HUMAN SYMBOLIC MATCHING-TO-SAMPLE PERFORMANCE: EFFECTS OF REINFORCER AND SAMPLE-STIMULUS PROBABILITIES

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Four experiments, each with 6 human subjects, varied the distribution of reinforcers for correct responses and the probability of sample-stimulus presentation in symbolic matching-to-sample procedures. Experiment 1 held the sample-stimulus probability constant and varied the ratio of reinforcers obtained for correct responses on the two alternatives across conditions. There was a positive relation between measures of response bias and the ratio of reinforcers. Experiment 2 held the ratio of reinforcers constant and varied the sample-stimulus probability across conditions. Unlike previous studies that used pigeons as subjects, there was a negative relation between bias and the ratio of sample-stimulus presentations. In Experiment 3, the sample-stimulus probability and the reinforcer ratio covaried across conditions. Response bias did not vary systematically across conditions. In Experiments 1 to 3, correct responses were reinforced intermittently. Experiment 4 used the same procedure as Experiment 3, but all correct responses now produced some scheduled consequence. There was a positive relation between response bias and the ratio of reinforcers. The results suggest that human performance in these tasks was controlled by both the relative frequency of reinforced responses and the relative frequency of nonreinforced responses.

Key words: signal detection, symbolic matching to sample, sample-stimulus probability, reinforcer ratio, discriminability, response bias, humans

The present research investigates performance in what, to various readers, would be termed a conditional discrimination, a symbolic matching-to-sample procedure, or a signal-detection procedure. Each trial in such a procedure starts with the presentation of one of two sample stimuli. This is followed by a choice phase, during which the subject behaves differentially on the basis of which sample was presented. Finally, in the outcome phase, "correct" responses are typically rewarded on some schedule of reinforcement.

Many studies have focused on two particular aspects of performance in these procedures. The first, called here *discriminability*, concerns the extent to which the sample stimuli control behavior during the choice phase. Discriminability is most obviously related to physical or psychophysical differences between the sample stimuli. The second aspect of performance is *bias*, a tendency to make one or the other of the choice responses irrespective of the sample stimuli. Such biases are often

attributed to the influence of cognitive, motivational, or payoff factors on performance.

The present study is primarily concerned with bias. Previous research with pigeons has shown that reinforcers change bias in these procedures in a manner consistent with contemporary models of choice. Here, the performance of human subjects is investigated under similar conditions.

Background

Models of reinforcer effects in symbolic matching-to-sample (SMTS) procedures are typically based on the model of choice known as the matching law (e.g., Davison & Tustin, 1978; Nevin, Jenkins, Whittaker, & Yarensky, 1982). The relationship between the matching law and SMTS tasks can be understood by focusing on the choice and outcome phases of these procedures and, for the moment, ignoring the sample-stimulus phase. The choice phase consists of two concurrently available response alternatives, and the outcomes form schedules of reinforcement associated with each alternative. The matching law describes behavior allocation between such concurrent schedules by the straight line equation,

$$\log\left(\frac{B_1}{B_2}\right) = a \log\left(\frac{R_1}{R_2}\right) + \log c, \quad (1)$$

where B refers to number of responses, R re-

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fers to number of obtained reinforcers, and the subscripts 1 and 2 denote the two concurrent alternatives. The slope of the line, the parameter a , measures the extent to which changes in the reinforcer ratio (R_1/R_2) produce changes in the response ratio (B_1/B_2) (Baum, 1974). This is frequently called the sensitivity of behavior to changes in the reinforcer ratio (Lobb & Davison, 1975). The intercept of the line, the parameter $\log c$, measures any systematic preference for one or the other alternative that is constant across changes in the reinforcer ratio. Such constant preferences are typically attributed to uncontrolled asymmetries in the apparatus or subject (Baum, 1974).

Davison and Tustin (1978) extended the matching law to account for performance in SMTS procedures. In their model, Equation 1 described the effects on choice-phase performance of the outcomes for choices (i.e., the obtained reinforcer ratio) and of any unplanned asymmetries in the apparatus or subject. However, they also proposed that the sample stimuli introduced another source of constant, systematic preference during the choice phase. The magnitude of this preference measured the discriminability between the sample stimuli. For example, Equation 2 describes performance for trials presenting the sample stimulus, S_1 , following which responses to the first choice alternative (B_w) are correct and responses to the second choice alternative (B_x) are incorrect:

$$\log\left(\frac{B_w}{B_x}\right) = a \log\left(\frac{R_w}{R_x}\right) + \log c + \log d. \quad (2)$$

In words, Equation 2 states that behavior allocation during the S_1 choice phase (B_w/B_x) is a function of the overall reinforcer ratio (R_w/R_x), any inherent constant preference for an alternative ($\log c$), and a systematic preference ($\log d$) for the correct, and occasionally reinforced, choice that can be attributed to the S_1 presentation.

Similarly, Equation 3 describes performance on trials presenting the sample stimulus, S_2 , following which responses to the first choice alternative (B_y) are incorrect and responses to the second choice alternative (B_z) are correct:

$$\log\left(\frac{B_y}{B_z}\right) = a \log\left(\frac{R_w}{R_z}\right) + \log c - \log d. \quad (3)$$

Note that the constant preference for the correct response ($\log d$) is subtractive because correct responses (B_z) are the denominator in the response ratio. In all other respects, the right sides of Equations 2 and 3 are identical. Furthermore, both Equations 2 and 3 reduce to the matching law (Equation 1) when the sample stimuli are indistinguishable (i.e., $\log d = 0$).

Algebraic subtraction of Equations 2 and 3 provides a measure of the effects of the discriminability between the sample stimuli independent of the effects of other factors. This expression takes the form,

$$\frac{1}{2} \log\left(\frac{B_w B_z}{B_x B_y}\right) = \log d, \quad (4)$$

where all subscripts, variables, and parameters are as described above. In words, Equation 4 states that the discriminability between S_1 and S_2 ($\log d$) is measured by the geometric mean of the correct and incorrect response ratios across S_1 and S_2 trials. This measure is equivalent to the measures of discriminability derived from the choice theory (Luce, 1963) of signal detection (e.g., McMillan & Creelman, 1990; Swets, 1986).

