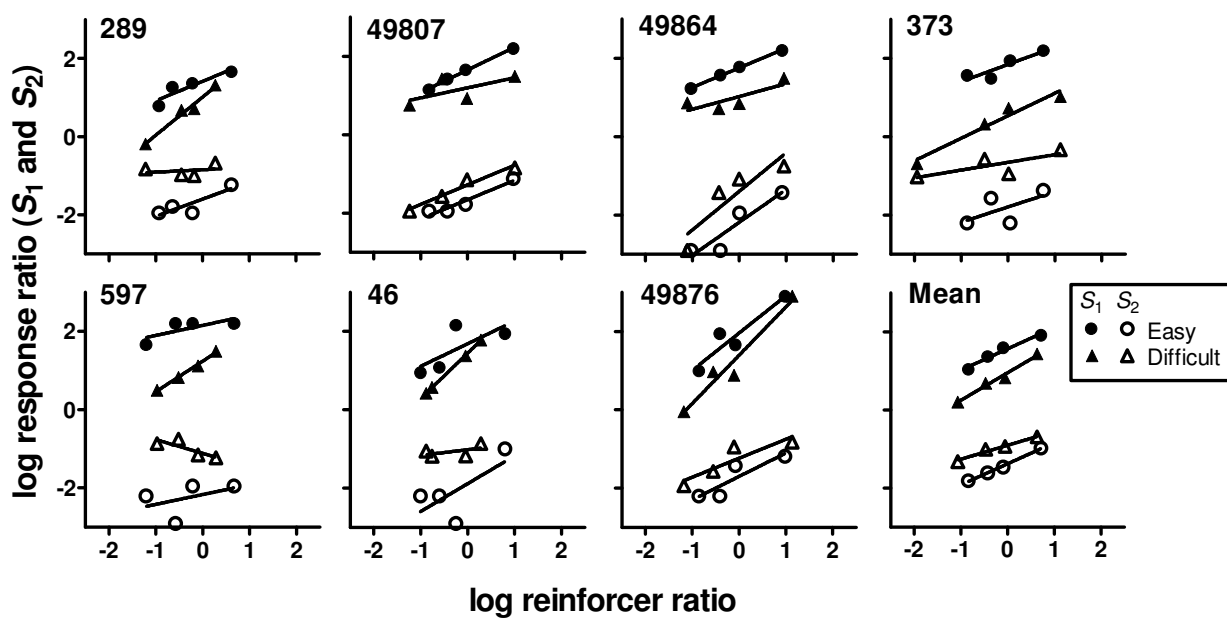
Figure 13. Log response ratios for both S_1 and S_2 trials as a function of the log reinforcer ratio during easy and difficult trials for all pigeons during the retention-interval condition. Other details as in Figure 12.

more than during S_1 trials for most pigeons (with the exception of pigeon 49864 and

46), indicating a greater biasing effect of reinforcer ratios on long sample easy trials.

Second, variation of reinforcer ratios had a much more consistent effect on response bias

during difficult trials than during easy trials. Third, for all pigeons, the response ratios

during both S_1 and S_2 trials were more extreme during easy trials than during difficult

trials, indicating that as disparity decreased (difficulty increased) the correct choice of B_1

and B_2 on S_1 and S_2 trials, respectively, decreased.

Figure 13 shows the results of the analysis conducted on the data from the

retention-interval condition. There are several notable results. First, for most pigeons,

variation of reinforcer ratios biased responding somewhat more during S_1 trials than

during S_2 trials, indicating that choice responding was more biased by variation of

reinforcer frequency on short-sample trials than on long-sample trials. The exceptions to

this result were for pigeons 49807 and 49864. Second, in general, the response ratio was

more extreme during easy S_1 trials than during difficult S_1 trials, indicating that as

retention interval increased, the correct choice of B_1 on S_1 trials decreased. A similar

result was observed during S_2 trials. Together, these results show that choice responding

was biased by reinforcer variation more on S_1 trials than on S_2 trials, and that increasing

retention intervals decreased accuracy on both S_1 and S_2 trials.

To facilitate comparison of the biasing effects of reinforcer-ratio variation within

and across the sample-stimulus disparity and retention-interval conditions, Figure 14

shows the estimates of sensitivity (slopes) obtained from regressions of Equation 4a (for

S_1 trials) and 4b (for S_2 trials) on the response bias data from Figures 12 and 13. Consider
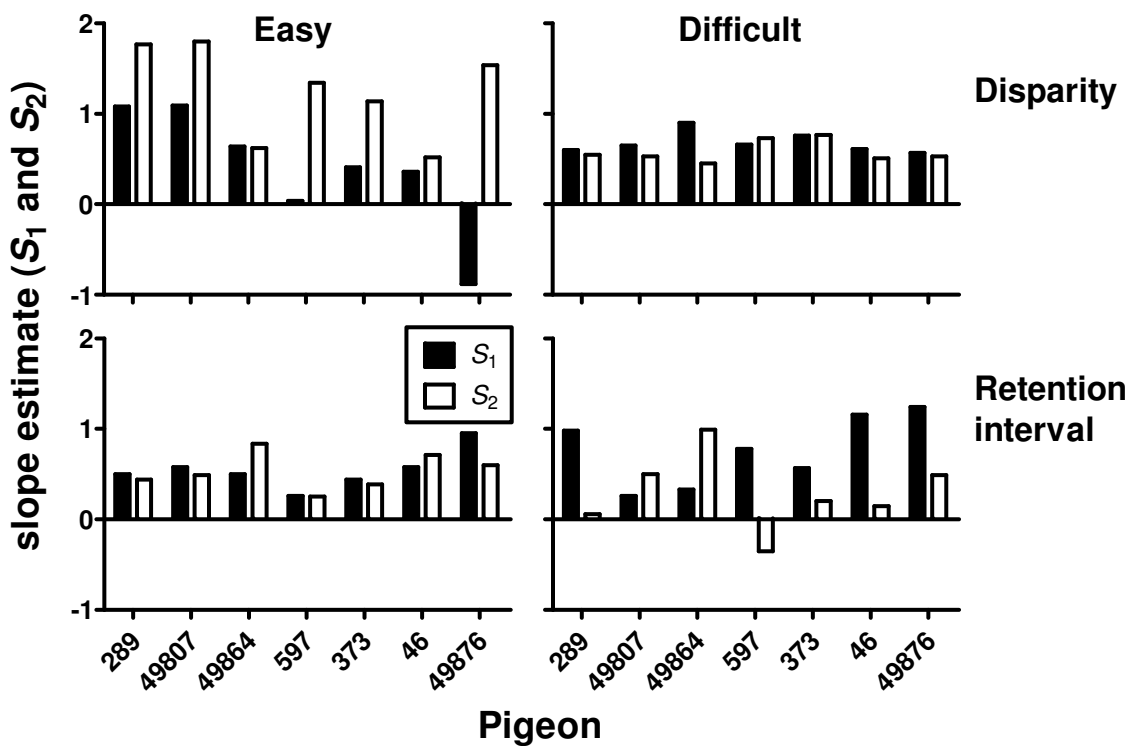
Figure 14. Slope estimates obtained from regression of Equations 4a and 4b on the response-bias data from S_1 and S_2 trials, respectively, during easy and difficult trials for the sample-stimulus disparity and retention-interval conditions.

first the data from the sample-stimulus disparity condition (top row). During easy

trials, the slope estimates were higher for all pigeons (except 49864) during S_2 trials than

during S_1 trials, indicating a greater biasing effect of the reinforcer ratio on long trials.

