QUANTITATIVE ANALYSES OF MATCHING-TO-SAMPLE PERFORMANCE

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Six pigeons performed a simultaneous matching-to-sample (MTS) task involving patterns of dots on a liquid-crystal display. Two samples and two comparisons differed in terms of the density of pixels visible through pecking keys mounted in front of the display. Selections of Comparison 1 after Sample 1, and of Comparison 2 after Sample 2, produced intermittent access to food, and errors always produced a time-out. The disparity between the samples and between the comparisons varied across sets of conditions. The ratio of food deliveries for the two correct responses varied over a wide range within each set of conditions, and one condition arranged extinction for correct responses following Sample 1. The quantitative models proposed by Davison and Tustin (1978), Alsop (1991), and Davison (1991) failed to predict performance in some extreme reinforcer-ratio conditions because comparison choice approached indifference (and strong position biases emerged) when the sample clearly signaled a low (or zero) rate of reinforcement. An alternative conceptualization of the reinforcement contingencies operating in MTS tasks is advanced and was supported by further analyses of the data. This model relates the differential responding between the comparisons following each sample to the differential reinforcement for correct responses following that sample.

Key words: matching-to-sample, signal-detection, discriminated operant, quantitative models, reinforcement contingencies, key peck, pigeons

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Quantitative models of the discriminated operant are mathematical expressions of the roles played by each of the terms in the three-term contingency (i.e., discriminative stimulus, response, and reinforcer) in determining the probability of that operant occurring. Inspired by empirical evidence for the functional equivalence of varying each of the three terms, some behavior analysts have pursued a unified descriptive account in which parameters measuring each term remain invariant with changes in parameters measuring other terms (see Davison & Nevin, 1999, for a review of these studies). The present experiment contributes to this literature by comparing the predictions offered by two such models with behavior under novel experimental conditions. One model was proposed by Davison and Tustin (1978), and the other by Alsop (1991) and Davison (1991).

Davison and Tustin's (1978) model was offered originally as a description of independent-variable effects in the standard "yes-no" signal-detection procedure, and it has been investigated extensively in analogues of this procedure using nonhuman subjects. It has also been applied to a set of procedures known as conditional discriminations where a choice between two discriminated operants usually is presented simultaneously and other (conditional) stimuli signal the contingencies of reinforcement operating for each. The matching-to-sample (MTS) task is a conditional discrimination arranged as discrete trials. Here, each trial starts with the presentation of one of two sample stimuli (S_1 or S_2) on a central operandum. A response to the sample advances the trial by presenting a choice between two comparison stimuli (C_1 and C_2) on separate operanda. The sample presented on a trial, and the positions of C_1 and C_2 (e.g., on left and right operanda), are randomly determined on each trial. Responding on C_1 is reinforced in the presence of S_1, and responding on C_2 is reinforced in the presence of S_2. Choosing either C_2 on S_1 trials, or C_1 on S_2 trials, is an error and produces a time-out. This paradigm is often illustrated as a 2×2 matrix and is described using specific notation (see Figure 1). The terms B_w and B_x refer to the

comparison stimuli

Fig. 1. A matrix defining the notation used in the models of MTS performance offered by Davison and Tustin (1978), Alsop (1991), and Davison (1991). S_1 and S_2 denote Sample 1 and Sample 2, C_1 and C_2 denote Comparison 1 and Comparison 2, and Rft and Ext denote reinforcement and extinction.

frequency of correct and incorrect responses, respectively, on S_1 trials; B_y and B_z to the frequency of incorrect and correct responses, respectively, on S_2 trials; and R_w and R_z to the frequency of reinforcers obtained for B_w and B_z responses, respectively.

Davison and Tustin (1978) arrived at essentially the same bias-free measure of sample-stimulus discriminability as that of classical signal-detection theory (d', Green & Swets, 1966) by adapting an empirically-validated quantitative description of simple choice known as the generalized matching law (GML, Baum, 1974, 1979). They argued that choice between responding ''yes'' or ''no'' in the presence and absence of the signal would be biased toward either alternative to a degree that depended on the discriminability of the signal from noise and the history of reinforcement for each response (see Nevin, Jenkins, Whittaker & Yarensky, 1982, for the same argument). The GML was used to describe the effects of both the frequency with which responses had been reinforced and inherent biases, and another parameter was added to account for the bias that was attributable to discriminating the signal from noise (or sample stimuli). Davison and Tustin's model involved two equations, one predicting choice on signal or S_1 trials, and another

predicting choice on noise or S_2 trials. On S_1 trials,

$$\frac{B_w}{B_x} = cd\left(\frac{R_w}{R_z}\right)^a, \qquad (1a)$$

and on S_2 trials,

$$\frac{B_y}{B_z} = c\frac{1}{d}\left(\frac{R_w}{R_z}\right)^a, \qquad (1b)$$

where B_w, B_x, B_y, B_z, R_w and R_z are as defined in Figure 1. The free parameters (a and c) modify the effects of the obtained reinforcer ratio in the same manner as they do in the GML. The parameter a is called sensitivity to reinforcement (Lobb & Davison, 1975) and measures the extent of change in response ratios when the reinforcer-frequency ratio (R_w/R_z) is varied. The parameter c is called inherent bias and measures any preference for one response over the other that remains constant as this reinforcer ratio is varied. Their parameter measuring signal/sample discriminability (d) measures the bias toward C_1 on S_1 trials, and toward C_2 on S_2 trials, and is theoretically independent of the terms describing response bias (i.e., inherent bias and some sensitivity to the obtained reinforcer ratio). Values of each parameter are usually found by fitting logarithmic transformations of Equations 1a and 1b to log response ratios from a number of conditions varying the reinforcer ratio (R_w/R_z). Because log response ratios are predicted to be a linear function of the log obtained reinforcer ratio, the slopes of best-fitting lines through each set of data provide estimates of a, and calculations involving their y-intercepts provide estimates of c and d (albeit the logarithms of these parameters). Thus, the following two equations are fitted by linear regression: On S_1 trials,

$$\log\frac{B_w}{B_x} = a_{r1}\log\left(\frac{R_w}{R_z}\right) + \log c + \log d, \quad (2a)$$

and on S_2 trials,

$$\log\frac{B_y}{B_z} = a_{r2}\log\left(\frac{R_w}{R_z}\right) + \log c - \log d. \quad (2b)$$

The value of log c can be found by averaging the y-intercepts of the two fitted lines, and log d can be found by halving the difference between them. Alternatively, if a_{r1} is assumed to equal a_{r2}, then an estimate of log d

from a single condition with any reinforcer ratio (i.e., a point estimate) can be found by subtracting Equation 2b from Equation 2a and dividing both sides by two. Similarly, a point estimate of response bias that is theoretically independent of sample discriminability arises when Equations 2a and 2b are added because log *d* drops out in this manipulation (see Davison & Tustin for these workings).

Davison and Tustin's (1978) model has accurately described the data obtained in a range of signal-detection and MTS procedures, and when a number of independent variables have been studied (see Davison & McCarthy, 1988, and Davison & Nevin, 1999, for reviews). In addition, their point estimate of sample discriminability (log *d*) has been used extensively in models of performance in delayed MTS (DMTS) tasks where memorial processes are inferred because comparison stimuli are presented some time after the sample appeared (e.g., Harnett, McCarthy & Davison, 1984; White & McKenzie, 1982; White & Wixted, 1999). Davison and Tustin's model, however, makes a number of important assumptions that predict certain parameter invariances that have not always been supported by empirical research (see Alsop, 1991; Alsop & Davison, 1991; Davison & Nevin; Godfrey & Davison, 1999; Jones & White, 1992 for a discussion of these violations). A number of theoretical short-comings that limit the generality of the model have been identified as well (Alsop, 1991; Davison, 1991; Godfrey & Davison, 1998). Of particular concern has been its application to MTS tasks where, unlike signal-detection procedures, the disparity of the comparison stimuli could vary and have similar effects as the disparity of the samples on the relative frequency of errors (i.e., B_w/B_x and B_y/B_z ratios). Because the model has no term measuring comparison-stimulus discriminability, log *d* cannot be a pure measure of sample discriminability, and the model cannot be complete.

Alsop (1991) and Davison (1991) each proposed an alternative to Davison and Tustin's (1978) model that addressed these and other shortcomings. (Their models are identical when two samples and two comparisons are arranged and so will be regarded here as one and the same: the Alsop–Davison, 1991, model.) Both authors logically extended Davison

and Jenkins' (1985) model of simple choice—an alternative to the GML that accounts for varying *a* values in terms of varying degrees of contingency discriminability—and offered a measure of sample discriminability and a measure of comparison (or contingency) discriminability that were conceptually similar but theoretically independent. They argued that the values of these measures, together with the obtained reinforcer ratios on S_1 and S_2 trials, determine the reinforcer ratios that response ratios on S_1 and S_2 trials will strictly match. These "effective" or "perceived" reinforcer ratios are predicted to deviate from those obtained whenever sample discriminability (stimulus-response discriminability, d_s, in their terms) or comparison discriminability (response-reinforcer or contingency discriminability, d_r, in their terms) is less than perfect (see Alsop & Davison, 1991, Alsop & Davison, 1992, or Davison & Nevin, 1999, for further explanation). The following two equations describe how sample and comparison discriminabilities are presumed to determine effective reinforcer ratios and, therefore, response ratios in the standard MTS task: On S_1 trials,

$$\frac{B_w}{B_x} = c\frac{d_s d_r R_w + R_z}{d_r R_z + d_s R_w}, \tag{3a}$$

and on S_2 trials,

$$\frac{B_y}{B_z} = c\frac{d_r R_w + d_s R_z}{d_s d_r R_z + R_w}, \tag{3b}$$

where all notation is as already defined. The values of d_s and d_r range from 1.0, when the sample and the comparison stimuli, respectively, are indiscriminable, to infinite, when both are perfectly discriminable. When $d_s = 1.0$, choice on S_1 and S_2 trials will be identical and will depend on d_r, the reinforcer ratio, and inherent biases in the manner described by Davison and Jenkins (1985). That is, Equations 3a and 3b will both reduce to the equation describing Davison and Jenkins' model for simple choice. When $d_r = 1.0$, choice on S_1 and S_2 trials will be identical, remain constant with variations of the reinforcer ratio, and reflect only inherent biases (measured by *c*) because no ability to discriminate the responses (or comparison stimuli) renders an ability to discriminate the samples unable to control differential responding.

Various differences between the Davison and Tustin (1978) and the Alsop–Davison (1991) models are worth highlighting. First, Alsop and Davison make a distinction between sample-stimulus discriminability (d_s) as a theoretical parameter and the discriminability measured in performance by applying Equations 1a and 1b (and the point estimate of log d) because the latter will be affected by contingency discriminability (d_r). Second, the Alsop–Davison model cannot be algebraically reduced to offer point estimates of sample discriminability (d_s) and contingency discriminability (d_r), although Davison and Nevin (1999) do consider the conditions under which Davison and Tustin's point estimates of sample discriminability (log d) and response bias (log b) will equal d_s and d_r, respectively. Third, their Equations 3a and 3b predict an ogival (i.e., non-linear) relation between log response and log reinforcer ratios, so a curve-fitting program is required to find estimates of d_s and d_r from conditions varying the reinforcer ratio (R_w/R_z). Fourth, their model predicts the interactions between d and a in Equations 1a and 1b that have been reported in empirical studies and were problematic for Davison and Tustin's model. Finally, Davison and Nevin have shown that the Alsop–Davison model can be logically generalized to variants of the MTS task that are clearly beyond the scope of Davison and Tustin's model (e.g., arranging more than two samples and comparisons, scheduling reinforcers for responses usually deemed errors, DMTS, delaying reinforcers for correct responses) and that it generates predictions in those procedures that have largely been borne out in experimental investigations.