Algebraic addition of Equations 2 and 3 provides a measure of the effects of reinforcers and other asymmetries independent of the discriminability between the sample stimuli. This expression takes the form,

$$\frac{1}{2} \log\left(\frac{B_w B_y}{B_x B_z}\right) = a \log\left(\frac{R_w}{R_z}\right) + \log c, \quad (5)$$

where all subscripts, variables, and parameters are as described above. In words, Equation 5 states that the effects of the reinforcer distribution, and any other constant asymmetries, are measured by the geometric mean of the response ratios of the first and second alternatives across S_1 and S_2 trials. For this reason, Equation 5 is often referred to as the *bias function*. The expression on the right side of the equation can also be applied to the data from one condition to provide a point estimate of bias, $\log b$. $\log b$ is equivalent to the measure of bias, $\log(b)$, associated with the choice theory (Luce, 1963) of signal detection (e.g., McMillan & Creelman, 1990).

Equations 4 and 5 make a number of specific

Fig. 1. The results are from each subject in each condition of McCarthy and Davison's (1979) study. The upper panels show the estimates of discriminability ($\log d$, Equation 4), and the lower panels show the estimates of bias ($\log b$, Equation 5), each plotted against the log obtained reinforcer ratio (Procedures A and C) or the log sample-stimulus ratio (Procedure B).

predictions. First, Equation 4 predicts that changes in the distribution of reinforcers for correct responses (R_w/R_z) will not affect the measure of discriminability ($\log d$). Second, Equation 5 predicts that varying the distribution of reinforcers for correct responses will produce changes in behavior allocation following a pattern consistent with the matching law. Finally, Equations 4 and 5 disregard the relative frequency with which the two sample stimuli (S_1 and S_2) are presented. In other words, discriminability and bias are independent of the sample-stimulus presentation probability (SPP).

McCarthy and Davison (1979) conducted a systematic study of these predictions. Their results are particularly germane to the present study, and they are reproduced in Figure 1. Pigeons were trained to discriminate between sample stimuli in three SMTS procedures. In what is called here Procedure A, S_1 was pre-

sented on 70% of trials (SPP = .7) in all five conditions. The ratio of obtained reinforcers (R_w/R_z) was varied across conditions. The top left panel of Figure 1 shows the measures of discriminability ($\log d$, Equation 4) for each subject in each condition. $\log d$ did not vary systematically as a function of changes in the reinforcer ratio. The lower left panel of Figure 1 shows that the measures of response bias ($\log b$, Equation 5) varied systematically as a function of the log reinforcer ratio in a manner consistent with the matching law.

In what is called here Procedure B, McCarthy and Davison (1979) arranged that the ratio of obtained reinforcers was equal (i.e., $R_w = R_z$) in each of five conditions. The SPP, however, was varied across these conditions. The center panels of Figure 1 shows that neither measures of discriminability ($\log d$, upper panel) nor measures of bias ($\log b$, lower panel) varied as a function of changes in the relative

frequency with which S_1 and S_2 were presented ($\log S_1/S_2$).

In what is called here Procedure C, McCarthy and Davison (1979) varied the SPP across five conditions. However, unlike Procedure B, the reinforcer ratio (R_w/R_z) was allowed to covary with changes in the SPP. The rightmost panels of Figure 1 show that $\log d$ did not vary systematically across conditions (upper panel), but the measures of bias ($\log b$) varied as a function of the reinforcer ratio in a manner consistent with the matching law (lower panel).

The data from these three procedures (Figure 1) support the predictions of Equations 4 and 5. Measures of bias ($\log b$) varied systematically as a function of changes in the reinforcer ratio, but not as a function of changes in SPP alone. On the other hand, measures of discriminability ($\log d$) did not vary systematically as a function of either reinforcer or SPP manipulations.

This system of equations (Equations 2 to 5) is known as the behavioral model of signal detection (Davison & Tustin, 1978). Although recent research has shown some limitations of this approach (e.g., Alsop & Davison, 1991; Davison & McCarthy, 1987, 1989), it remains a widely accepted and successful treatment of reinforcer effects in this type of procedure.

The Present Experiments

A number of researchers have noted that the behavioral model of signal detection should have much to offer human psychophysics (e.g., Dusior, 1983; McCarthy & Davison, 1981; McMillan & Creelman, 1990). However, there has been little systematic research of SMTS reinforcer effects with human subjects to bridge the gap between human and nonhuman studies. Therefore, the present experiment systematically replicated the study of McCarthy and Davison (1979) using human subjects. Experiment 1 varied the reinforcer ratio (R_w/R_z) across three conditions while holding the SPP equal and constant. Experiment 2 varied SPP across 3 conditions while holding the number of reinforcers obtained on each response alternative equal and constant ($R_w = R_z$). In Experiment 3, the SPP and the reinforcer ratio covaried across three conditions. Experiment 4 used the same general procedure as Experiment 3, but all correct responses provided some form of differential consequence. Finally, each

experiment used two sets of sample stimuli in order to compare reinforcer effects at different levels of stimulus disparity.

EXPERIMENT 1

Experiment 1 was a systematic replication of McCarthy and Davison's (1979) Procedure A. The subjects were trained in three conditions. The reinforcer ratio varied across conditions (4:1, 1:1, and 1:4), but the two sample stimuli were presented equally often throughout. The results from this experiment are comparable to the results shown in the leftmost panels of Figure 1.

METHOD

Subjects

Three women and 3 men were randomly selected from the subject pool of first-year psychology students at the University of Otago. Their ages ranged from 18 to 20 years.

Apparatus

The experiment was conducted in a quiet room. An NEC 286 computer, keyboard, and VGA video monitor were used throughout. The software controlling the experimental events was developed using TurboPascal 5.5. The stimuli consisted of two pairs of lines. The "easy" pair of lines measured 70 pixels (approximately 25.6 mm) and 72 pixels (approximately 26.4 mm) horizontally and 2 pixels (approximately 1 mm) vertically. The "hard" pair of lines measured 140 pixels (approximately 51.2 mm) and 142 pixels (approximately 52 mm) horizontally and 2 pixels vertically. The two response alternatives were the "S" and "L" keys of the keyboard.