This effect was confirmed by a paired-samples t test, $t(6) = 2.79$; $p = .03$. During difficult

trials, slope estimates were not significantly different on S_1 and S_2 trials, $t(6) = 1.53$; $p =$

.18. Slope estimates for S_1 trials were not different on easy and difficult trials, $t(6) = 1.16$;

$p = .29$, but were significantly greater during S_2 trials on easy trials, $t(6) = 3.46$; $p = .01$,

than on difficult trials. During the retention-interval condition, the slope estimates for S_1

and S_2 trials were not significantly different during either easy, $t(6) = .16$; $p = .88$, or

difficult, $t(6) = 1.82$; $p = .82$, trials. Across conditions, there was a significant difference

on easy S_1 trials, $t(6) = 2.87$; $p = .03$, but no other comparisons were significantly

different (ps $> .05$).

Figure 15 summarizes the results of the entire experiment. The figure shows

sensitivity as a function of discriminability (log d) for all pigeons during both the sample-

stimulus disparity and retention-interval condition. In contemporary analyses of

sensitivity as a function of discriminability, it is customary to fit a line via regression to

the data from all subjects to assess the relation between sensitivity and discriminability.

The significance of the relation is determined by how much variability the line accounts

for (e.g., Alsop & Porritt, 2006). As is clear from the figure, the relation between

sensitivity and discriminability in the present experiment was not statistically significant.

Indeed, there seems to be little relation whatsoever.
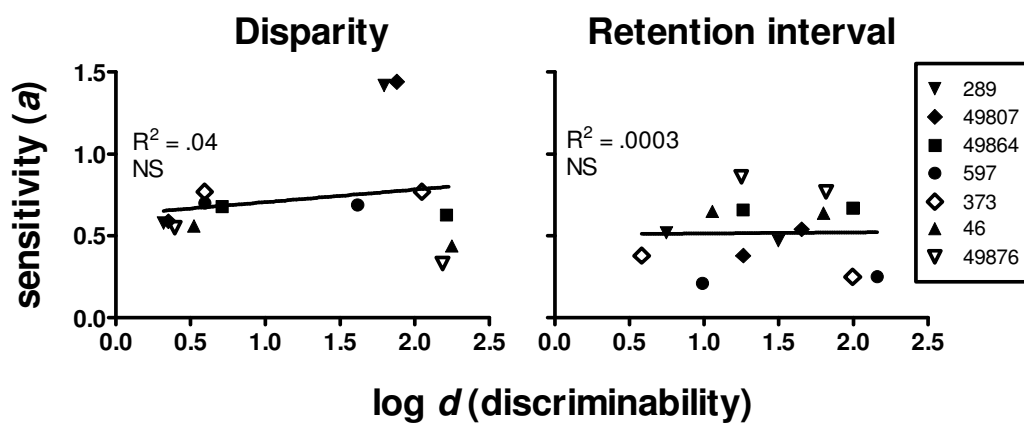
Figure 14. Sensitivity (a; Equation 6) as a function of discriminability (Equation 5) for all pigeons in the sample-stimulus disparity (left panel) and retention interval (right panel) conditions. Straight lines through the data points indicate the best fitting linear regression (see text for details).

DISCUSSION

The theory of direct remembering (White, 2001), a contemporary behavioral account of remembering, suggests that performance in DMTS procedures is no different than in immediate discrimination procedures. Rather than relying on a declining memory trace to account for decreasing discrimination accuracy as a function of increasing retention interval, the theory of direct remembering suggests that performance in DMTS procedures reflects discriminative behavior under delayed stimulus control. Thus, according to the theory, decreasing sample-stimulus disparity and increasing retention-interval duration (both ways of decreasing discrimination accuracy) should be functionally equivalent in their effects on DMTS performance.

The present experiment provided a test of this functional equivalence by assessing sensitivity to variations in reinforcer frequency as a function of both sample-stimulus disparity and retention interval. While previous investigations have also attempted to characterize this relation, the results of these studies are difficult to interpret because of the many procedural differences across experiments. The present experiment, therefore, manipulated both sample-stimulus disparity and retention-interval duration while keeping as many procedural variables constant as possible to facilitate a direct comparison of the effects of sample-stimulus disparity and retention intervals on sensitivity to variation of relative reinforcer frequency.

Four major results emerged from the present experiment. First, decreasing sample-stimulus disparity and increasing retention-interval duration decreased discrimination accuracy. Second, variation of reinforcer frequency ratios was effective in

biasing choice responding in both the sample-stimulus disparity and retention-interval conditions. Third, there was no difference between the estimates of sensitivity to relative reinforcer frequency as a function of discriminability in either the sample-stimulus disparity or retention-interval condition. Fourth, separate analysis of the data from S_1 and S_2 trials revealed different effects of reinforcer ratio variation on performance during easy and difficult S_1 and S_2 trials across the sample-stimulus disparity and retention-interval conditions. All of these results will be considered below.

<div align="center">Discrimination Difficulty and Accuracy

of Discrimination Performance</div>

Decreasing the physical disparity between the sample stimuli and increasing the retention-interval duration were both effective in decreasing discrimination accuracy. This result is in accord with numerous previous reports (e.g., Alsop & Davison, 1991; Alsop & Porritt, 2006; Davison & McCarthy, 1987; Jones & White, 1992; McCarthy & Davison, 1980; Sargisson & White, 2007; White, 2001). In addition, there was no systematic relation between log d and the reinforcer ratio (the relation between proportion correct and the reinforcer ratio in Figures 4 and 5 is due to the confounding influence of bias on the estimate of proportion correct; see Figures 12 and 13 for quantification of this bias). Such independence is consistent with the predictions of the Davison-Tustin model of conditional discrimination as well as with the results of numerous prior studies (e.g., McCarthy & Davison, 1980; Nevin et al., 1993).

Although increasing retention-interval duration decreased overall discrimination accuracy, it did not produce selective decreases in accuracy on long-sample trials. This

result may seem peculiar to readers who are familiar with the results of other studies that have assessed the effects of retention intervals on performance during temporal-discrimination procedures. For example, it has been well documented that when retention intervals are inserted between samples and comparisons in temporal-discrimination procedures, accuracy on long-sample trials declines sharply as a function of delay, whereas accuracy on short-sample trials remains high across delays, a phenomenon known as the *choose-short effect* (e.g., Fetterman, 1995; Spetch & Wilkie, 1982; 1983; see Spetch & Rusak, 1992, for review). A large empirical literature has been dedicated to theoretical characterization of this effect, and to delineating the conditions under which it will occur. Failure to find the choose-short effect in the present study may therefore seem puzzling.