Despite substantial differences between these models, the equations describing each provide similar predictions of response ratios (i.e., B_w/B_x and B_y/B_z) over the range of reinforcer ratios typically studied in MTS tasks (i.e., 1:9 to 9:1). Furthermore, the sets of obtained data supporting these predictions will be essentially indistinguishable from one another over this range given the usual degree of noise seen in MTS data. This similarity between predictions has been illustrated graphically in Figure 2, where sets of theoretical functions from each model are shown. The solid curves show the log response ratios on S_1 and S_2 trials (i.e., log B_w/B_x and log $B_y/$

B_z) that were predicted by the Alsop–Davison (1991) model (logarithmic transforms of Equations 3a and 3b) using different values of d_s and d_r, and assuming no inherent bias ($c = 1$). Davison and Tustin's (1978) Equations 2a and 2b were fitted to the Alsop–Davison predictions, and the resultant best-fitting lines are shown over each set of ogives. The vertical lines drawn in each panel depict the lowest and highest log reinforcer ratios (a measure of the differential between rates of reinforcement for the two correct responses) that are usually arranged. This figure shows that the descriptive accuracy of the models would be better compared by including conditions with more extreme reinforcer ratios than are normal, and arranging disparities between samples and between comparisons that produced intermediary values of d_s and d_r. On the one hand, Davison and Tustin's model predicts that log response-ratios on S_1 and S_2 trials (i.e., log B_w/B_x and log B_y/B_z) will remain different, and that both will continue increasing at a constant rate, with increasing reinforcement-rate differentials, and, thus, increasing log reinforcer ratios. The Alsop–Davison model, on the other hand, predicts that while log response ratios on S_1 and S_2 trials will generally increase with increasing log reinforcer ratios, this increase will progressively lessen and asymptotes will be approached. Both response ratios (log B_w/B_x and log B_y/B_z) are predicted to approach an asymptote of one value when R_w greatly exceeds R_z, and approach an asymptote of another value when R_z greatly exceeds R_w. Consequently, the two response ratios are predicted to draw closer together, the more extreme the reinforcer ratio becomes. The present experiment, therefore, assessed the predictive validity of each model by varying the reinforcer ratio (or the reinforcement-rate differentials) over a range that was wider than normal, and at various disparities between the samples and between the comparisons.

The two models being compared here also predict specific and different results in a condition where correct responses on either S_1 or S_2 trials are never reinforced (i.e., extinction is arranged for either B_w or B_z). For example, when R_w is set to 0 in Equations 1a and 1b, Davison and Tustin's (1978) model predicts that responding on S_1 and S_2 trials
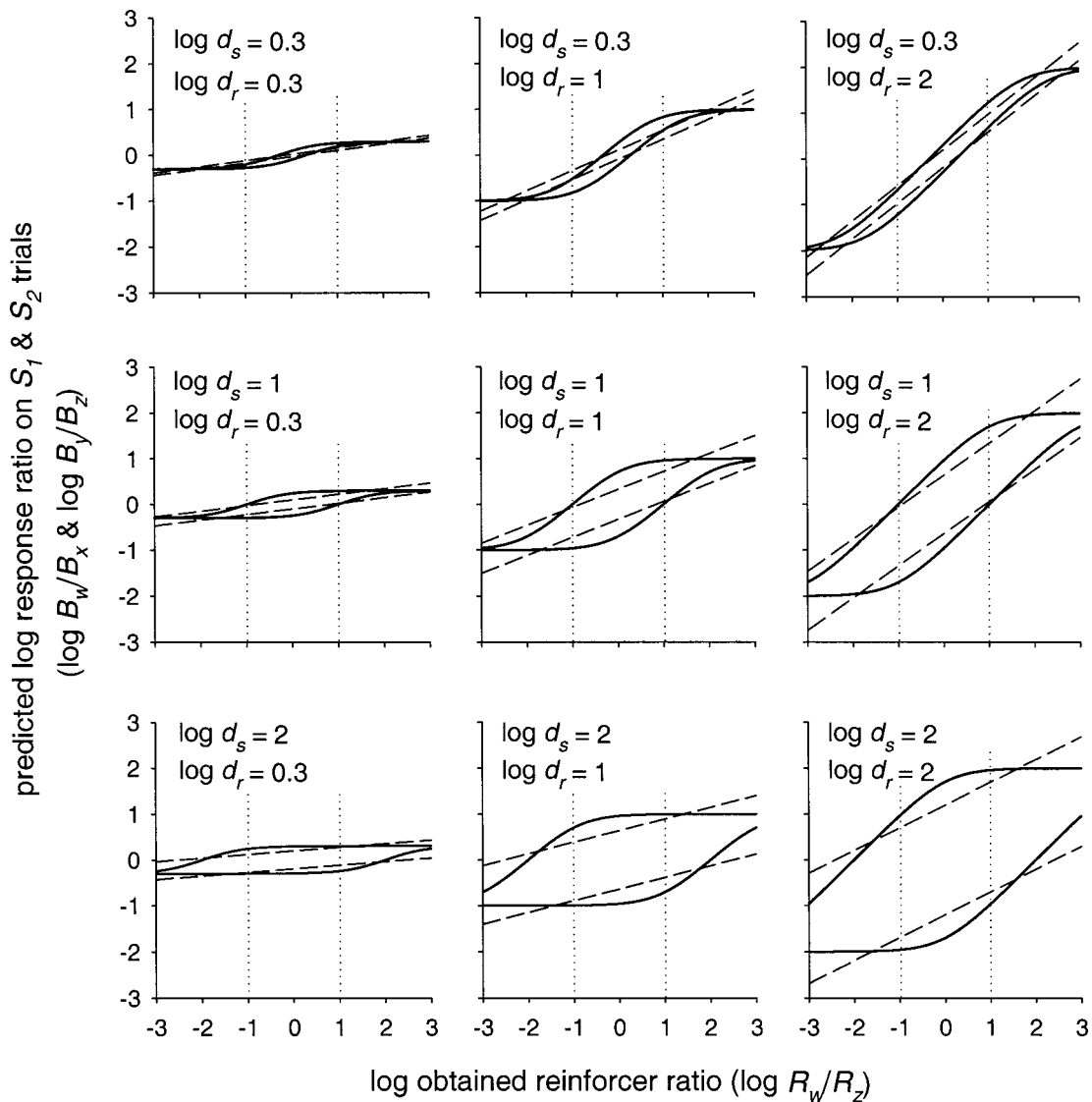
Fig. 2.   Theoretical functions depicting the log response ratios on S_1 and S_2 trials (i.e., log B_w/B_x and log B_y/B_z) that are predicted at varying log reinforcer ratios by the Alsop–Davison (1991) model (logarithmic transforms of Equations 3a and 3b) and the Davison and Tustin (1978) model (Equations 2a and 2b). The Alsop–Davison predictions were generated using different values of d_s and d_r, and assuming no inherent bias ($c = 1$). They are shown as solid curves. Davison and Tustin's model was fitted to the Alsop–Davison predictions, and the resultant best-fitting lines are shown over each set of curves. The vertical lines drawn in each panel depict the lowest and highest reinforcer ratios that are usually arranged.

will be identical and exclusive to C_2 (i.e., B_w/B_x and $B_y/B_z = 0$) at all values of *d, a,* and *c.* According to the Alsop–Davison (1991) model (Equations 3a and 3b), however, responding to C_1 will not cease on either S_1 or S_2 trials when d_r is less than infinity; instead both response ratios will show equal biases for C_2, and reach an asymptote at a value represent-

ing c/d_r. Therefore, the present experiment also included a condition where extinction was arranged for B_w responses in order to assess and compare these predictions. As it happened, responses to C_1 *did* continue in this condition, so a further test of the Alsop–Davison model was conducted by comparing the obtained S_1 and S_2 response-ratios (i.e., $B_w/$

B_x and B_y/B_z) with those predicted when the values of d_r and c found from fits to earlier conditions were used in calculations.

The MTS task arranged here is similar to that reported by Godfrey and Davison (1998), and the rationale is similar to that used by Davison and Jones (1995). Davison and Jones compared predictions derived from the GML with those derived from Davison and Jenkins' (1985) model when extreme reinforcer ratios were arranged in a simple choice situation; namely, a concurrent schedule. They found significant nonlinearity between log response and log reinforcer ratios in the manner predicted by Davison and Jenkins. The present experiment simply compares the predictions of models that are applications of the GML and the Davison and Jenkins model. In doing so, however, it is also possible to assess whether these models of choice can indeed be applied to MTS tasks in the ways that have been suggested (e.g., Davison & Nevin, 1999).

METHOD

Subjects

Six homing pigeons were maintained at 85% ± 15 g of their free-feeding body weights by supplementary feeding of mixed grain after each training session. Unrestricted access to water and grit was provided. All pigeons had prior training on a MTS task involving bright- and dim-yellow sample stimuli, red and green comparison stimuli, and delays between presentation of sample and comparison stimuli. Pigeon 16 died midway through Condition 20. The data collected prior to this condition have been analyzed and reported.

Apparatus

Six identical cages served as both holding cages and the environments in which experimental sessions were conducted. These cages were in a large room containing approximately 90 other similar cages. The room had no windows and was lit with fluorescent tubes according to a 14:10 hr light/dark cycle reversed relative to normal daylight hours.

Each cage measured 370 mm wide, 380 mm deep and 380 mm high. The left and rear walls were constructed of galvanized iron sheets and the floor, ceiling, and front wall consisted of galvanized rods spaced 50 mm apart. Two wooden perches inside the cage were arranged at a right angle to enable access to water and grit, and access to an interface panel mounted on the right wall. The interface panel consisted of three response keys and an aperture through which wheat could be delivered. The response keys were made of transparent plexiglass, were 25 mm in diameter, were arranged horizontally (47 mm between centers) and centered on the panel, and were mounted 215 mm above the perch. When activated, the keys could be operated by pecks exceeding about 0.1 N. An aperture measuring 52 mm wide and 52 mm high was located below the center key and 65 mm above the perch. Presentations of the food hopper through this aperture were accompanied by illumination of the aperture and extinction of all key stimuli.

A monochromatic liquid-crystal display (LCD) module of the sort used in electronic typewriters was mounted behind the response keys with its imaging surface 6 mm from the rear of the keys. This LCD presented black pixels (0.49 mm square) on a green background and was backlit with white light. Three equally sized regions of the display, each containing 5,120 pixels (80 pixels wide by 64 pixels high), were controlled independently to present different images behind each key. The backlight illuminated the entire display and, therefore, all three keys simultaneously. Approximately 1,452 pixels could be viewed through each response key.

The control of the LCD modules and all experimental contingencies was arranged on an IBM®-compatible computer running a program written in Turbo Pascal™ and remotely situated from the experimental cages. This computer also recorded the time and type of all stimulus events and key pecks for later analyses.

Procedure

As all of the pigeons had received extensive training on an MTS task prior to this study, they were introduced immediately to a variant of the procedure that operated for the remainder of the experiment.

Each pigeon received one training session per day, 7 days per week. The sessions for each pigeon occurred successively (starting with Pigeon 11 and finishing with Pigeon 16) and while other unrelated experiments were running. Pigeon 11's session began at 1:00

a.m., one hour after the lights in the room were lit, and Pigeon 16's session began at around 5:10 a.m., nine hours before the lights were extinguished. No person entered the room while sessions were in progress.

Each session involved a discrete-trials MTS task. A trial started with the illumination of the LCD by the backlight and the appearance of a random-dot pattern on the center key. This pattern was very likely unique on each trial because it was generated by the computer sweeping across 5,120 pixels and interrogating either of two probabilities of lighting each pixel (a or b in Table 1). This resulted in patterns of dots that were either relatively sparsely or densely distributed over the area behind the response key. The more sparse patterns were designated instances of S_1 and the more dense patterns were designated instances of S_2. (The density of lit pixels also determined the luminance of the key, so it is possible that the brightness of the two samples was the functional dimension exerting control.) The presentation of S_1 or S_2 on a trial was random. A single response to either stimulus resulted in two other random-dot patterns appearing on the side keys (i.e., a simultaneous MTS task because the sample stimulus and the comparison stimuli were presented simultaneously). One pattern was designated C_1, was generated by lighting a pixel with a relatively low probability (c in Table 1), and produced a sparse pattern. The other pattern was designated C_2, was generated with a higher probability (d in Table 1), and produced a denser pattern. Thus, as with the samples, the actual patterns representing comparison stimuli were likely unique on each trial. The location of the two patterns behind the left and right keys was randomized across trials. A response to either side key extinguished the backlight and all pixels on the LCD. Responses to the side key presenting C_1 on trials where the sample was S_1, and responses to the side key presenting C_2 on S_2 trials were deemed correct (B_w and B_z, respectively, in Figure 1). These responses were occasionally reinforced with 3-s access to the food hopper. Incorrect responses (responses to C_2 on S_1 trials and to C_1 on S_2 trials, or B_x and B_y, respectively, in Figure 1) and correct responses for which no food access was scheduled both earned a 3-s time-out from the task. Thus, a correction procedure

was not arranged. A 5-s intertrial interval then ensued before the next trial was presented. Sessions ended in blackout after 45 minutes had elapsed, or after 50 reinforcers had been obtained, whichever occurred sooner.