Procedure

Subjects were seated with their heads approximately 40 cm directly in front of the monitor. They were told that they must make judgments about the comparative lengths of lines, and that full instructions would be presented on the computer monitor. The experimenter then started the software, and the following instructions and demonstration appeared:

On each trial you will see: 2 Warning Flashes [the symbol * was flashed twice in the center of the screen], then a LINE will flash on [one of the easy pair of lines flashed briefly on the

screen], followed by a second LINE [the other of the easy pair of lines flashed briefly on the screen].

So the sequence looks like: [The sequence of two warning flashes and successive presentations of the two lines was repeated without interruption. In an experimental trial, the 200-ms warning flashes were separated by a 200-ms delay, and the 500-ms presentations of the lines were separated by a 250-ms delay.]

If the SECOND line was SHORTER than the first, hit the "S" key. If the SECOND line was LONGER than the first, hit the "L" key. Hit any key to continue [the screen cleared].

From time to time, but NOT always, CORRECT responses will be signaled and 10 points added to your score. There is a \$25 dollar cash prize for the highest total score. Hit any key to continue [the screen cleared].

If the task is not clear, ask the experimenter. If the task is clear, hit any key [the screen cleared].

Get ready for the experiment. Put a finger of your left hand on the "S" key. Put a finger of your right hand on the "L" key. Hit either key to start [the screen cleared and the final instruction appeared].

First is a series of smaller [or, for half the sessions, bigger] pairs of lines.

The subject then received a block of 50 trials with the easy (or hard) pair of lines. Correct responses occasionally produced the following consequences for 750 ms: The word "correct" appeared in the center of the screen, immediately below appeared "total points =" with the cumulative number of points gained, and a tone sounded. For nonreinforced correct responses and incorrect responses, the screen was blank for this period. There was a 250-ms intertrial interval with the screen blank before the warning flashes signaled the start of the next trial. This initial block was followed by a block of 50 trials using the other pair of lines. Following each block of trials, the screen displayed the message, "If needed, relax for a while. Hit any key to continue the test." The blocks of easy and hard pairs of lines alternated until the subject completed a total of 10 blocks (500 trials).

In Experiment 1, the computer controlled the distribution of sample-stimuli presentations and reinforcers received by the subjects. Trials in which the second line was shorter than the first (S_1) and trials in which the second line was longer than the first (S_2) occurred with equal probability (i.e., $SPP = .5$) in all

conditions. The probability with which the reinforcers were assigned for correct responses following S_1 or S_2 presentations was varied across conditions. Following a reinforcer, the computer randomly selected, with a fixed probability, the next type of trial (S_1 or S_2) for which a correct response would be reinforced. No other reinforcers were available until the subject obtained that reinforcer. This procedure is analogous to the dependent scheduling of concurrent-schedule reinforcers developed by Stubbs and Pliskoff (1969). In Condition A, the probability of reinforcer assignment was equal (i.e., $\log R_w/R_z = 0$). In Condition B, reinforcers were assigned for S_1 correct responses four times as often as for S_2 correct responses (i.e., $\log R_w/R_z = 0.70$). Condition C was a reversal of Condition B, and reinforcers were assigned for correct S_2 responses four times as often as for S_1 correct responses (i.e., $\log R_w/R_z = -0.70$).

The subjects received one session of each condition. The order of the conditions differed for each subject, and conditions beginning with blocks of easy or hard pairs of lines were also counterbalanced. The first four blocks were discarded as training (i.e., 100 trials with each pair of lines, which made 200 trials in total with the reinforcer contingencies). The data from the last six blocks were used in the analyses.

RESULTS AND DISCUSSION

The results of Experiment 1 are shown in Table 1 and Figure 2. Table 1 shows the raw data summed across individual subjects; that is, the number of responses to the two keys following S_1 and S_2 presentations (B_w , B_x , B_y , and B_z) and the number of reinforcers (signaling "correct" and awarding points) on each alternative (R_w and R_z) in each condition. The corresponding measures of discriminability (Equation 4) and bias (Equation 5) are also provided for each condition. Figure 2 shows these measures of discriminability and bias for each subject separately. Figure 2 also shows the effectiveness of the controlled reinforcer-ratio procedure. The grouping of obtained reinforcer ratios across the 6 subjects for each condition varied little from the arranged values.

The results of Experiment 1 show the same effects as McCarthy and Davison (1979) found using pigeons as subjects (Figure 1, left pan-

Table 1

The number of responses to the “S” and “L” keys following S_1 presentations (B_w and B_x) and S_2 presentations (B_y and B_z) and the number of reinforcers for correct responses (R_w and R_z). The data have been summed across subjects for each condition in Experiments 1, 2, 3, and 4. Results from the easy and hard pairs of lines are shown separately. Measures of discriminability ($\log d$, Equation 4), bias ($\log b$, Equation 5), the log reinforcer ratio ($\log r$), and the log sample-stimulus presentation ratio ($\log s$) are also provided.