Although the choose-short effect is a robust phenomenon, and reports if it are pervasive in the DMTS literature, recent investigations have demonstrated that one can reduce the probability of obtaining the choose-short effect with a simple procedural manipulation. In many DMTS procedures, the delay and ITI are not differentiated (they both are dark). Under these conditions, the choose-short effect is common. Zentall and colleagues, however, have demonstrated that differentiating the ITI in some way by, for example, illuminating the houselight during trials (including the retention interval) and extinguishing it during the ITI, greatly reduces the occurrence of the choose-short effect (e.g., Sherburne, Zentall, & Kaiser, 1998; see Zentall, 2006, for discussion). The theoretical interpretation of this result is beyond the scope of this discussion. Of direct relevance, however, is the fact that in the present study, the retention interval and ITI were differentiated (in anticipation of the interpretive difficulties the occurrence of the

choose-short effect would introduce). Therefore, the fact that a choose-short effect was not observed is perhaps not surprising and further supports the effectiveness of differentially signaling the retention interval and ITI as a means of eliminating this effect.

<center>Sensitivity to Reinforcer Variation as a</center>

<center>Function of Discriminability</center>

Although variation of reinforcer frequency effectively biased choice responding (estimates of sensitivity were similar to those obtained previously; see Baum, 1983), there was no difference in sensitivity as a function of discriminability in either the sample-stimulus disparity or retention-interval conditions (see Figure 14). Although this result was replicable across conditions and subjects, it appears problematic given the many reported results of a clear relation between sensitivity and discriminability discussed above. With regard to this result, one aspect of the data that merits discussion is that there was a significant difference between accuracy on difficult trials across the sample-stimulus disparity and retention-interval conditions (as calculated by both proportion correct and log d). While this difference is less desirable from an empirical standpoint, it is unlikely that it influenced the present results in a meaningful way. The reason is that the important comparison in the present study is between sensitivity on easy and difficult trials. Previous studies have shown clear relations between sensitivity and discriminability within the range of discriminability values reported here (e.g., Alsop, 1991; Alsop & Davison, 1991; Jones & White, 1992; White & Wixted, 1999). Because the present study was not concerned with predicting exact values of sensitivity as a function of discriminability, but rather with predicting the overall relation (an ordinal

comparison), the fact that the absolute values of discriminability differed is likely not problematic. Furthermore, differences in values of discriminability would be most problematic had there been differing relations between sensitivity and discriminability obtained across conditions. Such was not the case; in both conditions, sensitivity was independent of discriminability. Thus, the difference in accuracy on difficult trials across conditions is likely not a problem here. There may be a previously overlooked difference between the present experiment and those conducted previously which may help to explain this seemingly incongruent result (independence of sensitivity and discriminability).

The present experiment was conducted partly to assess the generality of results obtained with samples of other dimensions using temporal-sample stimuli. Only one other study has used a traditional temporal-discrimination procedure in the assessment of the relation between sensitivity and discriminability. That study was one of the initial empirical assessments of this relation (McCarthy & Davison, 1980). Recall that in that procedure, temporal-sample stimuli of either short or long duration were presented. The difference between the short and long sample durations was varied across two conditions (5 vs. 30 s and 20 vs. 30 s), and the reinforcer ratio for correct short and long choices was varied within these conditions to assess the relation between sensitivity and discriminability. Discrimination accuracy decreased with decreases in the difference between short and long samples. When the data were analyzed according to the Davison and Tustin (1978) model of conditional-discrimination performance, sensitivity was found to be independent of discriminability (it did not change as a function of changes in accuracy).

Thus, both McCarthy and Davison (1980) and the present study found independence between sensitivity and discriminability. Interestingly, both studies also used temporal-sample stimuli. The one other study that used temporal-sample stimuli was conducted by Davison and McCarthy (1987). They reported an inverse relation between sensitivity and discriminability. Their procedure, however, was an atypical temporal discrimination task. In traditional temporal-discrimination procedures, samples are presented and then the subject categorizes the presented sample as either short or long by making a choice response to the appropriate comparison option (e.g., Stubbs, 1968). In the Davison and McCarthy procedure, a sample was presented and the pigeon was required to discriminate whether the presented sample was the target duration (5 or 20 s, across conditions), or one of 12 other durations. Thus, choice of one comparison option was correct following presentation of one sample duration, while choice of the other was correct following presentation of 12 other sample durations. This procedural difference may be important in light of results showing that pigeons utilize different memory strategies (involving different types of memory codes) depending on the number of sample stimuli that are mapped onto a given comparison stimulus (e.g., Grant & Spetch, 1993, 1994; Urciuoli, Zentall, Jackson-Smith, & Steirn, 1989; Zentall, Sherbourne, & Steirn, 1993). Thus, it is possible that this procedural difference may have influenced the obtained relation between sensitivity and discriminability in the Davison and McCarthy study.

The one study that reported independence between sensitivity and discriminability as a function of retention-interval duration was Harnett and colleagues (1984). In their study, they did not use temporal samples, yet still obtained independence between

sensitivity and discriminability. The reasons for this obtained independence are unclear, as other studies have used similar sample stimuli and reported a clear relation between sensitivity and discriminability.

<div align="center">

Effects of Reinforcer Probability on Persistence

of Temporal-Discrimination Accuracy

</div>

Although it is unclear why differing relations between sensitivity and discriminability may be obtained depending on sample-stimulus modality, recent data from our laboratory suggest that the effects of other reinforcer manipulations may also differ depending on the modality of the sample stimuli used in the discrimination procedure. In a recent set of experiments, this author has assessed the relation between reinforcement probability and persistence of temporal-discrimination accuracy (Ward & Odum, 2008b). By way of background, considerable research indicates that behavior that is reinforced at a higher rate is more persistent in the face of disruption than behavior that is reinforced at a lower rate (see Nevin & Grace, 2000, for review and discussion). This relation between persistence and reinforcer rate holds for simple responding as well as for discrimination accuracy (e.g., Nevin, Milo, Odum & Shahan, 2003; Nevin, Ward, Jimenez-Gomez, Odum, & Shahan, 2008; Odum, Shahan, & Nevin, 2005).

Previous assessments of the effects of reinforcer rate on the persistence of discrimination accuracy have used visual sample stimuli (key colors or line orientations). The experiments conducted by Ward and Odum (2008b) were designed to assess whether the same results would be obtained if temporal-sample stimuli were used in the discrimination procedure. Briefly, the design consisted of presenting pigeons with a

multiple schedule of discrimination procedures (two experimental contexts, signaled

by different stimuli alternating within the same session). In one component, correct

choices were reinforced with a high probability (0.8), and in the other, correct choices

were reinforced with a low probability (0.2). Once accuracy was stable, performance was

disrupted in some fashion (e.g., presession feeding, extinction), and the persistence of

discrimination accuracy under disruption was assessed. The results of the experiments

showed that the positive relation between reinforcer rate and persistence of

discrimination accuracy held when color, but not when temporal, samples were used.

These results, together with those of the present experiment, suggest that the

effects of variations of reinforcer variables on both persistence of discrimination accuracy

and sensitivity to reinforcement as a function of discriminability that have been

previously demonstrated may not hold when the procedure involves discrimination

between samples that vary in temporal duration. Future work will need to be done to

clarify the generality of these results, and to elucidate the specific reasons for the

different results between experiments that use visual, and those that use temporal sample

stimuli. This work will entail identifying the important differences between temporal and

other types of discrimination procedures and how (or if) they relate to differences in the

effects of reinforcer variable on discrimination performance.