Access to the food hopper for correct responses was scheduled as follows. Before the first trial of a session, and after every presentation of the food hopper throughout the session, food access was allocated to the next correct response on an S_1 trial (B_w in Figure 1) with probability x. If the reinforcer was not allocated to the next B_w response, then it was allocated to the next correct response on an S_2 trial (B_z in Figure 1). Each arranged reinforcer remained set up, and no other reinforcers were arranged until that reinforcer was obtained. For example, if the first reinforcer of a session was set up for the next B_w response, any subsequent B_z responses would go unreinforced until a B_w response was made, the arranged reinforcer was delivered, and a reinforcer was set up for the next B_z. This procedure is analogous to dependent scheduling in concurrent schedules of reinforcement (Stubbs & Pliskoff, 1969) and ensures that the reinforcer ratio obtained for the two correct responses (i.e., R_w/R_z in Figure 1) closely approximates the ratio that was arranged.

Previous studies that have arranged similar MTS procedures and varied the same procedural parameters (e.g., Godfrey & Davison, 1998, 1999; Jones & Davison, 1998) have found that percentage correct scores and measures of response bias usually stabilize within 20 sessions of a condition change. In the present experiment, therefore, experimental conditions remained in effect for at least 40 sessions so that data from the last 20 sessions could be used in analyses. In addition, conditions lasted until all pigeons had received at least 20 reinforcers on the leaner alternative and were conducted longer if new sets of sample and/or comparison stimuli were being used. Requiring that some minimum number of reinforcers were obtained meant that conditions arranging the more extreme reinforcer ratios were conducted longer than those arranging less extreme ratios.

Table 1 shows the probabilities used to generate S_1, S_2, C_1, and C_2 (i.e., a, b, c, and d, respectively), the probability of assigning a re-

Table 1

The sequence of conditions, the probabilities used to generate the sample stimuli (*a* & *b*) and the comparison stimuli (*c* & *d*), the probability of assigning the next reinforcer to a correct S_1 response (*x*), the arranged ratio of S_1/S_2 reinforcers (*Arr* R_w:R_z), and the number of training sessions in each condition of the present experiment. PT refers to Preliminary Training.

Part	Condition	*a*	*b*	*c*	*d*	*x*	Arr. R_2:R_z	Sessions
PT	1	.3	.7	.3	.7	.5	1:1	150
PT	2					.9	9:1	75
PT	3					.5	1:1	75
1	4	.3	.7	.3	.7	.9	9:1	40
	5					.048	1:20	40
	6					.976	40:1	40
	7					.012	1:80	85
	20					.5	1:1	113
	21					.994	160:1	116
	22					.333	1:2	42
	23					.8	4:1	40
	24					.1	1:9	59
2	8	.3	.7	.4	.6	.5	1:1	107
	9					.9	9:1	40
	10					.048	1:20	40
	11					.976	40:1	48
	12					.012	1:80	40
	13					.994	160:1	78
	14					.333	1:2	42
	15					.8	4:1	40
	16					.1	1:9	43
	17[a]					.9	9:1	40
	18[a]					.5	1:1	40
	19					0	0:1	150
3	25	.45	.55	.3	.7	.012	1:80	70
	26					.976	40:1	45

[a] Replication.

inforcer to the next B_w response (i.e., *x*), and the number of training sessions in each condition. In preliminary training conditions and those of Part 1, samples and comparisons were of intermediate disparity. In the conditions of Part 2, sample disparity remained unchanged, but comparison disparity was reduced. In Part 3, sample disparity was reduced and an intermediate comparison disparity was arranged. Within each part, *x* varied so as to vary the ratio of reinforcers for the two correct responses (R_w and R_z in Figure 1) and, therefore, the reinforcement-rate differential. Nine different reinforcer ratios were arranged in Parts 1 and 2, and two were arranged in Part 3. Those in Parts 1 and 2 ranged from 1:80 to 160:1, and those in Part 3 from 1:80 to 40:1. Part 2 included a condition where extinction was arranged for B_w responses and continuous reinforcement for B_z responses (Condition 19). Finally, two conditions in Part 2 were replicated: Condition 17 was a replication of Condition 9, and Condition 18 was a replication of Condition 8.

RESULTS

Figure 3 shows matching accuracies for each pigeon in each condition except Condition 19. The proportion of trials on which the correct comparison was chosen is plotted as a function of the relative rate of reinforcement obtained for correct C_1 responses in a condition [i.e., $R_w/(R_w + R_z)$]. The results of the two replication conditions (Conditions 17 and 18) are denoted by unfilled triangles. Proportion correct exceeded .5 (the value expected if the samples had not influenced comparison choice) for all pigeons in all conditions, although there were clear differences between pigeons. Matching accuracies were generally highest in Part 1 (where sample and comparison disparity were both highest), lowest in Part 3 (where sample disparity was low-
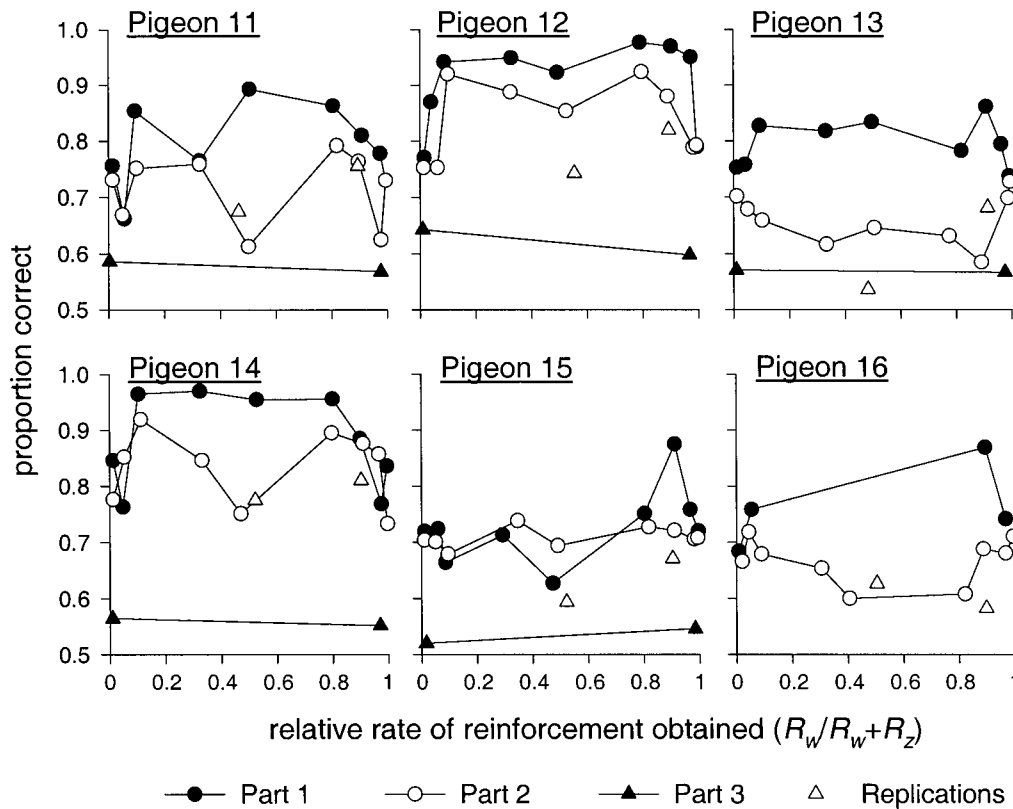
Fig. 3. Proportion correct scores for each pigeon in each condition plotted as a function of the relative rate of reinforcement obtained for correct S_1 responses in that condition. The results of the two conditions that replicated others (Conditions 17 and 18) are denoted by triangles.

est and comparison disparity was highest), and intermediate in Part 2 (where sample disparity was highest and comparison disparity was lowest). Accuracies varied widely within parts, but there appeared to be no systematic relation between accuracy and the relative rate of reinforcement obtained for C_1 responses across pigeons. Pair-wise comparisons within pigeons showed that the data from Conditions 17 and 9, and those from Condition 18 and 8, were not systematically different. These results confirm that variations of the disparity between samples and comparisons, and variations of the probabilities of reinforcement for the two responses, were effective. In addition, the replication conditions show that replicable and steady-state performances were likely obtained from the final 20 sessions of experimental conditions.

Figure 4 shows data plotted in a manner appropriate for fitting the two models being

compared. For each pigeon in each condition of Parts 1 and 2, Figure 4 plots log C_1/C_2 response ratios on S_1 trials (i.e., log B_w/B_x), and on S_2 trials (i.e., log B_y/B_z), as a function of the log reinforcer ratio obtained in that condition (i.e., log R_w/R_z). This figure shows that the log B_w/B_x ratios were consistently higher than the log B_y/B_z ratios at each reinforcer ratio, and, therefore, that choice was always more biased toward C_1 on S_1 trials than on S_2 trials, and more biased toward C_2 on S_2 trials than on S_1 trials. The figure also shows that S_1 and S_2 response ratios varied systematically with the ratio of reinforcers obtained for the two types of correct responses. In both parts, as the log ratio of reinforcers (i.e., log R_w/R_z) increased, choice on both S_1 and S_2 trials generally became more biased towards C_1 (i.e., B_w and B_y responses). This result is the usual finding when reinforcer-frequency ratios are varied in MTS tasks, and

PART 1

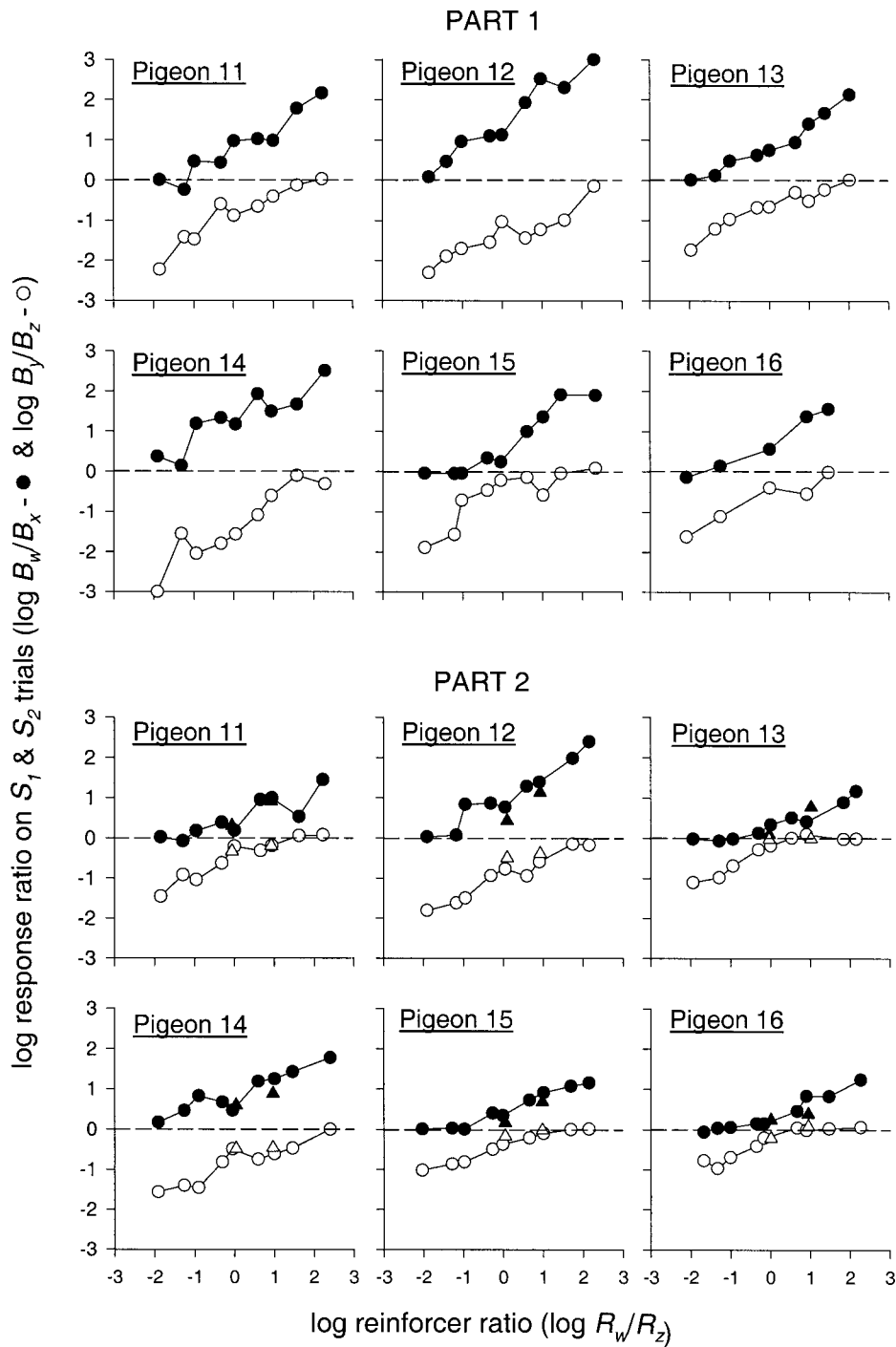## PART 2

Fig. 4. Log C_1/C_2 response ratios on S_1 trials (i.e., log B_w/B_x), and on S_2 trials (i.e., log B_y/B_z) in each condition of Part 1 (top panel) and Part 2 (bottom panel), as a function of the log reinforcer-ratio obtained (i.e., log R_w/R_z) in those conditions. The results of the two conditions that replicated others (Conditions 17 and 18) are denoted by triangles.

so suggests that typical MTS behavior was obtained in the present study.