Condi- tion	Responses				Reinforcers		Calculated values			
	B_w	B_x	B_y	B_z	R_w	R_z	$\log d$	$\log b$	$\log r$	$\log s$
Experiment 1										
Easy lines										
B	314	137	99	350	60	294	0.45	-0.09	-0.69	0.00
A	326	125	176	273	173	177	0.30	0.11	-0.01	0.00
C	371	80	209	240	324	59	0.36	0.30	0.74	0.00
Hard lines										
B	203	247	104	346	54	272	0.22	-0.30	-0.70	0.00
A	258	192	177	273	156	149	0.16	-0.03	0.02	0.00
C	302	149	213	236	258	52	0.18	0.13	0.70	0.00
Experiment 2										
Easy lines										
B	122	25	298	455	111	119	0.44	0.25	-0.03	-0.71
A	324	124	137	315	185	191	0.39	0.03	-0.01	0.00
C	479	268	31	122	113	115	0.42	-0.17	-0.01	0.69
Hard lines										
B	97	58	307	438	87	89	0.19	0.03	-0.01	-0.68
A	261	193	168	278	148	145	0.17	-0.04	0.01	0.01
C	384	365	48	103	95	91	0.18	-0.15	0.02	0.70
Experiment 3										
Easy lines										
B	104	41	214	541	29	167	0.40	0.00	-0.76	-0.72
A	313	139	140	308	103	107	0.35	0.01	-0.02	0.00
C	557	193	39	111	189	44	0.46	0.00	0.63	0.70
Hard lines										
B	98	54	260	488	42	156	0.27	-0.01	-0.57	-0.69
A	288	164	137	311	98	106	0.30	-0.06	-0.03	0.00
C	471	283	41	105	153	32	0.31	-0.09	0.68	0.71
Experiment 4										
Easy lines										
B	50	103	149	598	22	187	0.14	-0.46	-0.93	-0.69
A	332	121	199	248	94	82	0.27	0.17	0.06	0.01
C	660	92	111	37	199	14	0.19	0.67	1.15	0.71
Hard lines										
B	44	104	131	621	17	219	0.15	-0.52	-1.11	-0.71
A	243	204	162	291	85	108	0.17	-0.09	-0.10	-0.01
C	603	147	103	47	192	16	0.14	0.48	1.08	0.70

els). Table 1 and Figure 2 (upper panels) show that the discriminability between the pairs of lines (Equation 4) did not vary systematically as a function of changes in the distribution of reinforcers for the correct responses ($\log R_w/R_z$). This was the case for both the easy and hard pairs of lines. Although there was some variability within and across subjects, this can

be attributed in part to the relatively small number of trials (150) available to calculate each of the ratio measures. Note also that the comparable estimates from McCarthy and Davison’s (1979) study show a similar variability (Figure 1, upper left panel), and that the range of the ordinate in Figure 1 (0 to 2.25) is double that used in Figure 2 (0 to

Fig. 2. The results are from each subject in each condition of Experiment 1. The upper panels show the estimates of discriminability ($\log d$, Equation 4), and the lower panels show the estimates of bias ($\log b$, Equation 5), each plotted against the log obtained reinforcer ratio ($\log R_w/R_z$).

1.10). It was also clear that both types of line pairs were relatively difficult to discriminate (i.e., "easy" might be something of a misnomer). However, measures of discriminability from the easy pair of lines were reliably greater than their corresponding measures from the hard pair of lines (15 of 18 individual comparisons, Figure 2).

As predicted, Figure 2 (lower panels) shows that measures of bias [$\log (B_w B_y) / (B_x B_z)$] varied as a function of the reinforcer ratio in a manner consistent with the generalized matching law (Equation 5). A least squares regression line fitted to the data in Figure 2 found a statistically significant positive relation between $\log b$ and the log reinforcer ratio for both the easy pair (slope = 0.33, $p < .01$) and hard pair (slope = 0.36, $p < .01$) of lines. Figure 2 and the regression analysis also show that the size of this effect was similar across the two types of line pairs. For comparison, a regression analysis of McCarthy and Davi-

son's (1979) Procedure A (Figure 1, lower left panel) had a slope of 0.40 ($p < .01$).

On the other hand, it appears that the subjects showed a small constant tendency to choose the "shorter" response during the blocks of easy pairs of lines independent of the effects of the reinforcer distribution (Figure 2, lower left panel), but not during blocks with the hard pairs of lines. In other words, most of the data points from the easy pairs of lines (lower left panel) lie further up the ordinate than their corresponding points from the hard pairs of lines (lower right panel). The regression analysis also found a statistically significant nonzero intercept for the data from the easy line pairs (intercept = 0.10, $p < .05$). In Equations 2, 3, and 5, this would be reflected by a nonzero value for the parameter $\log c$. Although this result was unexpected, it does not contaminate the overall pattern of results produced by the changes in the reinforcer ratio.

Experiment 1 showed that the distribution

of reinforcers in SMTS tasks affects human subjects in a fashion similar to pigeons. In and of itself, this result is not surprising. It is consistent with previous research (e.g., Dusior, 1983; McCarthy, 1991) and the assumptions underlying traditional approaches to signal detection (e.g., Green & Swets, 1974). Experiment 1, however, provides the systematic link between this previous research and the behavioral approach to signal detection, and it is a necessary companion for Experiments 2, 3, and 4.

EXPERIMENT 2

Experiment 2 was a systematic replication of McCarthy and Davison's (1979) Procedure B. As in Experiment 1, the subjects received three experimental conditions. In Experiment 2, however, the arranged reinforcer ratio was constant and equal (1:1) throughout, and the SPP was varied across conditions. The results from this experiment are comparable to the results shown in the middle panels of Figure 1.

METHOD

Subjects and Apparatus

Three women and 3 men were randomly selected from the subject pool of first-year psychology students at the University of Otago. Their ages ranged from 18 to 26 years. The apparatus was identical to that used in Experiment 1.

Procedure

The general procedure and instructions were the same as in Experiment 1. As in Experiment 1, the distribution of reinforcers and presentation of sample stimuli were controlled throughout. However, in Experiment 2, the number of reinforcers obtained for correct "shorter" and correct "longer" responses were equal in each condition. The probability with which S_1 and S_2 were presented was varied across conditions. In Condition A, S_1 and S_2 were presented equally often (i.e., $\log S_1/S_2 = 0$). In Condition B, S_1 was presented four times as often as S_2 (i.e., $\log S_1/S_2 = 0.70$), and Condition C was a reversal of Condition B (i.e., $\log S_1/S_2 = -0.70$).

RESULTS AND DISCUSSION

Table 1 again provides response and reinforcer totals summed across subjects, and Fig-

ure 3 shows the measures of discriminability (Equation 4) and bias (Equation 5) for each subject in each condition of Experiment 2. The results of the analysis of bias (Equation 5) differed markedly from those of McCarthy and Davison's (1979) Procedure B. McCarthy and Davison found no effect of varying the ratio of S_1 and S_2 presentations on measures of $\log b$ (Figure 1, middle lower panel). However, Figure 3 (lower panels) and the group data in Table 1 show a negative relation between bias and the ratio of S_1 and S_2 presentations. A least squares linear regression performed on the data shown in Figure 3 supports this finding. The log sample-stimulus ratio produced statistically significant changes in bias for both the easy pair (slope = -0.37 , $p < .01$) and the hard pair (slope = -0.16 , $p < .01$) of lines. In addition, the size of this negative relation for the easy pair of lines was similar to the size of the positive relation found in Experiment 1. The intercepts did not differ significantly from zero.