Differences Between Temporal and Other Types

of Discrimination Procedures

There may be differences between temporal and other types of discrimination procedures that could be of potential importance in explaining the differences in the effects of reinforcer variables obtained in the present experiment and described above. For example, temporal- discrimination procedures are symbolic in nature. In a traditional matching-to-sample experiment, a color sample is presented (red or green) and the subject receives food for choosing the comparison option that matches the sample (e.g., red or green side key). In temporal-discrimination procedures, the samples are environmental events that are presented for some duration, and each comparison option comes to be associated with a sample of a particular duration through a history of reinforcement. Thus, the symbolic nature of temporal-discrimination procedures is the first difference that may play a potential role in the differential results obtained in the present study and by Ward and Odum (2008b).

Although the symbolic nature of the discrimination procedure may affect results in some way, the results of a number of other studies that have used symbolic matching-to-sample procedures have produced very clear relations between sensitivity and discriminability (see Table 2). Thus, it seems unlikely that this difference is responsible for the present results. An experiment is currently being conducted in our laboratory to assess whether persistence of discrimination accuracy as a function of reinforcer rate depends on the nature of the discrimination procedure (symbolic vs. matching-to-

sample). Future research should attempt to identify other important difference (if any) between temporal and other types of sample stimuli.

<center>Different Effects of Reinforcer Ratio Variation</center>

<center>Across Conditions as a Function of</center>

<center>Trial Difficulty and Trial Type</center>

When the effects of reinforcer-ratio variation were considered separately for S_1 and S_2 trials, the data differed both within and across the sample-stimulus disparity and retention-interval conditions. While there were several differences, the most striking was that the response ratios on S_2 (long) were more biased by variations in reinforcer ratios during the sample-stimulus disparity condition than during the retention-interval condition. This result is particularly interesting given the fact that the sample presented on S_2 easy trials was the same across conditions; a 11-s sample, followed by a 0.1-s retention interval. Given that the present study was the first to vary sample-stimulus disparity and retention-interval within the same general procedural framework, this result seems without precedent. Although this sample was the same across conditions, the within-session context in which this sample was experienced was quite different. In the sample-stimulus disparity condition, this sample alternated with three others (1, 5, and 7 s) while in the retention interval condition, the two short and long samples were always the same (1 and 11 s), and only the retention interval varied. Perhaps the context in which each sample was experienced across conditions influenced the biasing effect of the reinforcer ratio in some way. Future research could assess this possibility.

In the sample-stimulus disparity condition, the effects of decreasing difficulty differed between S_1 and S_2 trials. As noted above, Alsop and Porritt (2006) found differences in the effects of reinforcer ratio variation between S_1 and S_2 trials and as a function of discrimination difficulty using color stimuli that varied in brightness. Furthermore, they found an asymmetry in the effects of reinforcer ratio variation on S_1 and S_2 trials after reanalyzing another previous dataset (Godfrey, 1997). Given these previous results, it is unclear whether the pattern of results observed during S_1 and S_2 trials during the sample-stimulus disparity condition was due to the use of temporal samples, and future research could explore this possibility. Nevertheless, the present data further underscore the importance of considering performance on S_1 and S_2 trials separately in order to achieve a more complete understanding of the effects of variation of reinforcer frequency on conditional discrimination performance.

<div align="center">

Future Assessments of the Relation Between

Sensitivity and Discriminability

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Although the data from the present experiment were clear and the results suggest some important considerations regarding temporal-sample stimuli in discrimination experiments, the question of the relation between sensitivity and discriminability remains to be satisfactorily answered. Future experiments should assess the relation between sensitivity and discriminability using a similar procedural design as the present experiment (keeping as many procedural variables invariant as possible) using visual sample stimuli.

These types of parametric studies take a great deal of time, and this can be a dissuading factor when deciding whether to undertake such a study. In typical assessments of sensitivity to reinforcer frequency in conditional discrimination, reinforcer ratios are varied across at least three, and in most cases, five conditions (e.g., 1:9, 1:3, 1:1, 3:1, 9:1). Each reinforcer ratio is typically in place for at least 20 (and generally 30 or more) sessions, for an entire experimental time frame of at least 100 sessions. In the present experiment, the reinforcer-ratio manipulations alone took at least 200 days to accomplish (in most cases more; see Appendix for individual subject experimental timelines). When initial training, preliminary training under each condition (sample-stimulus disparity and retention interval), and successive approximations to the final procedure are taken into account, the present experiment will have taken 16 months (nearly a year and a half) to complete.

Given the importance of parametric manipulation of reinforcer variables in developing and testing quantitative descriptions of discrimination performance, it would be useful to develop a more practical way to assess sensitivity to reinforcer variation in discrimination procedures. Recently, this author has developed a procedure in which sensitivity to reinforcer frequency can be assessed within session (Ward & Odum, 2008a). The procedure was based on one developed by Davison and Baum (2000) to assess sensitivity to reinforcer variation in simple concurrent schedules. In their procedure, pigeons were exposed to a 7-component mixed schedule (components were separated by 10-s blackouts and were not differentially signaled) in which the ratio of reinforcers allocated to two concurrent-schedule response options was varied across components from 1:27 to 27:1. The distribution of choice responses in each component

eventually came to reflect the component reinforcer ratios, with estimates of sensitivity increasing as components progressed. Thus, their procedure generated reliable estimates of sensitivity within-session. These results have been replicated in numerous experiments (e.g., Aparicio & Baum, 2006; Davison & Baum, 2002, 2003, 2007; Krägeloh & Davison, 2003; Landon & Davison, 2001).

In our procedure, pigeons are exposed to a 3-component multiple schedule of conditional-discrimination procedures in which the reinforcer ratio is varied across components from 1:9 to 9:1. The major difference between our procedure and that of Davison and Baum (2000; aside from the number of components) is that the component reinforcer ratios in effect in each component are signaled in our procedure, whereas in the Davison-Baum procedure they were unsignaled. This procedural difference has proven necessary to establish reliable within-session estimates of sensitivity to reinforcer variation.

Using this procedure, we showed that stable estimates of sensitivity could be obtained in 20-30 sessions, thus greatly increasing efficiency and possibly decreasing variability that may occur across conditions. As noted above, all previous assessments of the relation between sensitivity and discriminability have used parametric variation of reinforcer ratios across conditions. This author suggests that this procedure may provide a practical alternative to this approach. In addition, assessing the relation between sensitivity and discriminability as a function of both sample-stimulus disparity and retention interval in this procedure, in which reinforcer ratios are varied within session, would help to establish the generality of results obtained from experiments that have varied reinforcer ratios across conditions.