However, another feature of the data in Figure 4 is not typical. In the majority of studies where reinforcer ratios are varied in a MTS (or DMTS) task, instances of more errors than correct responses on either S_1 or S_2 trials have been reported when one response is reinforced more frequently than the other and, thus, the reinforcer ratio has deviated from unity. (This effect is likely to depend on the absence of a correction procedure following errors because a number of studies have shown an overall improvement in matching accuracy [a "differential-outcomes effect" or DOE] when the two correct responses are reinforced at different frequencies and errors are followed by the repetition of a trial [e.g., Urcuioli, 1990, 1991]. Peterson and her colleagues [Peterson & Trapold, 1980; Peterson, Wheeler, & Trapold, 1980] have also argued that a correction procedure may be crucial to obtaining a DOE when differential reinforcement probabilities follow the two correct responses.) In the notation used here, B_x often exceeds B_w when R_z exceeds R_w (resulting in negative values of log B_w/B_x at negative values of log R_w/R_z), and B_y often exceeds B_z when R_w exceeds R_z (resulting in positive values of log B_y/B_z at positive values of log R_w/R_z). In both parts of the present experiment, however, negative values of log B_w/B_x and positive values of log B_y/B_z seldom occurred. In Part 1 (top panel in Figure 4), log B_w/B_x was negative when log R_w/R_z was negative in only 5 out of 26 cases, and log B_y/B_z was positive when log R_w/R_z was positive in only 3 out of 24 cases. In Part 2 (bottom panel in Figure 4), these frequencies were 5 from 29, and 9 from 37. Moreover, whenever log B_w/B_x was negative and log B_y/B_z was positive, their values were small. (The median log B_w/B_x value when it was negative was -0.05, and the median log B_y/B_z value when it was positive was 0.05. These values correspond to response ratios of 1:1.13 and 1.11:1, respectively.) Thus, although both response ratios generally became more biased as the obtained reinforcer ratio deviated from unity, this increase in bias lessened as the reinforcer ratio became more extreme. In Part 2, and to a lesser extent in Part 1, the paths of log B_w/B_x ratios point to asymptotes around zero as the log reinforcer ratio decreases, and the paths of log B_y/B_z

ratios point to asymptotes around zero as the reinforcer ratio increases. Put another way, choice between C_1 and C_2 on S_1 trials approached indifference as the frequency of reinforcers for B_w responses (i.e., R_w) decreased, and choice on S_2 trials approached indifference as the frequency of reinforcers for B_z responses (i.e., R_z) decreased.

Davison and Tustin's (1978) model and the Alsop–Davison (1991) model were both fitted to the data shown in Figure 4 (excluding data from replication conditions) using the Optimizer in Quattro Pro for Windows®. This is an iterative curve-fitting program that employs a modified Newtonian algorithm and can find solutions to linear and nonlinear equations. Fitting the Davison and Tustin model involved finding the values of log c, log d, and a in Equations 2a and 2b that minimized the sum of squared deviations between the obtained log response ratios and the log response ratios predicted by these equations. For each set of data, the two equations were fitted simultaneously and no constraints were placed on the values that could be taken by each of the free parameters. The Alsop–Davison model was fitted in an identical manner but by finding the best-fitting values of log c, log d_s, and log d_r in logarithmic transforms of Equations 3a and 3b. (Note that a_{r1} in Equation 2a was forced to equal a_{r2} in Equation 2b in order that a single best-fitting value of a was obtained and comparisons could then be made between the descriptive accuracy of the two models when each involved three free parameters.) Table 2 shows the results of these fits along with the percentage of variance accounted for (%VAC) in each case, and Figure 5 illustrates the best-fitting functions of each model when they were fitted to the group data. Group data were calculated by summing the response and reinforcer frequencies shown in the appendix across pigeons.

Table 2 shows that the %VAC by Davison and Tustin's (1978) model was higher than that accounted for by the Alsop–Davison (1991) model in all 12 comparisons. The former ranged from 91% to 98%, whereas the latter ranged from 67% to 95%. In addition, neither model described the data from Part 1 better than those from Part 2, or vice versa. With respect to parameter values, a, log d and log d_r were higher for each pigeon in Part 1

Table 2

Results of fitting Davison and Tustin's (1978) model (Equations 2a & 2b) and a logarithmic transformation of the Alsop-Davison (1991) model (Equations 3a & 3b) to log C_1/C_2 response ratios (i.e., log B_w/B_x & log B_y/B_z) in the conditions of Parts 1 and 2 as a function of the log reinforcer ratios obtained (i.e., log R_w/R_z) in those conditions. The best-fitting values of the free parameters in each model are shown, as are the percentages of variance in the data that were accounted by each fit (i.e., %VAC). See text for further explanation.

Pigeon	Davison & Tustin (1978)				Alsop-Davison (1991)			
	log c	log d	a	%VAC	log c	log d	a	%VAC
Part 1								
11	−0.07	0.85	0.52	96	−0.07	1.39	1.50	86
12	0.01	1.41	0.53	97	0.01	1.98	2.10	94
13	0.08	0.80	0.45	97	0.09	1.52	1.27	87
14	−0.07	1.31	0.53	96	−0.07	1.87	1.99	94
15	0.02	0.67	0.49	90	0.02	1.14	1.27	74
16	0.07	0.71	0.45	98	0.07	1.45	1.23	95
Part 2								
11	−0.05	0.51	0.35	92	−0.04	1.31	0.84	78
12	0.00	1.00	0.49	98	0.00	1.65	1.57	90
13	−0.02	0.36	0.29	91	−0.02	0.93	0.60	67
14	−0.01	0.88	0.36	97	−0.01	1.93	1.17	89
15	0.02	0.47	0.30	98	0.02	1.37	0.74	82
16	0.02	0.37	0.30	93	0.03	1.06	0.63	74

than Part 2, log d_s values were not systematically different across parts, and log c values were all close to zero (ranging from −0.07 to 0.09) and inconsistent with respect to sign.

The data and fitted functions plotted in Figure 5 are representative of those obtained for individual pigeons. This figure shows that the predicted functions of both models (see Figure 2) deviated systematically from the obtained data. The nature of these deviations was consistent with that expected given the data paths that were apparent in Figure 4 and described above. That is, both models predicted incorrectly that negative log B_w/B_x ratios would be obtained (i.e., that B_x would exceed B_w) in the conditions that arranged a reinforcer ratio of 1:80 (the leftmost filled circle in each panel of Figure 5), and that positive log B_y/B_z ratios would be obtained (i.e., that B_y would exceed B_z) in the conditions that arranged a reinforcer ratio of 160:1 (the rightmost unfilled circle in each panel of Figure 5). In addition, both models underestimated the bias toward C_1 on S_1 trials when the reinforcer ratio was 160:1 (the rightmost filled circle in each panel), and the bias toward C_2 on S_2 trials when the reinforcer ratio was 1:80 (the leftmost unfilled circle in each panel). Finally, as a result of the response ratios obtained in conditions arranging ex-

treme reinforcer ratios, the predicted log response ratios of both models tended to exceed those obtained in conditions arranging less extreme reinforcer ratios (i.e., the intermediate data points). Suffice to say, although Table 2 indicated that the Davison and Tustin model described these data accurately, both models failed to predict the results of arranging extreme reinforcer ratios and, therefore, reinforcing one of the two responses very infrequently.

The data from the condition that arranged extinction for B_w responses and continuous reinforcement for B_z responses (Condition 19) were analyzed by comparing the obtained response ratios on S_1 and S_2 trials with those that were predicted by each model. Recall these predictions. Davison and Tustin's (1978) model predicts that responding will be exclusive to C_2 (i.e., log B_w/B_x and log $B_y/B_z = \infty$), no matter the values of log d, log c, and a. In contrast, the Alsop–Davison (1991) model predicts that responding will not be exclusive to C_2, but instead will be only biased toward C_2 to a degree that depends on the values of log c and log d_r. The best-fitting values of log c and log d_r that were obtained in fits to the data in Part 2 (see Table 2) were, therefore, used in Equations 3a and 3b to calculate the Alsop–Davison predictions when
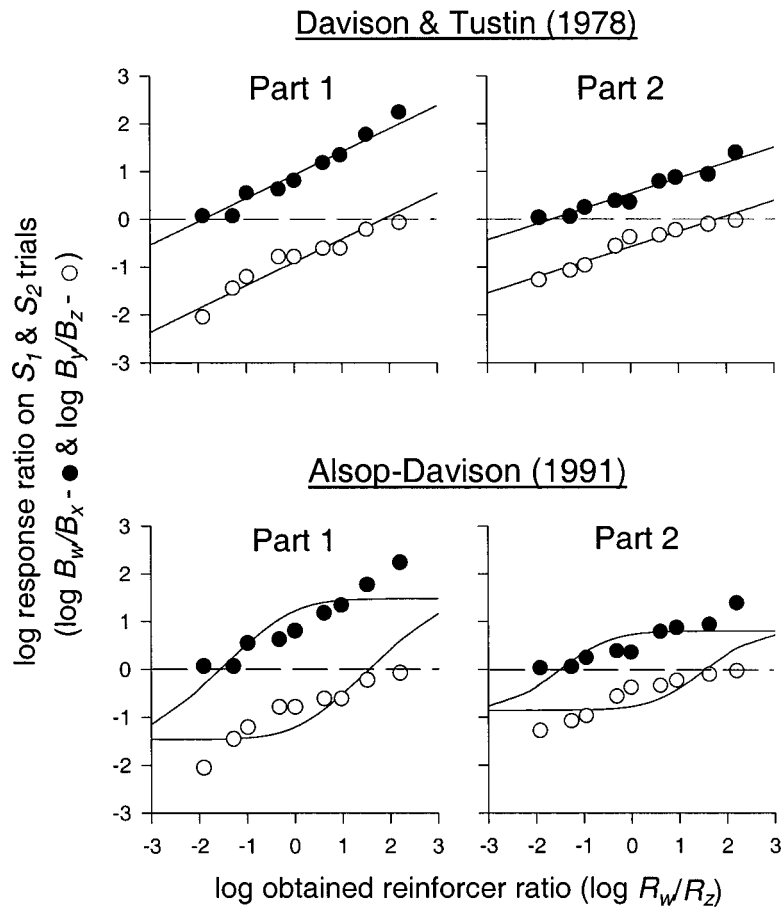
Davison & Tustin (1978)

Alsop-Davison (1991)

Fig. 5.   Log C_1/C_2 response ratios on S_1 trials (i.e., log B_w/B_x), and on S_2 trials (i.e., log B_y/B_z) calculated after collating the data from individual pigeons in the conditions of Part 1 and Part 2, as a function of the log reinforcer-ratio obtained (i.e., log R_w/R_z) in those conditions. The top panels show the best-fitting functions that were obtained when Davison and Tustin's (1978) model (Equations 2a and 2b) was fitted to the data, and the bottom panels show the best-fitting functions that were obtained when the Alsop–Davison (1991) model (logarithmic transforms of Equations 3a and 3b) was fitted. See text for further explanation.

$R_w = 0$. Figure 6 shows these predictions alongside the log response ratios that were obtained in Condition 19. Because all log ratios were negative (except Pigeon 15's obtained log B_w/B_x), they have been converted to absolute values for ease of plotting.

Contrary to the Davison and Tustin (1978) prediction, but consistent with the Alsop–Davison (1991) prediction, Figure 6 shows that the log B_w/B_x ratios obtained were never infinite, and, therefore, that responding to C_1 on S_1 trials was maintained by all pigeons. Contrary to the predictions of both models, however, obtained log B_w/B_x and log B_y/B_z ratios differed markedly for all but Pigeon 15. Obtained log B_y/B_z ratios indicated strong bi-

ases toward choosing C_2 on S_2 trials (continuous reinforcement), and the magnitudes of these log B_y/B_z biases exceeded those predicted by the Alsop–Davison model. In addition, log B_w/B_x ratios were close to zero indicating indifference on S_1 trials (extinction). Thus, these results are similar to those seen in the extreme reinforcer ratio conditions of Parts 1 and 2 (Figure 4). To summarize, when the rate of reinforcement for choosing one comparison was very low, choice on trials where that comparison was correct approached indifference between C_1 and C_2.