The difference between the bias results of Experiment 2 and those of McCarthy and Davison's (1979) Procedure B are not easily reconciled, but full discussion of this difference would be premature here. Experiment 3 (below) considers the third of McCarthy and Davison's procedures, and the results of this experiment will influence the interpretation of the results of Experiment 2. However, Experiments 1 and 2 make an interesting prediction concerning the results of Experiment 3. Experiment 1 showed a positive relation between bias and the log reinforcer ratio, and Experiment 2 showed a negative relation between bias and the log sample-stimulus ratio. If these effects are reliable, then they might cancel each other when both the log reinforcer ratio and the log sample-stimulus ratio are covaried. In other words, Experiments 1 and 2 suggest that Experiment 3 might find no systematic changes in bias across conditions.

The results of the analysis of discriminability between the sample stimuli (Equation 4) in Experiment 2 were similar to those in Experiment 1. First, estimates of $\log d$ did not vary systematically across changes in the log reinforcer ratio (Figure 3, upper panels). Second, $\log d$ measures from the blocks of easy line pairs were generally greater than those from the corresponding blocks of hard pairs of lines (16 of 18 comparisons, Figure 3). Finally,

Fig. 3. The results are from each subject in each condition of Experiment 2. The upper panels show the estimates of discriminability ($\log d$, Equation 4), and the lower panels show the estimates of bias ($\log b$, Equation 5), each plotted against the log sample-stimulus ratio ($\log S_1/S_2$).

Table 1 shows that the absolute level of discriminability for the easy and hard pairs of lines in Experiment 2 was similar to the corresponding measures obtained in Experiment 1.

EXPERIMENT 3

Experiment 3 was a systematic replication of McCarthy and Davison's (1979) Procedure C (Figure 1, right panels). Again, the subjects received three experimental conditions. In Experiment 3, the SPP was varied across conditions. However, unlike Experiment 2, the reinforcer ratio was not controlled. Instead, correct responses on either alternative were reinforced on a variable-ratio (VR) 3 schedule; that is, on average, every third correct response on an alternative was reinforced. This meant that the obtained log reinforcer ratio could vary as a function of each subject's behavior.

METHOD

Subjects and Apparatus

Two women and 4 men volunteered from among the graduate and undergraduate psychology students at the University of Otago. Their ages ranged from 20 to 25 years. The apparatus was identical to that used in Experiments 1 and 2.

Procedure

The general procedure and instructions were the same as in Experiments 1 and 2. As in Experiment 2, the ratio of S_1 and S_2 presentations was controlled. Condition A presented the two sample stimuli with equal frequency ($\log S_1/S_2 = 0$). Condition B presented S_1 four times as often as S_2 ($\log S_1/S_2 = 0.70$), and Condition C presented S_2 four times as often as S_1 ($\log S_1/S_2 = -0.70$). In all conditions, correct responses on each alternative were as-

Fig. 4. The results are from each subject in each condition of Experiment 3. The upper panels show the estimates of discriminability ($\log d$, Equation 4), and the lower panels show the estimates of bias ($\log b$, Equation 5), each plotted against the log obtained reinforcer ratio ($\log R_w/R_x$).

sociated with independent VR 3 schedules of reinforcement; that is, once the subject had made a correct response, there was a .33 probability that a reinforcer ("correct" and points) would be presented.

RESULTS AND DISCUSSION

The group data from Experiment 3 are shown in Table 1, and measures of discriminability (Equation 4) and bias (Equation 5) for each subject in each condition are shown in Figure 4. Figure 4 also shows one of the by-products of arranging an uncontrolled reinforcer-ratio procedure; that is, there was considerable variability in the obtained reinforcer ratio across subjects in each condition (see Figure 2 for comparison). McCarthy and Davison's (1979) data show a similar effect (Figure 1, right panels).

The results of the bias analysis (Equation 5) of Experiment 3 were consistent with the results of Experiments 1 and 2, but did not

replicate McCarthy and Davison's (1979) results (Figure 1, lower right panel). Figure 4 (lower panels) shows that there were no systematic changes in bias across the three experimental conditions, and the estimates of $\log b$ were evenly distributed around a value of approximately zero. This was supported by fitting least squares linear regressions to the data in Figure 4. Estimates of slope and intercept were not statistically significantly different from zero.

Once again, estimates of discriminability ($\log d$) did not vary systematically across conditions for the 6 subjects (Figure 4, upper panels), and the overall levels of discriminability for both pairs of lines were similar to those obtained in Experiments 1 and 2 (Table 1). Estimates of $\log d$ from the easy pairs of lines were higher than the corresponding measures from the hard pair of lines (12 of 17 possible comparisons) more often than not.

The results of Experiments 1, 2, and 3 are

internally consistent. Varying the reinforcer ratio alone (Experiment 1) produced a positive relation between response bias and the log reinforcer ratio (Figure 2). Varying the sample-stimulus presentation ratio alone (Experiment 2) produced a negative relation between response bias and the log sample-stimulus ratio (Figure 3). When the reinforcer ratio and the sample-stimulus ratio covaried (Experiment 3), there were no systematic changes in response bias (Figure 4); that is, the effects found in Experiments 1 and 2 appear to have canceled each other.