Implications for Theoretical Models and

Applied Treatment Protocols

The present results have theoretical, as well as applied relevance. First, there are a number of extant theoretical models of conditional-discrimination performance (most of which are based on the original Davison-Tustin model; see Alsop & Davison, 1991; Davison & Nevin, 1999) that attempt to describe in quantitative terms the relation between reinforcer variables and discrimination performance. While the complexity of these models is ever increasing in an attempt to account for a variety of behavioral outcomes in DMTS procedures (see Nevin, Davison, Odum, & Shahan, 2007, for examples of some phenomena which are in need of being modeled), a core assumption of all of them is that the effects of reinforcer variables are the same across sample stimuli of different dimensions. If, as the results of the current experiment and Ward and Odum (2008b) suggest, the effects of reinforcer variables differ with sample stimuli of different dimensions, these models will have to be modified to take this into account. Such modification will likely involve changes to Equation 6 (or its counterpart in other theories). This author has no suggestions as to specific modifications, and conjecture at this point seems premature. Suffice it to say that such modifications would greatly increase the complexity of the already complex extant theoretical accounts of conditional-discrimination performance. Nevertheless, such modification and added complexity would be necessary to accurately and completely describe the relation between reinforcer variables and discrimination performance.

The applied relevance of these findings is perhaps more straightforward. Many applied interventions involve discrimination training, with visual, verbal, and other types of stimuli and cues (e.g., Carr, 2003; Dube, Iennaco, & McIlvane, 1993; Kelly, Green, & Sidman, 1998). If the effects of reinforcer variables on discrimination performance depend on the stimulus dimension to be discriminated, this information would be important to consider when constructing and implementing applied treatment protocols. In particular the results of Ward and Odum (2008b) suggest that the effects of reinforcer variables on *persistence* of discrimination accuracy may differ depending on the stimulus dimension to be discriminated. This result may potentially be important when considering issues of generalization of trained behavior outside of the training context (see Stokes & Baer, 1977; Dunlap, 1994, for reviews and discussion), an area of concern among applied practitioners.

CONCLUSION

So what of the question of functional equivalence, then? On the one hand, the present results support the notion that manipulation of sample-stimulus disparity and retention interval are functionally equivalent. Both manipulations decreased discrimination accuracy, and the relation between sensitivity as a function of discriminability was similar (albeit different than results from previous studies). These results could be taken as support for functional equivalence.

More detailed analysis, however, revealed that even the obtained independence between sensitivity and discriminability (similar slope estimates) came about as a result of different effects of reinforcer-ratio variation on S_1 and S_2 trials across conditions. Furthermore, effects of reinforcer-ratio variation on easy and difficult trials differed across conditions (see Figures 12 and 13). Thus, at one level of analysis, functional equivalence was supported, while at another, the effects of sample-stimulus disparity and retention-interval duration appeared to be quite different.

In some sense, the definition of functional equivalence is equipped to deal with such differences. After all, functional equivalence does not imply the same mechanism of action, only that the functional effect on the outcome of interest is the same. A claim of functional equivalence in the present case, however, seems problematic, particularly with regard to the sensitivity data. It seems suspect to claim functional equivalence as supported by the overall relation between sensitivity and discriminability when manipulation of sample-stimulus disparity and retention-interval duration had clearly different effects on the component parts of that relation (performance on S_1 and S_2 trials).

It should be noted that the different effects of reinforcer-ratio variation observed here could be tied to the use of temporal samples in the present study, and further research should assess this possibility. Nevertheless, the results of the present study highlight the importance of considering similar behavioral outcomes at several levels of empirical analysis. Such careful consideration is warranted because there may be any number of different behavioral processes that could interact in such a way as to produce a functionally equivalent outcome from a different set of underlying mechanisms.

The question then becomes what is the appropriate level of analysis at which to measure functional equivalence? Is it gross behavioral output, component parts of that behavioral output, or activity at the neural level (see Hineline, 2001)? These questions have yet to be answered, and the answers will almost certainly differ depending on how much is known about the underlying mechanisms of the behavior of interest. In some cases, appealing to functional equivalence as an explanation of the effects of some manipulation on behavior may be appropriate from a descriptive point of view, but may actually impede efforts to theoretically characterize important processes underlying behavioral outcomes. As more is learned about specific processes underlying different behavioral outcomes, perhaps the level of analysis used to justify claims of functional equivalence should also shift.

With regard to the question of functional equivalence of sample-stimulus disparity and retention-interval duration on discrimination performance, such a claim would be better supported with similar results at several levels of analysis. Similar results at only one, somewhat general level of analysis may best be viewed with some skepticism. Given

the results of the present experiment, together with the discrepant results from other

assessments of the relation between sensitivity and discriminability in the DMTS

literature, the question of the functional equivalence of sample-stimulus disparity and

retention-interval duration on discrimination performance remains open to debate.

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APPENDIX

The number of session per condition, the number of responses to each choice alternative and the number of reinforcers obtained for correct responses following S_1 and S_2 presentations for all pigeons in all conditions of the experiment. Also shown are estimates of discriminability (log d), response bias (log b), sensitivity to reinforcer frequency (a), inherent bias (log c), and the proportion of variance accounted for by Equation 6.

Pigeon	Condition	SR ratio	# of sessions	Trial type	B_w	B_x	B_z	B_y	R_w	R_z	log d	log b	(a)	log c	R^2
289	Sample-Stimulus Disparity	1:9	25	Easy	190	10	200	0	31	180	2.086	-0.82	1.42	0.32	0.99
				Difficult	29	171	191	9	3	178	0.274	-1.04	0.58	0	1
		1:3		Easy											
				Difficult											
		1:1	30	Easy	199	1	190	10	113	107	1.736	0.467			
				Difficult	147	53	130	70	85	72	0.355	0.087			
		9:1	25	Easy	200	0	125	75	172	30	1.562	1.341			
				Difficult	184	16	58	142	162	8	0.333	0.721			
	Retention-Interval	1:9	30	Easy	172	28	198	2	22	186	1.365	-0.58	0.47	-0.09	0.91
				Difficult	79	121	174	26	6	98	0.319	-0.5	0.52	0.08	0.91
		1:3	26	Easy	190	10	197	3	39	170	1.526	-0.26			
				Difficult	165	35	181	19	32	90	0.822	-0.15			
		1:1	27	Easy	192	8	198	2	90	147	1.656	-0.29			
				Difficult	168	32	182	18	66	98	0.858	-0.14			
		9:1	26	Easy	196	4	189	11	175	42	1.445	0.219			
				Difficult	191	9	165	35	170	90	0.993	0.322			
49807	Sample-Stimulus Disparity	1:9	26	Easy	188	12	200	0	34	184	2.045	-0.86	1.44	0.29	0.98
				Difficult	28	172	190	10	3	173	0.242	-1.03	0.59	-0.02	0.98
		1:3	25	Easy	199	1	199	1	76	149	2.202	0			
				Difficult	89	111	173	27	30	133	0.354	-0.45			
		1:1	30	Easy	199	1	190	10	124	102	1.736	0.467			
				Difficult	141	59	160	40	86	81	0.489	-0.11			
		9:1	29	Easy	200	0	117	83	165	24	1.526	1.377			
				Difficult	191	9	63	137	147	16	0.49	0.826			
	Retention-Interval	1:9	30	Easy	187	13	198	2	28	185	1.548	-0.4	0.54	0	0.99
				Difficult	170	30	198	2	11	189	1.348	-0.6	0.38	-0.04	0.9
		1:3	27	Easy	193	7	198	2	61	164	1.685	-0.26			
				Difficult	193	7	195	5	50	175	1.498	-0.07			
		1:1	25	Easy	196	4	195	3	110	120	1.722	-0.06			
				Difficult	179	21	186	13	101	103	1.037	-0.11			
		9:1	28	Easy	199	1	186	14	189	20	1.659	0.543			
				Difficult	194	6	175	25	184	18	1.167	0.326			
49864	Sample-Stimulus Disparity	1:9	25	Easy	196	4	200	0	33	186	2.284	-0.62	0.63	-0.02	0.89
				Difficult	25	175	198	2	6	183	0.552	-1.39	0.68	-0.22	0.99
		1:3	26	Easy	199	1	199	1	62	139	2.202	0			
				Difficult	78	122	190	10	26	145	0.537	-0.73			
		1:1	27	Easy	198	2	199	1	120	113	2.074	-0.13			
				Difficult	167	33	176	24	101	93	0.781	-0.08			
		9:1	28	Easy	200	0	196	4	190	18	2.284	0.62			
				Difficult	196	4	150	50	184	9	1.07	0.594			
	Retention-Interval	1:9	27	Easy	189	11	200	0	18	191	2.065	-0.84	0.67	-0.21	0.94
				Difficult	176	24	200	0	15	192	1.883	-1.02	0.66	-0.19	0.97
		1:3	26	Easy	195	5	200	0	65	164	2.237	-0.67			
				Difficult	168	32	193	7	59	161	1.072	-0.35			
		1:1	25	Easy	197	3	198	2	114	112	1.864	-0.08			
				Difficult	175	25	185	15	108	108	0.963	-0.12			
		9:1	26	Easy	199	1	193	7	188	23	1.814	0.388			
				Difficult	194	6	170	30	181	20	1.121	0.371			