Part 3 involved two conditions with moderately extreme reinforcer ratios (1:80 in Condition 25, and 40:1 in Condition 26) and
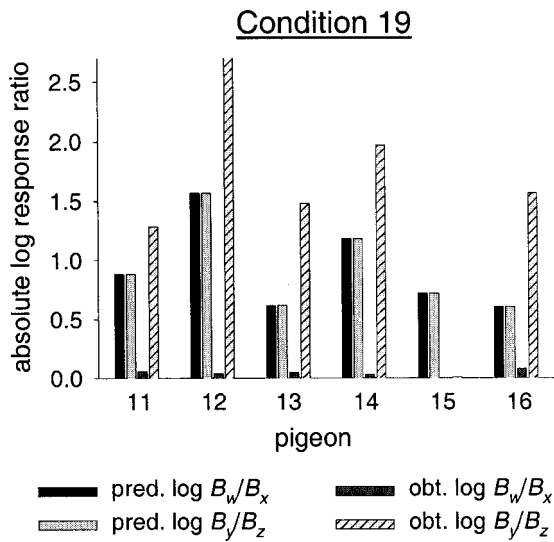
Condition 19

Fig. 6.   Absolute values of the log C_1/C_2 response ratios on S_1 trials (i.e., log B_w/B_x), and on S_2 trials (i.e., log B_y/B_z) that were obtained in Condition 19, and predicted for this condition by Alsop's (1991) and Davison's (1991) model.

sample stimuli that were more difficult to discriminate than those arranged in Parts 1 and 2 (see Table 1 and Figure 3). These conditions were arranged to investigate whether degrading sample discriminability might alter the relation between response and reinforcer ratios that was observed in Parts 1 and 2. Figure 7 shows the results obtained in Part 3. For each pigeon in each condition, this figure plots log response ratios on S_1 trials (i.e., log B_w/B_x), and log response ratios on S_2 trials (i.e., log B_y/B_z), as a function of the log ratio of reinforcers obtained in that condition (i.e., log R_w/R_z). The differences between these data and those obtained in Parts 1 and 2 (Figure 4) are clear. First, the differences between log B_w/B_x and log B_y/B_z ratios at each reinforcer ratio were considerably smaller for each pigeon than those seen in the conditions of Part 1 that arranged the same reinforcer ratios (Conditions 6 and 7). This decrease in response-ratio differences corresponds to a measured decrease in pro-

PART 3
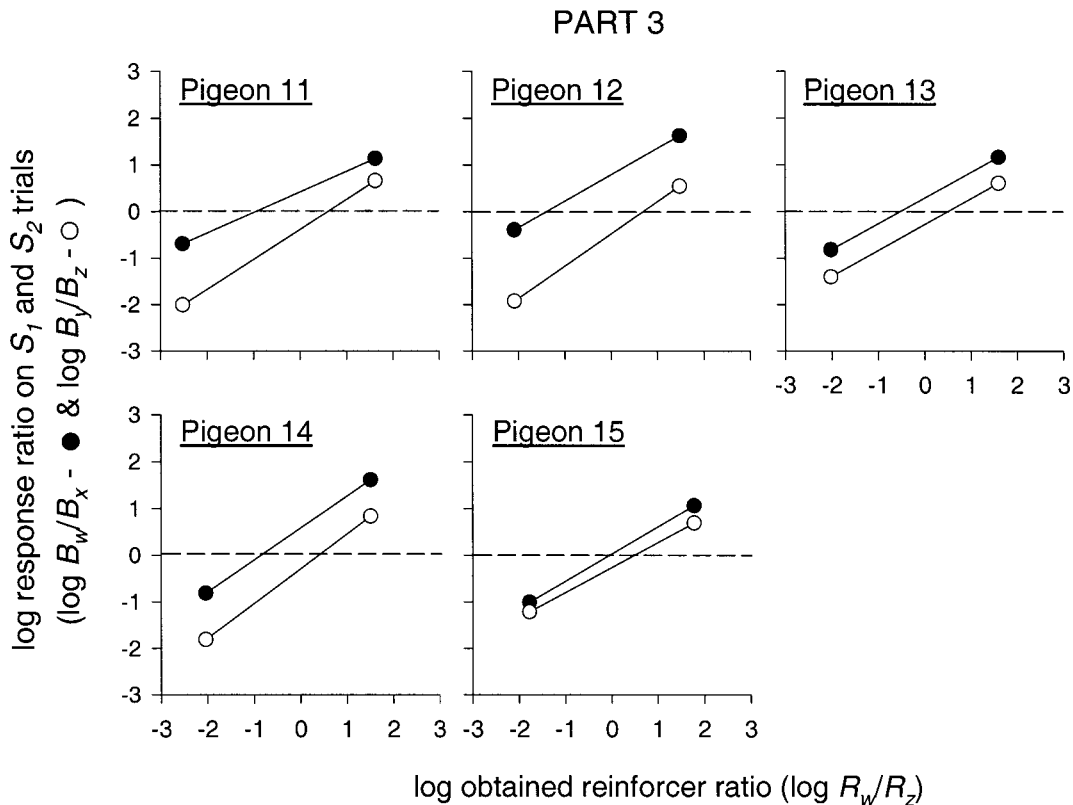

Fig. 7.   Log C_1/C_2 response ratios on S_1 trials (i.e., log B_w/B_x) and on S_2 trials (i.e., log B_y/B_z) in each condition of Part 3 as a function of the log reinforcer-ratio obtained (i.e., log R_w/R_z) in those conditions.

portion-correct scores and Davison and Tustin's (1978) index of sample discriminability. Second, and of more importance, Figure 7 shows that the log B_w/B_x ratios for all pigeons were now negative when the log obtained reinforcer ratio was negative, and the log B_y/B_z ratios were now positive when the log obtained reinforcer ratio was positive (cf. Figure 4). That is, responding by all pigeons in Part 3 was biased toward C_2 on S_1 trials (i.e., $B_x > B_w$) when R_z exceeded R_w, and toward C_1 on S_2 trials (i.e., $B_y > B_z$) when R_w exceeded R_z.

DISCUSSION

This experiment investigated which, if either, of two widely used and empirically validated quantitative models of MTS performance best described the results of arranging extreme reinforcer ratios and extinction in a MTS task. Although these conditions seem contrived and would unlikely occur in typical applications of MTS procedures, they permit an assessment of the predictive accuracy of each model and, therefore, of the treatment of reinforcement variables in them. An understanding of how reinforcement operates in these procedures is, in turn, important for theory and its effective practical use.

The models proposed by Davison and Tustin (1978), and by Alsop (1991) and Davison (1991), were each fitted to two sets of conditions differing in terms of comparison-stimulus disparity (i.e., Parts 1 and 2). Each also provided predictions about the effects of never reinforcing correct responses following one of the samples (Condition 19). Davison and Tustin's model consistently accounted for high percentages of the variance in the data, and described the data more accurately than the Alsop–Davison model. However, neither model predicted the data accurately in some conditions. Both models predicted a bias toward choosing C_2 on S_1 trials (i.e., that B_x would exceed B_w) in conditions where R_z greatly exceeded R_w, and a bias toward choosing C_1 on S_2 trials (i.e., that B_y would exceed B_z) in conditions where R_w greatly exceeded R_z, but neither bias occurred regularly. Instead, choice between C_1 or C_2 on S_1 trials in Parts 1 and 2 approached indifference as the frequency of reinforcers for correct C_1 responses (i.e., R_w) decreased, as did choice on S_2 trials as the frequency of reinforcers for

correct C_2 responses (i.e., R_z) decreased. The results of arranging extinction for responses to C_1 (Condition 19 shown in Figure 6) were similar; choice on S_1 trials was close to indifference rather than exclusive to C_2 as the Davison and Tustin model predicts, or biased to C_2 on both trials equally as the Alsop–Davison model predicts. It was only when the disparity between the sample stimuli was reduced in Part 3 that choice at extreme reinforcer ratios was biased toward C_2 on S_1 trials or C_1 on S_2 trials (see Figure 7). These results suggest that both models describe inadequately the effects of reinforcement rates and sample-stimulus disparity (and their interaction) in a MTS task.

It is important to note that both models being compared here assume that a subject's ability to discriminate the samples will bias its choice on S_1 and S_2 trials equally at all reinforcer ratios. In addition, any change in the two response ratios (i.e., B_w/B_x and B_y/B_z) with variation of the reinforcer ratio (R_w/R_z) is assumed to reflect only changing biases for choosing one comparison more often than the other. Consequently, these models consider any difference between matching accuracies (e.g., proportion correct scores) on S_1 and S_2 trials evidence of a response bias (see Jones & Davison, 1998, for a critical discussion of these assumptions). The fact, however, that choice between comparisons in the present study was seldom biased toward more errors than correct responses suggests another way to consider the effects of non-unity reinforcer ratios on MTS performance. This view involves assuming a degree of independence between performances on S_1 and S_2 trials, and interpreting the indifference shown between C_1 and C_2 as a failure (or unwillingness) to discriminate the comparison stimuli. (The two models examined here would view this indifference as a response bias arising from asymmetrical reinforcer frequencies combining with, and canceling, a bias toward correct responding.) Specifically, it could be that at extreme reinforcer ratios pigeons did not respond differentially to the comparison stimuli after one sample because doing so resulted in food delivery so infrequently. In other words, whatever behavior was involved in discriminating the comparisons (e.g., focusing a retinal image of the random-dot patterns, moving between the side

keys) became less likely as its rate of rein-
forcement fell. In fact, on trials with a very
low rate of reinforcement, advancing to the
next trial, and the possibility of obtaining
food there, may have been the only effective
reinforcer for pecking a comparison stimulus,
and this consequence occurred regardless of
which comparison was pecked. Consequently,
neither comparison was chosen significantly
more often than the other.

This interpretation predicts that the extent
to which differential responding will be lost
should depend on the discriminability be-
tween the samples because samples should be
less effective in signaling a low (or zero) rate
of food reinforcement when they are less dis-
criminable. This prediction was confirmed in
Part 3 where differential responding to the
comparison stimuli was apparent at extreme
reinforcer ratios when sample disparity was
reduced (albeit biases toward choosing C_2 on
S_1 trials, and toward choosing C_1 on S_2 trials).

This interpretation also highlights the
need to distinguish between situations where
a subject *cannot* respond differentially to stim-
uli because those stimuli engender indiscri-
minable perceptual energies, and situations
where a subject *will not* respond differentially
because the consequences for the two re-
sponses are identical (see also Davison & Nev-
in, 1999, for this distinction). In the former
situation, nondifferential responding results
from perceptual limits, whereas in the latter,
nondifferential responding is obligatory. (Af-
ter all, pigeons in the present experiment
were able to discriminate comparison stimuli
on trials involving medium to high reinforcer
rates.) Additionally, this interpretation im-
plies that the reinforcer ratio obtained in a
MTS task may be less important than the ab-
solute rates of reinforcement obtained (and
potentially signaled) on either trial type. It is
interesting to note that both Logue and Cha-
varro (1987) and Alsop and Elliffe (1988) re-
ported results that have a similar implication
for understanding simple choice in concur-
rent schedules. These authors showed that
the value of *a* in the GML (measuring sensi-
tivity to reinforcement) increased with in-
creasing overall reinforcer rates. This result
implies that the numbers of reinforcers ob-
tained (or the probability of reinforcement),
and not simply the ratio of reinforcers ob-
tained, was the critical dimension of rein-

forcement controlling choice. Whether or
not this relation holds in MTS tasks has im-
portant implications for the Davison and Tus-
tin (1978) and the Alsop–Davison (1991)
models because both identify the obtained re-
inforcer ratio as the main independent vari-
able in their equations.

The appearance of position biases at the
comparison phase of trials for some pigeons
corroborated the present interpretation of
comparison indifference. These analyses in-
volved measuring any bias toward choosing
the left- or the right-side key on S_1 and S_2
trials separately in the conditions of Parts 1
and 2. Given that C_1 and C_2 were allocated
randomly to side-key positions, the frequency
with which C_1 appeared on the left and C_2
appeared on the right closely approximated
the frequency with which the other assign-
ment occurred. Consequently, there will be
minimal (or no) opportunity for position bi-
ases when comparison selection is errorless,
but at lower accuracies, position biases will be
less constrained. For example, when accuracy
is at 50% correct, the ratio of left to right
responses can range between zero (exclusive
to the right) and infinite (exclusive to the
left) with a mid-point at 1.0 (i.e., no position
bias). Figure 8 shows log left/right response
ratios on S_1 and S_2 trials separately, plotted as
a function of the log obtained reinforcer ra-
tio in the conditions of Parts 1 and 2. The
biases obtained when extinction was ar-
ranged for C_1 responses (i.e., Condition 19)
have been included but are disconnected
from the functions.