The problem is reconciling the results of Experiments 1, 2, and 3 with the earlier study of McCarthy and Davison (1979). Their results clearly showed no effect of varying the sample-stimulus presentation ratio alone, and showed a positive relation between response bias and the log reinforcer ratio when the sample-stimulus ratio and the reinforcer ratio covaried (Figure 1). There are three obvious procedural differences between the two studies. First, different species were used as subjects (humans vs. pigeons). This difference should not be dismissed out of hand, but perhaps other, more easily tested alternatives should be the first recourse. The second difference concerns the amount of training. McCarthy and Davison trained their pigeons for several weeks in each experimental condition. In the present study, the subjects were trained in each condition for one session only. Although this difference cannot be ignored, some other points relating to this issue are worth noting. It was not simply the case that the present study failed to find an effect. The present study showed clear effects of the independent variables in two of the three experiments, and the size of these effects was comparable to those obtained by McCarthy and Davison (Figure 1). Also, a comparison with McCarthy and Davison's data shows that the present results (Figures 2, 3, and 4) are surprisingly orderly, both within and across subjects, especially given that relatively fewer trials contributed to each log d or log b measure. Finally, the humans received instructions that should have, to some extent, offset the differences in amount of training. Unfortunately, it is difficult to train human subjects as extensively as nonhuman subjects.

The final procedural difference between McCarthy and Davison's (1979) study and the present experiments offers the simplest solution to the impasse. McCarthy and Davison

arranged different consequences for nonreinforced correct responses (a 3-s presentation of the magazine light) and incorrect responses (a 3-s blackout). In the present study, nonreinforced correct and incorrect responses were indistinguishable (750 ms of a blank screen). Since McCarthy and Davison's study, some researchers have signaled nonreinforced correct responses using the magazine light (e.g., McCarthy & Davison, 1980a, 1980b, 1984), and others have not (e.g., Alsop & Davison, 1991; Davison & McCarthy, 1989; Nevin et al., 1982). There has been little evidence of any systematic differences between these two types of procedure, and the common impression has been that the two procedures are functionally equivalent. For example, McCarthy and Davison (1982) trained pigeons in one procedure that signaled nonreinforced correct responses (3 s of the magazine light) and another procedure that arranged identical consequences for both nonreinforced correct and incorrect responses (3 s of blackout). They reported no difference in measures of discriminability across these two procedures. However, they did not report any analysis of the bias measures. Overall, it still remains possible that this procedural difference produced the difference between the results of Experiments 1, 2, and 3 and those of McCarthy and Davison's (1979) study. Experiment 4 investigated this possibility.

EXPERIMENT 4

Experiment 3 found no change in measures of response bias when the sample-stimulus presentation ratio and the reinforcer ratio covaried across conditions. Experiment 4 used the same general procedure as Experiment 3, but all correct responses were signaled in some way. If the difference between the results of McCarthy and Davison's (1979) study and the present research involves the signaling of nonreinforced correct responses, then Experiment 4 should show a positive relation between response bias and the log reinforcer ratio (e.g., Figure 1, lower right panel).

METHOD

Subjects and Apparatus

Five women and 1 man volunteered from among the graduate and undergraduate students at the University of Otago. Their ages

Fig. 5. The results are from each subject in each condition of Experiment 4. The upper panels show the estimates of discriminability ($\log d$, Equation 4), and the lower panels show the estimates of bias ($\log b$, Equation 5), each plotted against the log obtained reinforcer ratio ($\log R_w/R_z$).

ranged from 21 to 24 years. The apparatus was identical to that used in Experiments 1, 2, and 3.

Procedure

The general procedure and the instructions were the same as in Experiment 3.

The only procedural difference between Experiments 3 and 4 involved the consequences for nonreinforced correct responses. In Experiment 3 (and Experiments 1 and 2), nonreinforced correct responses had the same consequence as incorrect responses; that is, 750 ms with the screen blank. In Experiment 4, nonreinforced correct responses produced the message "correct" on the center of the screen for 750 ms. Although this stimulus was likely to have reinforcing effects in its own right, this signal seemed to be the most analogous to the magazine light presentations used by McCarthy and Davison (1982).

RESULTS

The results of Experiment 4 supported the suggestion that the consequences for nonreinforced correct responses were responsible for the difference between the results of Experiments 1, 2, and 3 and the results of McCarthy and Davison's (1979) study. This is shown in the bottom panels of Figure 5, which plots the measures of response bias (Equation 5) for each subject as a function of the log obtained reinforcer ratio. There was a clear positive relation between response bias and the log reinforcer ratio. Least squares linear regressions fitted to these data showed that this effect was statistically significant for both easy pairs (slope = 0.65, $p < .01$) and hard pairs (slope = 0.48, $p < .01$) of lines. This result differed markedly from Experiment 3, which found no systematic changes in bias, but it is consistent with the result of McCarthy and Davison's Procedure C (Figure 1, lower left panel), which also found

a significant positive relation (slope = 0.95, $p < .01$) between bias and the reinforcer ratio under similar conditions.

As in Experiment 3, the uncontrolled reinforcer-ratio procedure produced considerable variability in the log obtained reinforcer ratio across subjects in each condition (Figure 5). In addition, some subjects made no B_x errors, no B_y errors, or received no R_w or R_z reinforcers in some conditions, so some values could not be calculated using Equations 4 and 5.

The measures of discriminability between the sample stimuli showed more variability in Experiment 4 than in the previous experiments of this study. Overall, measures of log d from conditions with the easy pair of lines were greater than the corresponding measures from the hard pair of lines (13 of 17 comparisons). However, the group data suggest that the subjects discriminated more poorly between the easy pair of lines in Experiment 4 than in Experiments 1, 2, and 3.

GENERAL DISCUSSION

Although the results of our experiments did not replicate McCarthy and Davison's (1979) findings, the experiments clearly demonstrated the importance of the major focus of the behavioral approach to signal detection; that is, the consequences of subjects' choices are a powerful determinant of performance in these procedures. For example, the negative relation between SPP and response bias found in Experiment 2 is not predicted by contemporary models of signal detection. The problem, however, is providing an explanation for the pattern of results obtained in the present study, and its differences to previous research.

A comparison of Experiments 3 and 4 suggests that the total number of reinforcers (reinforced correct responses) relative to the total instances of nonreinforcement (unreinforced correct responses or errors) obtained on an alternative contributed to performance as well as the distribution of reinforcers across alternatives did. A simple explanation of the results of these two experiments is that higher overall rates of reinforcement provided greater control by the reinforcer distribution. Indeed, Alsop and Elliffe (1988) provided evidence that this occurs in simple concurrent schedules. In Experiment 4, the presentations of the word "cor-

rect," following what were nonreinforced correct responses in the earlier experiments, were probably an additional source of reinforcement, and hence the overall reinforcer rate was probably greater than in Experiment 3. However, McCarthy and Davison (1982) found no change in the signal-detection performance of pigeons across a range of different overall reinforcer rates. Furthermore, an account based on overall reinforcer rate does not explain the negative relation between SPP and response bias found in Experiment 2.