(table continues)

Pigeon	Condition	SR ratio	# of sessions	Trial type	B_w	B_x	B_z	B_y	R_w	R_z	log d	log b	(a)	log c	R^2
373	Sample-Stimulus Disparity	1:9	25	Easy	198	2	199	1	33	184	2.074	-0.13	0.77	0.39	0.7
				Difficult	18	182	197	3	2	3	0.392	-1.39	0.77	-0.05	0.97
		1:3	25	Easy	200	0	199	1	69	157	2.553	0.351			
				Difficult	97	103	195	5	32	151	0.772	-0.8			
		1:1	35	Easy	199	1	190	10	106	104	1.736	0.467			
				Difficult	136	64	128	72	72	63	0.288	0.039			
		9:1	25	Easy	200	0	153	47	180	28	1.707	1.196			
				Difficult	192	8	37	163	166	10	0.363	1.005			
	Retention-Interval	1:9	27	Easy	195	5	198	1	25	187	1.885	-0.31	0.38	0.07	0.69
				Difficult	34	166	183	17	2	174	0.17	-0.86	0.39	-0.06	0.97
		1:3	25	Easy	194	6	189	11	63	146	1.359	0.133			
				Difficult	136	64	155	42	39	123	0.446	-0.12			
		1:1	30	Easy	198	2	199	1	129	115	2.074	-0.13			
				Difficult	169	31	179	20	98	95	0.84	-0.11			
		9:1	33	Easy	199	1	192	8	187	33	1.785	0.418			
				Difficult	183	17	136	64	172	13	0.676	0.35			
597	Sample-Stimulus Disparity	1:9	25	Easy	183	9	199	1	34	172	1.75	-0.45	0.69	0.03	0.97
				Difficult	44	156	193	7	9	164	0.439	-0.99	0.7	-0.11	1
		1:3	26	Easy	198	2	199	1	66	154	2.074	-0.13			
				Difficult	129	71	188	12	50	151	0.723	-0.46			
		1:1	32	Easy	197	3	198	2	116	108	1.864	-0.08			
				Difficult	169	31	181	19	100	113	0.854	-0.12			
		9:1	26	Easy	195	5	99	98	153	14	0.787	0.783			
				Difficult	180	20	76	123	136	14	0.37	0.579			
	Retention-Interval	1:9	26	Easy	196	4	199	1	12	194	1.933	-0.27	0.25	-0.01	0.6
				Difficult	152	48	176	24	10	94	0.68	-0.18	0.21	0.06	0.77
		1:3	25	Easy	199	1	200	0	48	183	2.553	-0.35			
				Difficult	174	26	170	30	32	106	0.786	0.036			
		1:1	26	Easy	199	1	198	2	89	146	2.074	0.129			
				Difficult	186	14	187	13	75	95	1.133	-0.02			
		9:1	48	Easy	199	1	198	2	177	38	2.074	0.129			
				Difficult	194	6	189	11	179	94	1.359	0.133			
46	Sample-Stimulus Disparity	1:9	25	Easy	199	1	199	1	28	181	2.202	0	0.44	0.53	0.58
				Difficult	71	129	194	6	14	177	0.617	-0.88	0.56	-0.04	0.86
		1:3	26	Easy	200	0	199	1	64	154	2.553	0.351			
				Difficult	118	82	152	48	38	115	0.328	-0.17			
		1:1	30	Easy	200	0	188	12	106	123	2.045	0.859			
				Difficult	168	32	130	70	90	83	0.493	0.225			
		9:1	26	Easy	200	0	194	6	187	32	2.198	0.706			
				Difficult	187	13	118	82	173	10	0.654	0.496			
	Retention-Interval	1:9	35	Easy	180	20	199	1	19	191	1.576	-0.63	0.64	-0.01	0.96
				Difficult	145	55	184	16	13	99	0.737	-0.32	0.65	0.21	0.97
		1:3	25	Easy	185	15	199	1	44	175	1.643	-0.56			
				Difficult	158	42	188	12	20	114	0.88	-0.31			
		1:1	42	Easy	199	1	200	0	84	147	2.553	-0.35			
				Difficult	192	8	188	12	79	88	1.277	0.09			
		9:1	27	Easy	198	2	182	18	182	29	1.472	0.473			
				Difficult	197	3	176	24	177	92	1.322	0.461			
49876	Sample-Stimulus Disparity	1:9	25	Easy	200	0	198	2	37	169	2.424	0.479	0.33	0.41	0.38
				Difficult	8	192	197	3	0	170	0.208	-1.58	0.55	-0.19	0.94
		1:3	26	Easy	200	0	200	0	75	145	2.904	0			
				Difficult	56	144	196	4	20	149	0.628	-1.04			
		1:1	30	Easy	200	0	199	1	126	113	2.553	0.351			
				Difficult	129	71	164	36	73	93	0.457	-0.2			
		9:1	25	Easy	196	4	108	92	164	26	0.867	0.797			
				Difficult	181	19	56	144	148	7	0.282	0.691			
	Retention-Interval	1:9	25	Easy	182	18	199	1	26	186	1.601	-0.6	0.77	0.13	0.99
				Difficult	94	105	197	2	12	181	0.947	-1	0.86	0.08	0.99
		1:3	30	Easy	198	2	199	1	65	167	2.074	-0.13			
				Difficult	181	19	195	5	43	154	1.272	-0.3			
		1:1	30	Easy	196	4	193	7	110	131	1.545	0.119			
				Difficult	177	23	180	20	92	118	0.916	-0.03			
		9:1	28	Easy	200	0	188	12	191	20	2.045	0.859			
				Difficult	200	0	174	26	192	14	1.863	1.041			