Figure 8 shows, for half of the pigeons (13,
15, and 16), strong position biases in those
conditions where choice between C_1 and C_2
on either S_1 or S_2 trials was close to indiffer-
ent (see Figures 4 and 6). These position bi-
ases were differential with respect to the sam-
ple stimuli and graded with respect to the
obtained reinforcer ratio. Consequently, for
these pigeons, there was an inverse relation
between the magnitude of position biases and
the magnitude of comparison-selection bias-
es. Consider Pigeon 13 in Part 2 as an ex-
ample. When this pigeon had position biases,
they were generally toward only the right key.
This bias increased systematically on S_1 trials
from near zero (i.e., log $B_{Left}/B_{Right} \approx 0$) to a
maximum of 1 to 33 as the log reinforcer ra-
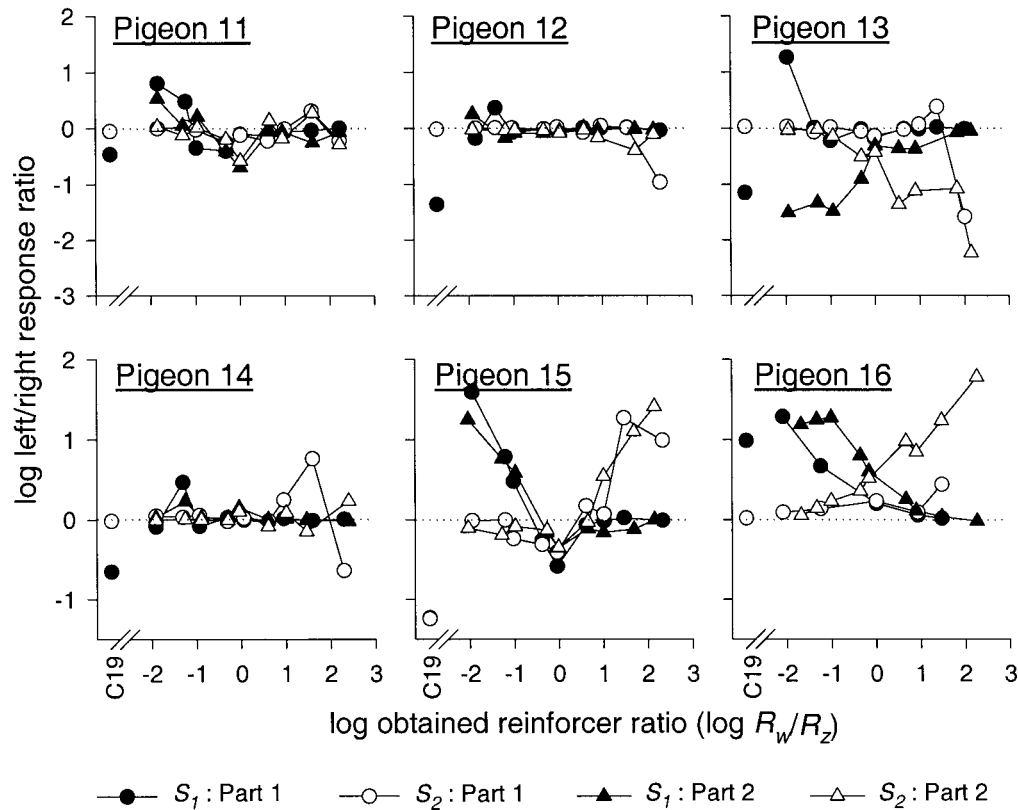tio increased, the rate of reinforcement for

Fig. 8. Log left/right response ratios on S_1 and S_2 trials in each condition of Parts 1 and 2 as a function of the log reinforcer-ratio obtained (i.e., log R_w/R_z) in those conditions.

correct C_1 responses (i.e., R_w) decreased, and choice between C_1 and C_2 approached indifference. Similarly, on S_2 trials, the bias toward choosing right began at near zero ($B_{Left}/B_{Right} = 1{:}1.1$) and increased to a maximum of 1 to 170 as the log reinforcer ratio increased, the rate of reinforcement for correct C_2 responses (i.e., R_z) decreased, and choice between C_1 and C_2 approached indifference. Figure 8 also shows that when a pigeon exhibited strong position biases, the conditions producing the smallest biases on either trial type were not those arranging similar rates of reinforcement for the two responses (and, therefore, log R_w/R_z reinforcer-ratios close to 0), but those where the rate of reinforcement for the correct response on that trial type was the highest. These results are consistent with the notion that changes in C_1/C_2 response ratios (i.e., B_w/B_x and B_y/B_z) across the conditions in Parts 1 and 2 reflect changes in comparison-discrimination accuracy rather than changes in response biases. (Position bi-

ases emerged as the stimulus control exerted by the density of pixels on the side keys, or the luminance of the two keys, weakened.) They also again imply that the effective independent variable controlling this discrimination was either the frequency with which correct responses were reinforced or the probability of reinforcement for correct responding signaled on a trial. Finally, for at least half of the pigeons, they suggest that moving between the side keys was part of the behavior-chain in conditions where they were accurately choosing the correct comparison.

Neither Davison and Tustin's (1978) model nor the Alsop–Davison (1991) model predict such orderly relations between sample-specific position biases and the obtained reinforcer ratio. Instead, both models collate left and right responses in their equations (see also Figure 1), and assume that the randomization of the correct comparison across positions in MTS tasks renders the position of a response an irrelevant feature of the stimulus. Accord-

ingly, as mentioned above, these models do not discriminate MTS tasks from yes-no signal-detection procedures. It is unlikely, however, that subjects in these latter procedures would be indifferent between the two responses when either the signal or the noise clearly signals a very low (or zero) rate of reinforcement. It is more likely that choice on both signal and noise trials would be biased toward the response that was being reinforced at the higher rate. Consider the situation when one response (e.g., saying ''yes'') was never reinforced but the signal was presented on half of the trials—an equivalent procedure to Condition 19 here. That the pigeon will respond ''yes'' on around 25% of trials (i.e., on 50% of the occasions when the signal was presented) seems a bizarre prediction, and yet an analogous result was found in the present study. It is conceivable, therefore, that complex discriminations are comprised of at least two subsets of procedures. In one subset, two topographically different responses can be made to the same or different operanda but identical comparison stimuli, as is the case for yes-no signal-detection tasks and those where left and right responses are designated correct after either of two samples (e.g., Davison & McCarthy, 1987; Davison & McCarthy, 1989; McCarthy & Davison, 1979; McCarthy & Davison, 1980b). In the other subset, responses are required to different comparison stimuli that are randomized across response operanda, as is the case in identity and symbolic MTS tasks and almost all DMTS tasks. In the first case, responses differ on a single (topographical) dimension, but in the second, responses of varying topographies are made to additional (comparison) stimuli. If one accepts that the relation between response biases and reinforcer variables may differ across these two sets of procedures, then one should question whether it is appropriate to apply Davison and Tustin's (1978) and Alsop and Davison's (1991) models to both sets of procedures. I argue below that neither model can successfully describe the latter subset of procedures (i.e., MTS and DMTS tasks) because they have both incorrectly conceptualized the contingencies of reinforcement operating in them. This conceptualization seems to have arisen from a central construct within Alsop's (1991) and Davison's (1991) models; namely,

that of contingency discriminability. Before considering their conceptualization, it is, therefore, important to examine this construct more closely.

The present introduction of the Alsop–Davison (1991) model described d_r as a measure of the discriminability between comparison stimuli because the disparity between these stimuli has often been considered an operation that should affect d_r (e.g., Davison & Nevin, 1999; Godfrey & Davison, 1998, 1999). Numerous authors, however, including Alsop (1991) and Davison (1991) themselves, describe d_r as a measure of the discriminability between the response-reinforcer relations (or the contingencies) in the task, essentially the same construct as that embodied by this parameter in Davison and Jenkins' (1985) model of simple choice. This description does not exclude effects of comparison disparity, but implies that a number of other operations should also affect d_r. Nevin, Cate, and Alsop (1993) investigated one such other operation in an assessment of the Alsop–Davison model. They arranged a discrete-trials procedure in which pigeons earned food access for pecking a key with a short latency if the key was dimly lit, and pecking with a longer latency if the key was brightly lit. Nevin et al. described these contingencies in terms of the notation defined in Figure 1, where bright and dim were cast as samples S_1 and S_2, respectively, and short- and long-latency responses were cast as the two available responses, B_1 and B_2. Panel A in Figure 9 illustrates their conceptualization. They identified three terms in the contingencies they arranged: Discriminative stimuli, topographically different responses, and differential consequences depending on which response was made to which stimulus.

Panel B in Figure 9 illustrates how Davison and Tustin (1978), Alsop (1991), Davison (1991), and Davison and Nevin (1999) have conceptualized reinforcement contingencies in MTS procedures such as those arranged by Godfrey and Davison (1998) and here. They ''identify the choice responses by the stimuli signaling them'' (Davison & Nevin, p. 457) and have simply replaced the term for topographically different responses in signal-detection paradigms (i.e., Panel A) with a term for responses to different comparison stimuli. (That is, choosing C_1 in MTS tasks was con-

A. Extant models: Nevin, Cate, & Alsop (1993)

Conditional stimuli	Discriminative stimuli	Responses	Consequences

S_1: Bright key
- B_1: Peck with short latency (B_w) ⟶ Food @ prob. x
- B_2: Peck with long latency (B_x) ⟶ No food

S_2: Dim key
- B_1: Peck with short latency (B_y) ⟶ No food
- B_2: Peck with long latency (B_z) ⟶ Food @ prob. 1-x

B. Extant models: Godfrey & Davison (1998), & present experiment

Conditional stimuli	Discriminative stimuli	Responses	Consequences

S_1: Bright center-key
- B_1: Peck bright (C_1) on left or right (B_w) ⟶ Food @ prob. x
- B_2: Peck dim (C_2) on left or right (B_x) ⟶ No food

S_2: Dim center-key
- B_1: Peck bright (C_1) on left or right (B_y) ⟶ No food
- B_2: Peck dim (C_2) on left or right (B_z) ⟶ Food @ prob. 1-x

C. Alternative Model: Godfrey & Davison (1998), & present experiment

Conditional stimuli	Discriminative stimuli	Responses	Consequences

S_1: Bright center-key
- $Conf_1$: Bright left-key & dim right-key
  - B_1: Peck left (B_w) ⟶ Food @ prob. x
  - B_2: Peck right (B_x) ⟶ No food
- $Conf_2$: Dim left-key & bright right-key
  - B_1: Peck left (B_x) ⟶ No food
  - B_2: Peck right (B_w) ⟶ Food @ prob. x

S_2: Dim center-key
- $Conf_1$: Bright left-key & dim right-key
  - B_1: Peck left (B_y) ⟶ No food
  - B_2: Peck right (B_z) ⟶ Food @ prob. 1-x
- $Conf_2$: Dim left-key & bright right-key
  - B_1: Peck left (B_z) ⟶ Food @ prob. 1-x
  - B_2: Peck right (B_y) ⟶ No food

Fig. 9. Conceptualizations of the contingencies of reinforcement that operated in the procedures arranged in three studies: Nevin, Cate, and Alsop (1993), Godfrey and Davison (1998), and the present experiment. Panels A and B illustrate the conceptualizations assumed in Davison and Tustin's (1978), Alsop's (1991), and Davison's (1991) models. Panel C illustrates an alternative conceptualization of the procedure arranged in MTS tasks.

sidered equivalent to emitting B_1, and choosing C_2 equivalent to emitting B_2.) A number of other authors have accepted this reasoning because varying the B_1-B_2 difference, and varying the disparity between C_1 and C_2, both seem likely to affect the discriminability between response-reinforcer relations; the construct embodied by d_r. In fact, Davison and Nevin explicitly state that varying the disparity between two comparisons ''permits the differentiation between B_1 and B_2 to be specified on the same experimental continuum as S_1 and S_2, but to be varied independently of the difference between S_1 and S2'' (p. 457). Similarly, Godfrey and Davison actually describe Nevin et al.'s (1993) procedure as a MTS task. Thus, these authors have asserted that MTS tasks also involve three-term contingencies.