Another possible explanation is that, unlike pigeons, the behavior of human subjects on these tasks was sensitive to the conditional probabilities of reinforcement on the two alternatives rather than to the reinforcer distribution per se. In Experiment 1, with constant and equal SPP and varied reinforcer distributions, the conditional probabilities of reinforcement would track the reinforcer distribution, and this predicts the results in Figure 2. In Experiment 2, with constant and equal reinforcer distribution and varied SPP, the conditional probabilities of reinforcement would be in the opposite direction as SPP, hence the pattern of results in Figure 3. Reinforcement of correct responses on equal VR schedules in Experiment 3 arranged constant and equal conditional probabilities of reinforcement on the alternatives, and this predicts constant response bias across changes in SPP, as shown in Figure 4. However, Experiment 4 also arranged constant and equal conditional probabilities on the two alternatives across conditions, and here there were systematic changes in bias across changes in SPP (Figure 5). Therefore, one must propose an additional explanation for Experiment 4, for example, that the higher overall reinforcer rate prompted subjects to switch from control by the conditional probabilities of reinforcement to control by the reinforcer distribution. Although this is possible, it is not a particularly parsimonious account.

A third and admittedly more speculative explanation focuses on the effect of "nonfeedback" following incorrect and nonreinforced correct responses on performance in Experiments 1, 2, and 3. Recent research with pigeons suggests that brief periods of blackout following responses should not influence performance markedly in choice procedures (Dunn, 1990). However, it might be that the

absence of feedback was somewhat aversive for human subjects in the present study, perhaps because answers followed by no reinforcement are more likely to indicate errors than correct responses in everyday experience. If this were the case, then consider Condition B of Experiment 2 in which the number of obtained reinforcers for responses on the two alternatives was equal, but S_1 ("shorter") was presented four times as often as S_2 ("longer"). A subject responding with no response bias for either alternative would experience a relatively greater number of unreinforced responses on the "S" key (i.e., "shorter"). If the absence of feedback was aversive, then research on choice and punishment (e.g., Deluty, 1976; Farley, 1980; Farley & Fantino, 1978) suggests that this should create a systematic preference for the alternative with the lower rate of punishment. This predicts the inverse relation between the log sample-stimulus ratio and bias ($\log b$) shown in Figure 3 (lower panels). This account is compatible with the positive relation between bias and the log reinforcer ratio found in Experiment 1 (Figure 2). If the number of S_1 and S_2 presentations are equal, then arranging relatively more reinforcers on one alternative also arranges relatively fewer punishers. The difference between the results of Experiments 3 and 4 is also consistent with a punishment explanation. In Experiment 3, the VR 3 schedules produced a situation in which increased responses to a particular alternative must increase both the number of feedback and nonfeedback trials. This allows the reinforcing effect of the increased number of feedback trials to be offset by the punishing effect of the increased number of nonfeedback trials when SPP was varied. This relation did not hold in Experiment 4, because all correct trials provided feedback in some way; therefore, Experiment 4 showed control by the reinforcer ratio, and Experiment 3 did not.

If the absence of feedback for incorrect and nonreinforced correct responses was aversive for human subjects, this would not require discarding the behavioral model of signal detection. The results of the present study could be accommodated by incorporating current models of punishment in concurrent schedules into the reinforcer term in Equations 2 to 5. The effects of punishers on a particular alternative could either subtract directly from the value of reinforcers on that alternative (Farley,

1980; Farley & Fantino, 1978) or add to the value of reinforcers on the other alternative (e.g., Deluty, 1976).

Whatever the underlying explanation of the present results, this focus on the effects of providing feedback for all or some correct responses in Experiments 3 and 4 encourages a reexamination of the comparable nonhuman animal research. As noted earlier, McCarthy and Davison (1982) appears to be the sole study that explicitly arranged groups of conditions that signaled or did not signal nonreinforced correct responses with pigeons as subjects. The relevant conditions from their experiment are analogous to those of the present Experiments 3 and 4 (Figures 4 and 5). In their study, SPP was varied across conditions and the reinforcer ratio was allowed to covary. Moreover, the stimulus that signaled nonreinforced correct responses (the magazine light) was likely to have acquired some reinforcing properties. McCarthy and Davison provided no analysis of bias for these two groups of conditions, but they did report the raw data for their 2 subjects. These data have been reanalyzed in the same manner as the results shown in the lower panels of Figures 1 to 5, and the measures of bias ($\log b$, Equation 5) are plotted as a function of the reinforcer ratio in Figure 6.

The reanalysis of McCarthy and Davison's (1982) data produced results consistent with Experiments 3 and 4 of the present study. As in Experiment 4, there was a positive relation between response bias and the log reinforcer ratio (slope = 0.71, $p < .01$) for those conditions that signaled nonreinforced correct responses (Figure 6, lower panel). Although the results from the conditions that did not signal nonreinforced correct responses (comparable to Experiment 3 of the present study) also appear to show a positive relation between response bias and the log reinforcer ratio (Figure 6, upper panel), the effect was smaller and the regression analysis was not statistically significant (slope = 0.57, $p = .07$). Therefore, as in the present study, signaling the nonreinforced correct responses increased control by the reinforcer ratio. However, some caution is required because the difference between the two groups of conditions is not completely convincing, and the data come from only 2 subjects.