CURRICULUM VITAE

Ryan David Ward
May, 2008

PERSONAL INFORMATION

Current Address	225 East 900 North
	Logan, UT 84341
Home Phone	(435) 792-3250
E-mail	ryanward@cc.usu.edu
Spouse	Beatrice K. Ward

EDUCATION

2008	Ph.D, Doctoral Program in Experimental and Applied Psychological Science
	Department of Psychology, Utah State University
	Dissertation: *Testing the functional equivalence of retention intervals and sample-stimulus disparity in conditional discrimination.*
	Dissertation Advisor: A. L. Odum, Ph.D.
2005	M.S., Doctoral Program in Experimental and Applied Psychological Science
	Department of Psychology, Utah State University
	Masters thesis: *The effects of morphine on the discrimination of subject-produced and experimenter-imposed durations.*
	Thesis Advisor: A. L. Odum, Ph.D.
2002	B.S., Psychology
	Utah State University

POSITIONS HELD

07/2007-*present*	Graduate Instructor, Department of Psychology, Utah State University.
05/2006-*present*	Graduate Research Assistant, Department of Psychology, Utah State University.
08/2005-05/2006	Graduate Instructor, Department of Psychology, Utah State University.
05/2004-05/2005	Graduate Research Assistant, Department of Psychology, Utah State University.
08/2003-05/2004	Graduate Teaching Assistant, Department of Psychology, Utah State University.

CURRENT PROFESSIONAL INTERESTS

Processes underlying temporal discrimination; discrimination and stimulus control; drug effects on discrimination and stimulus control; quantitative models of conditional-discrimination and signal-detection performance; conditioned reinforcement

AWARDS / HONORS

2008	Nominated for Graduate Researcher of the Year, Utah State University
2008	Graduate Research Assistant of the Year, College of Education and Human Services, Utah State University
2008	Travel Scholarship Utah State University School of Graduate Studies ($300)
2007	Travel Scholarship Utah State University Psychology Department ($300)
2007	Travel Scholarship Utah State University School of Graduate Studies ($300)
2006	BORG Scholarship and Research Productivity Award Recipient, Department of Psychology, Utah State University ($3500)
2006	Travel Scholarship Utah State University School of Graduate Studies ($300)
2005	Travel Scholarship Utah State University Department of Psychology ($300)
2005	Association for Behavior Analysis Student Presenter Grant
2004	Nominated for Student Representative Elect, Association for Behavior Analysis
2004	Travel Scholarship Utah State University School of Graduate Studies ($300)
2004	Travel Scholarship Utah State University Department of Psychology ($100)
2004	Association for Behavior Analysis Student Presenter Grant
2003	Travel Scholarship University of New Hampshire Department of Psychology ($100)
2003	Association of Behavior Analysis Student Presenter Grant
2002	Undergraduate Researcher of the Year, Department of Psychology, Utah State University
2002	Departmental Lab Assistantship, Department of Psychology, Utah State University

RESEARCH AWARDS-FUNDED

Principle Investigator	"Remembering,Sample-Stimulus Disparity, and Reinforcement." (Graduate Research Grant) Psi Chi: National Honor Society in Psychology Project dates: 10/01/06-9/30/07 Total costs: $1,225.20

TEACHING EXPERIENCE (INSTRUCTOR)-COURSES
UTAH STATE UNIVERSITY
2008 (Spring)	Basic Principles of Behavior Analysis (Online with lab)
2007 (Fall)	Drugs and Behavior
2007 (Fall)	Basic Principles of Behavior Analysis (Online with lab)
2007 (Summer)	Basic Principles of Behavior Analysis
2006 (Spring)	Advanced Behavior Analysis
2005 (Fall)	Advanced Behavior Analysis

TEACHING EXPERIENCE (TEACHING ASSISTANT)-COURSES
UTAH STATE UNIVERSITY
2005 (Spring)	Advanced Behavior Analysis
2004 (Spring)	Basic Principles of Behavior Analysis
2003 (Fall)	Basic Principles of Behavior Analysis
2001 (Spring)	Advanced Behavior Analysis
2000 (Fall)	Basic Principles of Behavior Analysis

UNIVERSITY OF NEW HAMPSHIRE
2003 (Spring)	Introduction to Behavior Analysis
2003 (Spring)	Behaviorism, Culture, and Contemporary Society
2002 (Fall)	Introduction to Behavior Analysis
2002 (Fall)	Addiction and Behavior

MEMBERSHIP IN PROFESSIONAL ASSOCIATIONS
Psi Chi National Honor Society
Golden Key National Honor Society
Association for Behavior Analysis (ABA) student affiliate
Society for the Quantitative Analysis of Behavior (SQAB)

PROFESSIONAL ACTIVITIES

AD HOC REVIEWER
Behavioural Processes
Brazilian Journal of Medical and Biological Research
Experimental and Clinical Psychopharmacology
Journal of the Experimental Analysis of Behavior

PUBLICATIONS AND PRESENTATIONS

REFEREED ARTICLES IN PRINT
Ward, R. D., & Higbee, T. S. (2008). Noncontingent reinforcement as treatment for
tub-standing in a toddler. *Education & Treatment of Children, 31,* 213-222.

Ward, R. D., Kynaston, A. D., Bailey, E. M., & Odum, A. L. (2008). Discriminative control of variable behavior: Effects of successive stimulus reversals. *Behavioural Processes, 78,* 17-24.

Ward, R. D., & Odum, A. L. (2007). Disruption of temporal discrimination and the choose-short effect. *Learning & Behavior, 35,* 60-70.

Odum, A. L., & Ward, R. D. (2007). Characterizing the effects of *d*-amphetamine on temporal discrimination. *Behavioural Processes*, *75,* 166-176.

Ward, R. D., Bailey, E. M., & Odum, A. L. (2006). Effects of *d*-amphetamine and ethanol on variable and repetitive keypeck sequences in pigeons. *Journal of the Experimental Analysis of Behavior, 86,* 285-305.

Odum, A. L., Ward, R. D., Barnes, Christopher A., & Burke, K. A. (2006). Effects of delayed reinforcement on variability and repetition of response sequences. *Journal of the Experimental Analysis of Behavior, 86,* 159-179.

Podlesnik, C. A., Jimenez-Gomez, C., Ward, R. D., & Shahan, T. A. (2006). Resistance to change of responding maintained by unsignaled delays to reinforcement: A response-bout analysis. *Journal of the Experimental Analysis of Behavior, 85,* 329-347.

Ward, R. D., & Odum, A. L. (2006). Effects of prefeeding, intercomponent interval food, and extinction on temporal discrimination and pacemaker rate. *Behavioural Processes, 71,* 297-306.

Ward, R. D., & Odum, A., L. (2005). The effects of morphine on temporal discrimination and color matching: General disruption of stimulus control or selective effects on timing? *Journal of the Experimental Analysis of Behavior, 84,* 401-415.