Panel C of Figure 9 illustrates an alternative conceptualization of MTS procedures, and one that seems to better accommodate the present findings. It is similar to that offered by Sidman (1986, 2000) and extends logically Cumming and Berryman's (1965) theoretical analysis of MTS procedures. Cumming and Berryman argued that the comparison stimuli in a MTS task are discriminative stimuli because they set the occasion for the reinforcement of a specific response, and that the samples are conditional stimuli that function as ''selector(s) of discriminations, rather than of individual responses'' (p. 285). Thus, whereas signal-detection tasks involve two three-term contingencies of reinforcement, MTS tasks are suggested to involve two four-term contingencies. Important details not apparent in Cumming and Berryman's expositions have, however, been added here. First, I have asserted that pecking the left and the right key in MTS tasks should be considered the response terms in these four-term contingencies. This seems reasonable because the disparity of these responses could vary and, if so, affect matching accuracy (see Eckerman, 1970, for an example). It is also consistent with how topographically different responses have been treated in Panel A and with the emergence of position biases in the present study. Second, I have asserted that the effective discriminative stimuli in MTS tasks (i.e., the stimuli which signal specific consequences for pecking left and pecking right) are not the two comparison stimuli themselves irre-

spective of their location as has been assumed by extant models (including Sidman's), but the 2 two-key stimulus configurations presented at the choice phase on a trial. (Cumming and Berryman, 1965, did, however, acknowledge that conceptualizing the comparisons as discriminative stimuli was an oversimplification of MTS contingencies. They reported sample-specific positions biases in some subjects, and suggested that the discrimination signaled by a sample ''consists of two distinct units—selecting the proper comparison when it is on the right, and selecting the same comparison when it is on the left'' [p. 327].) For example, the configuration of dense/dim on the left and sparse/bright on the right in the present procedure constitutes one discriminative stimulus and those stimuli in reverse positions constitute the other. When identical comparisons are arranged and a subject is simply cued when to choose between two topographically different responses (such as saying ''yes'' or ''no,'' or pecking left or right), this conceptualization logically reduces to that shown in Panel A because the absence of comparison-stimulus configurations renders the samples (or the signal and the noise) the discriminative stimuli.

If the above assertions are accepted, then the stimuli in Nevin et al.'s (1993) study are better viewed as functionally equivalent to the comparison stimuli in MTS tasks rather than the sample stimuli in these tasks as researchers have supposed. Similarly, varying the disparity between discriminative stimuli in Nevin et al.'s procedure (or in signal-detection tasks) cannot be considered equivalent to varying the disparity between samples in standard MTS tasks as numerous authors have assumed (e.g., Davison & Nevin, 1999; Godfrey & Davison, 1998), rendering previous comparisons between results questionable. More importantly, this alternative conceptualization implies that the Davison and Tustin (1978) and the Alsop–Davison (1991) models cannot reasonably apply to both sets of procedures. That is, to the extent that these models are accurate quantitative descriptions of the three-term contingency (i.e., the discriminated operant) they cannot also describe independent variable effects in MTS tasks because different aspects of the procedure constitute four-term contingencies in these
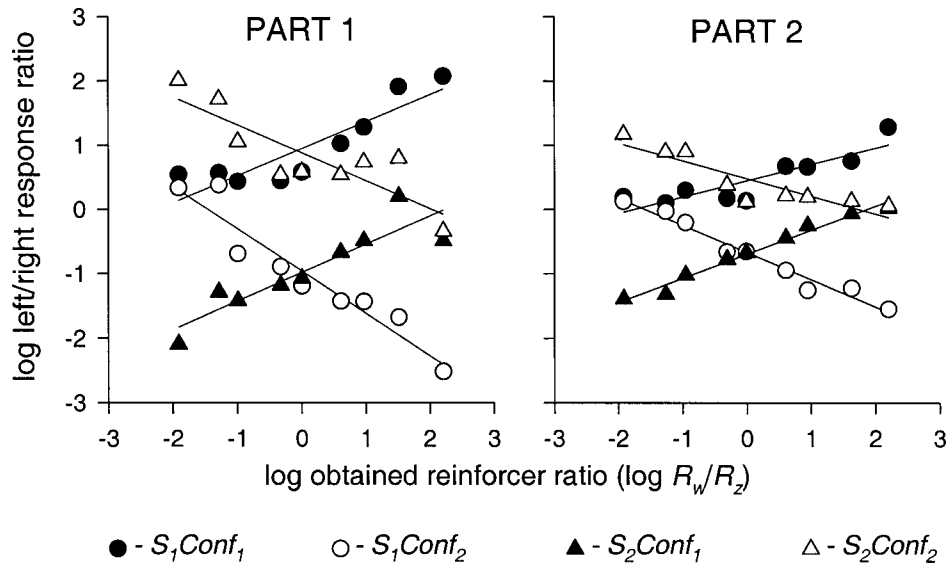
Fig. 10. Log left/right response ratios in the presence of each of the four conditional-stimulus-discriminative-stimulus combinations (i.e., S_1-$Conf_1$, S_1-$Conf_2$, S_2-$Conf_1$, and S_2-$Conf_2$) in the conditions of Part 1 and Part 2 as a function of the log reinforcer-ratio obtained (i.e., log R_w/R_z) in those conditions. Lines have been fitted through each of the four sets of data by least-squares linear regression only to highlight the trends within each set.

tasks. Both models must, therefore, be incomplete theories of performance in MTS tasks, just as the Davison and Tustin model has previously been described (e.g., Godfrey & Davison).

Although this alternative conceptual model organizes the stimulus and response terms of MTS procedures in a consistent and logical manner, evidence that this model describes regularities in the present set of data is still required. To this end, Figure 10 shows an analysis of the mean results obtained in Parts 1 and 2 in the terms offered in Panel C of Figure 9. The dependent variables that emerge from this model are the left/right response ratios for each of the four conditional-stimulus-discriminative-stimulus combinations (i.e., S_1-$Conf_1$, S_1-$Conf_2$, S_2-$Conf_1$, and S_2-$Conf_2$). The logarithms of these ratios have been calculated for each combination in each condition and plotted as a function of the logarithm of the ratio of reinforcers obtained in that condition (i.e., log R_w/R_z). Lines have been fitted through each of the four sets of data by least-squares linear regression only to highlight the trends within each set. Consider first the relation between the left/right response ratios obtained on S_1 trials and the reinforcer ratio in Parts 1 and 2. Response

ratios obtained in the presence of S_1-$Conf_1$ were similar to those obtained in the presence of S_1-$Conf_2$ in conditions where the frequency of reinforcement for correct responses on S_1 trials was very low (i.e., at strongly negative log reinforcer ratios; the leftmost filled and unfilled circles). Thus, left versus right responding in these conditions was nondifferential with respect to the two comparison-stimulus configurations. These response ratios, however, increasingly diverged as the obtained reinforcer ratio increased and, thus, the frequency of reinforcement for correct responses on S_1 trials increased. On S_1-$Conf_1$ trials, responding became progressively more biased toward the left key, and on S_1-$Conf_2$ trials, bias toward the right key increased; the key that was correct in both cases. A similar pattern is evident in the relation between the reinforcer ratio and the difference between the left/right response ratios obtained on S_2 trials in both parts. Such orderly changes in these four response ratios suggest that this alternative conceptual model is viable.

The major difference between the data from Part 1 and those from Part 2 in Figure 10 is that the $Conf_1$ and $Conf_2$ response ratios on both S_1 and S_2 trials are spaced further apart in Part 1 than in Part 2 throughout the
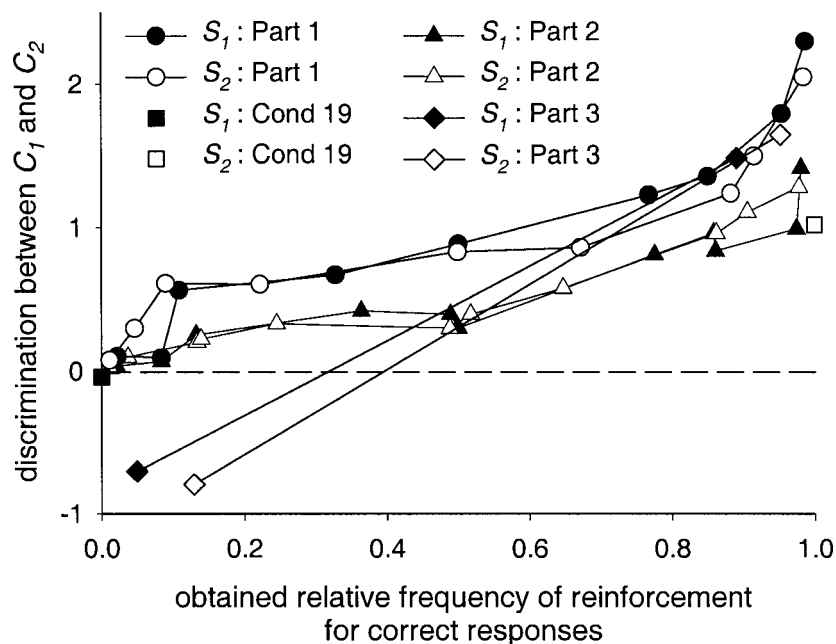
Fig. 11.   The geometric mean of log correct/error response ratios in the presence of the two comparison-stimulus configurations on S_1 and S_2 trials in each condition as a function of the obtained relative frequency of reinforcement on S_1 and S_2 trials in those conditions.

range of reinforcer ratios. This difference is consistent with how the procedures arranged in Parts 1 and 2 differed; namely, the disparity between the comparison stimuli was greater in Part 1 than in Part 2 (see Table 1). Consequently, a higher ceiling ought to have been, and was, placed on the response-ratio differentials in Part 1.

Figure 11 presents a further analysis of the present data in terms of the model proposed in Panel C of Figure 9. This analysis represents an extension of that shown in Figure 10 and provides further evidence for the utility of this model. For each pigeon in each condition, two measures of accuracy were calculated; one for S_1 trials and the other for S_2 trials. Each measure involved averaging the correct/error ratio on $Conf_1$ and $Conf_2$ trials. Specifically, the geometric mean of the correct/error ratios in the presence of the two comparison-stimulus configurations derived a measure of the degree of differential responding to the two configurations. Thus, the mean of left/right ratios on S_1-$Conf_1$ trials and right/left ratios on S_1-$Conf_2$ trials provided a measure of differential responding to the two configurations on S_1 trials. Similarly, the mean of right/left responses on S_2-$Conf_1$

trials and left/right ratios on S_2-$Conf_2$ trials provided a measure of differential responding on S_2 trials. The logarithm of these means is the same metric as Davison and Tustin's (1978) point estimate of log d. Moreover, these means effectively measure the stimulus control exerted by the comparison configurations on either S_1 or S_2 trials, or put more simply, the discrimination between the two comparison stimuli on those trials. Figure 11 shows these means calculated from pooled data and plotted as a function of the obtained relative frequency with which a correct response was reinforced on trials involving that sample. This independent variable has been considered frequently above. When cast in terms of the conceptual model shown in Panel C of Figure 9, however, it effectively measures the degree of differential reinforcement obtained for left versus right responding in the presence of a particular sample and comparison configuration.

A number of effects are apparent in Figure 11 and were also evident in the data of individual pigeons. First, when the relative frequency of reinforcement for correct responses was at its lowest in Parts 1 and 2 (the leftmost circles and triangles), the mean cor-

rect/error ratios were close to zero indicating little (or no) differential responding with respect to the two configurations, and, therefore, little (or no) discrimination between the comparison stimuli. Second, as the relative frequency of reinforcement increased, the discrimination between the comparisons in Parts 1 and 2 increased. Third, this discrimination was not systematically different on S_1 and S_2 trials within each part (although Pigeon 13 reliably showed higher discriminations on S_1 than on S_2 trials). Fourth, discriminations were consistently higher in Part 1 than in Part 2; a result that is consistent with the different comparison disparities across these parts. Fifth, the data points from the condition arranging extinction for correct S_1 responses (i.e., Condition 19 denoted by squares) lie on appropriate data paths. That is, discrimination on S_1 trials in this condition is near zero; discrimination on S_2 trials is generally higher here than it is on both S_1 and S_2 trials in those conditions of Part 2 arranging the highest probability of reinforcement but the same comparison disparity; and S_2 discrimination is generally lower here than it is in the conditions of Part 1 arranging the highest probability of reinforcement and a larger disparity between the comparisons. Finally, the effects of reducing the disparity between the samples in Part 3 are easily interpreted by assuming an interaction between the reinforcer rates obtained on S_1 and S_2 trials. That is, the high rate of reinforcement for responses on S_1 trials in Part 3 (the rightmost filled diamonds) should be effectively lowered by the low rate of reinforcement on S_2 trials, the differential responding between the comparisons on S_1 trials should decrease, and the data points should slide down the function describing Part 1 because the same disparity between comparisons was arranged there. In contrast, when the frequency of reinforcement following S_1 was low (the leftmost filled diamonds), a high reinforcement rate following S_2 should maintain more differential responding between the comparisons than in conditions when the samples are easier to discriminate, but choice will be biased toward the incorrect alternative and, hence, the logarithm of the correct/error ratios will be negative. Obviously, the same logic can be applied to performance on S_2 trials.