Future research in this area could progress in a variety of directions. First, it appears that

Fig. 6. Estimates of response bias ($\log b$) are plotted as a function of the log reinforcer ratio ($\log R_w/R_c$) from the 2 subjects in McCarthy and Davison's (1982) study. The upper panel shows the results from conditions that did not include a specific consequence for nonreinforced correct responses, and the lower panel shows the results from the corresponding conditions in which nonreinforced correct responses had explicitly arranged consequences.

a systematic comparison of human and non-human performance in symbolic matching-to-sample or signal-detection procedures is possible. Second, the data suggest that consequences for errors and nonreinforced correct responses in such procedures deserve attention by researchers, in particular when humans serve as subjects. Finally, these procedures might provide a useful framework for more general investigations of human choice behavior. Experiment 1 showed clear and consistent effects of the relative frequency of reinforcement, and it seems likely that other variables, such as the magnitude or delay of reinforcers

and punishers, could be investigated in a similar manner.

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APPENDIX

The responses to the left and right keys following S_1 and S_2 stimulus presentations (B_w , B_x , B_y , and B_z) and the reinforcers obtained in the left and right alternatives (R_w and R_z) made by each subject in each condition of each experiment.

Subject	Easy stimulus pair						Difficult stimulus pair					
	B_w	B_x	B_y	B_z	R_w	R_z	B_w	B_x	B_y	B_z	R_w	R_z
Experiment 1												
Condition A												
1	57	19	24	50	31	32	60	14	30	46	31	28
2	57	18	36	39	26	30	29	45	28	48	19	20
3	47	28	25	50	32	28	34	42	28	46	26	23
4	66	9	32	43	29	30	55	21	28	46	28	27
5	52	23	33	42	28	30	37	39	29	45	25	24
6	47	28	26	49	27	27	43	31	34	42	27	27
Condition B												
1	58	19	17	56	9	49	43	31	28	48	9	43
2	35	39	9	67	10	48	14	61	13	62	8	41
3	46	28	15	61	11	50	23	52	8	67	9	52
4	59	16	15	60	11	53	43	33	17	57	9	46
5	54	22	21	53	9	45	32	43	10	65	10	47
6	62	13	22	53	10	49	48	27	28	47	9	43
Condition C												
1	73	2	26	49	66	13	66	10	37	37	55	12
2	52	23	30	45	46	8	32	43	26	49	30	7
3	61	14	40	35	55	10	44	31	34	41	38	7
4	61	15	40	34	46	7	62	13	43	32	49	9
5	60	14	51	25	52	10	47	28	30	45	42	9
6	64	12	22	52	59	11	51	24	43	32	44	8
Experiment 2												
Condition A												
1	58	16	17	59	33	36	43	33	30	44	27	26
2	56	18	21	55	32	35	47	30	23	50	28	27
3	49	25	14	62	32	33	49	26	30	45	27	25
4	60	15	40	35	24	25	37	38	35	40	18	19
5	50	25	27	48	30	31	43	32	29	46	25	24
6	51	25	18	56	34	31	42	34	21	53	23	24
Condition B												
1	23	1	50	76	22	23	15	11	54	70	14	15
2	21	3	49	77	19	21	17	8	47	78	14	15
3	22	2	45	81	21	24	21	4	64	61	18	20
4	19	6	43	82	17	16	13	13	41	83	11	10
5	17	8	54	71	16	18	14	12	50	74	14	14
6	20	5	57	68	16	17	17	10	51	72	16	15
Condition C												
1	76	49	2	23	21	21	58	67	10	15	15	11
2	76	49	9	16	15	14	61	63	4	22	19	20
3	93	30	1	26	23	24	76	50	5	19	19	18
4	90	34	6	20	17	20	47	78	13	12	10	11
5	74	52	6	18	17	17	64	61	8	17	16	15
6	70	54	7	19	20	19	78	46	8	18	16	16
Experiment 3												
Condition A												
1	71	5	9	65	26	21	41	35	4	70	17	22
2	37	39	27	47	11	14	35	40	28	47	11	15
3	42	33	31	44	15	17	47	28	23	52	17	19
4	47	27	18	58	17	19	40	35	22	53	10	21
5	55	20	27	48	17	14	64	11	17	58	19	19
6	61	15	28	46	17	22	61	15	43	31	24	10

APPENDIX

(Continued)

Subject	Easy stimulus pair						Difficult stimulus pair					
	B_w	B_x	B_y	B_z	R_w	R_z	B_w	B_x	B_y	B_z	R_w	R_z
Condition B												
1	24	2	25	99	9	37	20	4	29	97	6	32
2	13	12	32	93	5	27	10	14	38	88	2	19
3	17	9	34	90	7	33	21	3	34	92	7	29
4	12	14	40	84	8	26	18	7	37	88	5	25
5	13	12	50	75	7	20	18	6	32	94	4	27
6	19	5	79	47	6	13	17	7	44	82	5	35
Condition C												
1	66	60	0	24	23	7	108	16	2	24	32	12
2	72	54	11	13	21	4	69	56	12	13	26	6
3	75	51	3	21	24	7	94	32	2	22	30	11
4	77	48	8	17	27	8	91	33	7	19	33	10
5	88	37	8	17	27	5	102	23	6	19	36	2
6	93	33	11	13	31	1	93	33	10	14	32	3
Experiment 4												
Condition A												
1	61	15	46	28	13	13	32	40	27	51	11	18
2	43	33	31	43	10	16	30	45	23	52	11	23
3	52	24	42	32	17	7	37	39	43	31	16	9
4	64	11	39	36	20	11	60	15	37	38	18	11
5	66	8	32	44	16	16	49	26	18	57	18	24
6	46	30	9	65	18	19	35	39	14	62	11	23
Condition B												
1	126	0	24	0	40	0	121	3	23	3	44	0
2	120	5	19	6	35	2	117	7	19	7	42	3
3	77	49	16	8	28	4	66	60	13	11	23	4
4	109	17	11	13	35	6	99	27	16	8	34	6
5	122	2	21	5	35	0	99	26	14	11	27	2
6	106	19	20	5	26	2	101	24	18	7	22	1
Condition C												
1	6	19	41	84	3	22	10	16	18	106	3	36
2	7	20	1	122	3	41	7	17	7	119	5	42
3	16	9	54	71	9	21	7	18	44	81	3	28
4	1	10	37	88	4	34	13	11	45	81	4	28
5	1	24	10	115	0	41	2	2	4	121	0	40
6	5	21	6	118	3	28	5	19	13	113	2	45