Odum, A. L., & Ward, R. D. (2004). The effects of morphine on the production and discrimination of interresponse times. *Journal of the Experimental Analysis of Behavior, 82,* 197-212.

MANUSCRIPTS ACCEPTED FOR PUBLICATION

Nevin, J. A., Ward, R. D., Jimenez-Gomez, C., Odum, A. L., & Shahan, T. A. (*in press*). Differential outcomes enhance discrimination accuracy but not resistance to change. *Journal of Experimental Psychology: Animal Behavior Processes*.

MANUSCRIPTS UNDER REVIEW

Ward, R. D., & Odum, A. L. Sensitivity to within-session variation of reinforcer frequency in conditional discrimination.

MANUSCRIPTS IN PREPARATION

Ward, R. D., Barrett, S. T., Johnson, R., & Odum, A. L. Effects of nicotine on temporal discrimination and attention to temporal samples.

Ward, R. D., & Odum, A. L. Stimulus dimension and resistance to change of conditional discrimination.

Podlesnik, C. A., Jimenez-Gomez, C., & Shahan, T. A. Resistance to change and the effects of stimuli uncorrelated with reinforcement.

PROFESSIONAL PRESENTATIONS

INVITED ADDRESSES

Ward, R. D. (2007, October). *Why do drugs disrupt timing?* Paper presented at the Fall Psychology Forum conducted at Brigham Young University, UT.

Odum, A. L., & Ward, R. D. (2006, May). *Characterizing the effects of drugs on temporal discrimination.* Paper presented at the annual meeting of the Society for the Quantitative Analysis of Behavior, Atlanta, GA.

CONFERENCE PRESENTATIONS

Ward, R. D., & Odum, A. L. (2007, May). Disruption of temporal discrimination and the choose-short effect. In K. A. Saulsgiver (Chair), *Pharmacological and non-pharmacological disruptors of timing: Current results and theoretical interpretations*. Symposium conducted at the 33rd annual meeting of the Association for Behavior Analysis, San Diego, CA.

Ward, R. D., & Odum, A. L. (2007, May). Stimulus dimension and resistance to change of conditional discrimination. In J. A. Nevin (Chair), *Conditional discriminations: Conceptual issues and new findings*. International Symposium conducted at the 33rd annual meeting of the Association for Behavior Analysis, San Diego, CA.

Ward, R. D., & Odum, A. L. (2007, May). Assessing sensitivity to within-session variation of reinforcer frequency in conditional discrimination. Poster presented at the 30th annual meeting of the Society for the Quantitative Analysis of Behavior, San Diego, CA.

Odum, A. L., Ward, R. D., Jimenez-Gomez, C., Shahan, T. A., & Nevin, J. A. (2007, May). Persistence of accuracy and response rate in delayed matching-to-sample with differential outcomes. In J. A. Nevin (Chair), *Conditional discriminations: Conceptual issues and new findings*. International Symposium conducted at the 33rd annual meeting of the Association for Behavior Analysis, San Diego, CA.

Kynaston, A., Ward, R. D., Bailey, E. M., & Odum, A. L. (2007, May). Discriminative control of variable behavior: Effects of successive stimulus reversals. Poster presented at the 33rd annual meeting of the Association for Behavior Analysis, San Diego, CA.

Ward, R. D., & Odum, A. L. (2007, February). The choose-short effect: Changes in memory for sample duration or disruption of attention to samples? In C. Brooks & M. Reilly (Chairs), *Modeling data: From description and significance to behavior and theories.* Focus session conducted at the Winter Conference on Animal Learning and Behavior, Winter Park, CO.

Ward, R. D., & Odum, A. L. (2006, May). Resistance to change of temporal discrimination. In K.   Lattal (Chair), *The temporal control of behavior.* Symposium conducted at the 32nd annual meeting of the Association for Behavior Analysis, Atlanta, GA.

Ward, R. D., & Odum, A. L. (2006, May). Effects of *d*-amphetamine on stimulus control and temporal   discrimination in position and color-matching variants of the interval-bisection procedure. In E. McClure (Chair), *Topics in timing*. Symposium conducted at the 32nd annual meeting of the Association for Behavior Analysis, Atlanta, GA.

Ward, R. D., Packer, R., & Odum, A. L. (2005, May). Effects of amphetamine on temporal discrimination: Position versus symbolic matching-to-sample procedures. In A. L. Odum (Chair), *Effects of amphetamine on timing*. Symposium conducted at the 31st annual meeting of the Association for Behavior Analysis, Chicago, IL.

Podlesnik, C. A., Jimenez-Gomez, C., Ward, R. D., & Shahan, T. A. (2005, May). *The response-reinforcer relation in resistance to change, effects of immediate, briefly-delayed, and longer-delayed reinforcement.* Poster presented at the 31st annual meeting of the Association for Behavior Analysis, Chicago, IL.

Bailey, E. M., Ward, R. D., & Odum, A. L. (2005, May). *Differential effects of amphetamine and ethanol on variable and repetitive behavior.* Poster presented at the 31st annual meeting of the Association for Behavior Analysis, Chicago, IL.

Ward, R. D., & Odum, A. L. (2004, May). *The effects of morphine on the discrimination of subject-produced and experimenter-imposed durations.* Paper presented at the 30th annual meeting of the Association for Behavior Analysis, Boston, MA.

Baily, E. M., Ward, R. D., & Odum, A. L. (2004, May). *The effects of amphetamine on variable and repetitive behavior.* Poster presented at the 30th annual meeting of the Association for Behavior Analysis, Boston, MA.

Odum, A. L., & Ward, R. D. (2003, May). The effects of morphine on the production and discrimination of duration. In A. L. Odum (Chair), *Time and the behavioral effects of drugs.* Symposium conducted at the 29th annual meeting of the Association for Behavior Analysis, San Francisco, CA.

Ward, R. D., & Odum, A. L. (2003, May). *The effects of retention intervals on the production and discrimination of interresponse times.* Poster presented at the 29th annual meeting of the Association for Behavior Analysis, San Francisco, CA.

Martin, J., Ward, R. D., & Odum, A. L. (2003, May). *The effects of d-amphetamine and haloperidol on timing assessed by two different methods.* Poster presented at the 29th annual meeting of the Association for Behavior Analysis, San Francisco, CA.

Barnes, C. A., Ward, R. D., & Odum, A. L. (2003, May). *Investigating the differential resistance of sequence variability and stereotypy.* Poster presented at the 29th annual meeting of the Association for Behavior Analysis, San Francisco, CA.

Osborne, J. G., Phillips, M., Evans, M., Engstrom, L., Warde, M., Ward, R., & Wood, L. (May, 2002). *Further explorations of taxonomic and thematic relations.* Poster presented at the 28th annual meeting of the Association for Behavior Analysis, Toronto, Canada.

Ward, R. D., & Jensen, P. (February, 2002). *Learning history and superstition.* Poster presented at the 20th annual meeting of the California Association for Behavior Analysis, San Francisco, CA.

Jensen, P., & Ward, R. D. (February, 2002). *Behavior patterns generated by periodic reinforcement.* Poster presented at the 20th annual meeting of the California Association for Behavior Analysis, San Francisco, CA.

References available on request