A final analysis of the present data in terms of this new conceptual model was conducted by calculating measures of position bias on S_1 and S_2 trials in each condition. Specifically, the geometric mean of the logarithm of left/right response ratios in the presence of the two comparison-stimulus configurations following one sample derived a measure of the degree of position bias on those trials. This measure is similar to Davison and Tustin's (1978) point estimate of response bias (log b) but it is applied here to the frequencies of left and right responses rather than to comparison-stimulus selections. These measures were plotted as a function of the obtained relative frequency of reinforcement on trials involving that sample. The results of this analysis could also be interpreted in a simple manner. For those pigeons who showed significant positions biases in Parts 1 or 2 (Pigeons 11, 13, 15 and 16 in Figure 8), the geometric means on S_1 and S_2 trials were similar, and both systematically approached zero (i.e., no bias) as the obtained rate of reinforcement signaled by a sample increased. Thus, there was an inverse relation between this left or right bias and the discrimination between C_1 and C_2 following either sample (Figure 11), as there logically could be.

Taken together, the results of the analyses shown in Figures 10 and 11 support the conceptual model advanced here because these results led to relatively simple, and internally consistent, interpretations of the main findings in this study. Various measures of performance in MTS tasks followed from the treatment of left and right as the response terms, of comparison-stimulus configurations as the discriminative stimuli, and of samples as conditional stimuli in four-term contingencies. This model also identified the relative frequency of reinforcement for correct responses as an alternative way of viewing the effects of varying reinforcer ratios, and one that equates to a measure of the differential reinforcement of correct responses in the proposed model. Most importantly, the results obtained in these analyses suggest that the degree of differential responding between the two configurations of comparison stimuli (and, thus, the discrimination between C_1 and C_2) was an orderly measure of behavior that depended on the disparity between those comparisons and the relative frequency of reinforcement for correct responses that could

be effectively signaled by a sample. Although mathematical expressions of these dependencies are possible, the empirical validation of how these equations combine various free parameters awaits further research and so are not presented here. For example, further conditions arranging various comparison-stimulus and sample-stimulus disparities are required, as are conditions that vary the left/right reinforcer ratio for the two correct responses.

The results obtained in the present experiment pose a challenge to extant quantitative models of MTS performance. Neither the Davison and Tustin (1978) model nor the Alsop–Davison (1991) model predicted the sample-specific effects of arranging extreme reinforcer ratios (Parts 1 and 2), and arranging extinction for correct responses following one sample (Condition 19). Similarly, neither model predicted that sample-stimulus disparity would modulate those effects (Parts 2 and 3). Instead, these results loaned support to a distinction between different types of complex discriminations and an alternative conceptualization of the contingencies of reinforcement operating in one subset; MTS tasks. This alternative conceptualization implies that while both the Davison and Tustin and the Alsop–Davison models might adequately describe signal-detection-like tasks (in that all agree that they involve three-term contingencies), neither model is a complete account of performance in MTS tasks because four-term contingencies operate in these procedures. Whether or not this conceptual model is the best way to characterize MTS tasks awaits further empirical investigation. Nevertheless, two implications are clear. First, analyses of sample-stimulus discriminability and response bias in prior MTS and DMTS studies warrant careful reexamination (e.g., Godfrey & Davison, 1998; Jones & White, 1992; McCarthy & Davison, 1991; McCarthy & Voss, 1995; White & Wixted, 1999), and second, the advancement of quantitative models of performance in these procedures cannot be without regard to conceptual analyses of the reinforcement contingencies that operate therein.

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APPENDIX

Numbers of responses made by each pigeon to C_1 on S_1 trials when C_1 appeared on the left key (Bw_{left}), to C_2 on S_1 trials when C_2 appeared on the left key (Bx_{left}), to C_1 on S_2 trials when C_1 appeared on the left key (By_{left}), to C_2 on S_2 trials when C_2 appeared on the left key (Bz_{left}), to C_1 on S_1 trials when C_1 appeared on the right key (Bw_{right}), to C_2 on S_1 trials when C_2 appeared on the right key (Bx_{right}), to C_1 on S_2 trials when C_1 appeared on the right key (By_{right}), to C_2 on S_2 trials when C_2 appeared on the right key (Bz_{right}), and the numbers of reinforcers obtained for correct responses on S_1 and S_2 trials (R_w & R_z respectively) summed over the final 20 sessions of each experimental condition. Note that Pigeon 16 died midway through Condition 20.

Pigeon	Condition	Bw_{left}	Bx_{left}	By_{left}	Bz_{left}	Bw_{right}	Bx_{right}	By_{right}	Bz_{right}	R_w	R_z
11	4	501	24	146	422	515	82	178	401	908	92
	5	359	490	32	542	53	227	9	533	56	944
	6	493	4	322	373	528	13	121	217	975	25
	7	410	419	3	503	74	56	3	502	14	986
	8	214	63	79	249	784	593	513	729	501	499
	9	541	22	147	308	558	91	295	390	897	103
	10	312	351	27	490	258	333	101	580	49	951
	11	387	62	410	382	582	225	228	192	957	23
	12	450	404	17	522	113	138	18	481	14	986
	13	468	20	182	135	557	17	316	289	994	6
	14	315	39	48	466	572	333	200	602	326	674
	15	457	45	207	378	501	63	117	307	760	168
	16	444	326	52	545	301	177	44	529	100	900
	17	484	37	283	374	576	96	150	318	894	106
	18	295	72	62	312	696	431	410	719	466	534
	19	122	147	6	488	365	410	46	512	0	1000
	20	481	18	24	469	545	92	109	535	505	495
	21	512	1	225	183	501	6	335	338	994	6
	22	323	35	33	448	593	303	236	617	326	674
	23	472	4	30	442	540	93	196	583	805	195
	24	306	42	8	517	527	245	27	530	94	906
	25	30	356	3	529	138	474	7	493	3	997
	26	512	3	372	4	552	74	507	189	977	23
12	4	504	1	40	494	496	2	17	463	902	98
	5	474	211	12	504	256	37	1	506	38	962
	6	515	2	70	452	491	3	26	482	973	27
	7	212	187	0	507	338	269	5	499	14	986
	8	469	74	58	464	513	94	109	520	525	475
	9	518	8	51	370	515	34	159	448	889	111
	10	254	197	9	504	355	320	16	538	62	938
	11	478	3	120	161	483	7	279	406	936	17
	12	334	321	9	496	194	171	7	525	12	988
	13	489	2	198	270	515	2	226	368	993	7
	14	439	47	50	487	511	84	66	514	325	675
	15	509	33	48	458	506	20	59	478	796	204
	16	441	39	15	487	489	96	17	516	99	901
	17	530	32	68	292	522	46	262	517	894	106
	18	453	137	99	422	578	246	227	595	555	445
	19	15	27	0	491	469	502	2	509	0	1000
	20	500	27	46	518	509	48	48	488	493	507
	21	486	0	22	78	523	1	402	509	995	5
	22	489	36	12	486	493	42	16	497	328	673
	23	513	4	16	419	497	8	17	493	791	210
	24	439	26	4	512	477	73	16	494	86	914
	25	173	379	2	477	118	334	10	535	8	992
	26	522	1	374	24	569	25	500	225	968	32
13	4	362	14	106	322	375	15	81	286	631	65
	5	148	115	13	232	150	108	18	266	20	462
	6	313	7	198	289	300	6	58	143	588	24
	7	353	331	9	389	14	23	5	367	8	748
	8	308	89	104	220	520	293	360	496	390	384

APPENDIX

Continued.

Pigeon	Condition	Bw_{left}	Bx_{left}	By_{left}	Bz_{left}	Bw_{right}	Bx_{right}	By_{right}	Bz_{right}	R_w	R_z
	9	290	37	52	24	495	266	545	458	662	82
	10	16	31	31	466	471	537	64	451	43	831
	11	436	34	48	32	476	83	457	501	891	13
	12	12	21	27	482	527	547	50	500	11	965
	13	487	22	4	2	526	46	501	519	993	7
	14	143	26	64	317	733	630	482	742	333	667
	15	351	35	31	22	621	265	603	608	686	200
	16	19	19	49	451	565	599	152	545	95	833
	17	433	30	33	23	528	131	521	547	838	80
	18	337	246	215	291	672	567	649	638	456	490
	19	17	34	11	361	346	371	12	334	0	695
	20	411	38	59	436	541	130	154	529	476	484
	21	472	2	17	8	478	5	481	468	928	9
	22	506	115	78	441	520	125	115	479	314	638
	23	519	66	188	363	544	55	194	392	780	174
	24	338	70	55	487	484	199	49	471	88	869
	25	47	355	14	513	74	437	25	472	9	945
	26	502	9	337	33	540	62	556	186	948	24
14	4	518	19	167	503	504	14	41	337	898	102
	5	449	363	16	481	180	94	10	449	43	880
	6	453	17	375	442	476	3	48	93	892	23
	7	335	137	1	529	398	178	0	473	12	988
	8	520	207	190	468	402	111	93	422	429	483
	9	481	22	124	412	455	31	66	372	858	86
	10	454	214	21	518	331	62	19	509	52	948
	11	491	26	83	344	504	12	173	422	966	34
	12	354	231	20	495	322	229	7	513	12	988
	13	499	5	333	374	509	12	222	187	996	4
	14	455	117	87	486	460	80	64	514	331	669
	15	514	27	61	422	493	39	98	485	797	203
	16	432	76	17	507	425	53	18	506	112	888
	17	481	38	127	426	511	93	193	504	902	98
	18	535	127	162	488	500	141	153	484	522	478
	19	79	101	2	461	390	403	8	470	0	931
	20	452	42	16	479	479	21	10	464	503	450
	21	490	2	10	169	483	1	302	468	970	5
	22	477	27	12	485	458	17	4	515	311	648
	23	492	4	36	470	510	8	41	479	801	200
	24	466	9	5	536	516	55	4	470	103	897
	25	17	413	8	515	119	470	8	519	9	991
	26	538	5	447	28	609	23	575	121	970	30
15	4	504	17	138	439	512	28	84	408	911	89
	5	432	496	18	529	75	76	11	540	58	942
	6	500	7	442	476	474	5	18	31	919	32
	7	529	561	2	499	3	25	11	505	11	989
	8	323	90	65	337	595	329	322	569	445	464
	9	453	18	449	491	570	107	84	184	909	91
	10	500	476	22	445	89	79	122	603	49	951
	11	455	6	514	535	529	77	50	33	960	20
	12	546	539	24	464	31	30	74	549	9	991
	13	512	19	545	542	482	50	26	16	970	7
	14	334	118	94	395	457	194	185	475	289	546
	15	374	49	196	295	442	105	191	330	673	151
	16	485	475	62	459	120	127	93	539	89	862
	17	325	30	387	388	444	130	57	74	645	69
	18	274	140	93	289	705	534	601	736	522	478
	19	41	51	43	37	789	773	689	707	0	744
	20	113	30	48	141	327	223	208	276	204	228
	21	315	2	307	275	316	6	44	15	630	3

APPENDIX

Continued.

Pigeon	Condition	Bw_{left}	Bx_{left}	By_{left}	Bz_{left}	Bw_{right}	Bx_{right}	By_{right}	Bz_{right}	R_w	R_z
	22	320	117	39	352	520	271	266	532	259	627
	23	335	13	180	235	345	56	110	168	482	119
	24	244	277	17	262	86	87	108	376	49	522
	25	29	286	7	294	30	317	32	343	9	542
	26	247	11	232	51	285	35	246	46	481	8
16	4	369	26	106	296	341	4	56	267	635	75
	5	274	204	42	301	65	37	1	250	29	508
	6	423	20	314	302	426	3	104	118	796	27
	7	121	150	5	135	0	14	1	112	2	246
	8	139	110	97	131	43	19	17	52	73	107
	9	251	48	233	241	211	19	34	33	370	47
	10	156	146	25	171	11	6	8	132	13	280
	11	169	33	179	170	168	17	12	8	319	11
	12	75	80	10	82	2	8	15	66	3	145
	13	180	11	194	169	188	10	4	2	364	2
	14	302	265	165	318	83	6	31	181	145	330
	15	234	120	257	241	175	22	33	19	305	66
	16	289	259	75	268	20	9	17	183	38	391
	17	185	108	191	178	101	9	24	1	238	27
	18	253	183	193	265	97	19	23	87	179	176
	19	456	467	21	480	7	87	5	472	0	952