Divided attention and the matching law: Sample duration affects sensitivity to reinforcement allocation

TIMOTHY A. SHAHAN AND CHRISTOPHER A. PODLESNIK

Utah State University, Logan, Utah

Previously, we have shown that changes in pigeons' divided attention performance resulting from changes in relative reinforcement are well described by the generalized matching law. In the present experiment, we examined whether sensitivity of performance to variations in relative reinforcement would be dependent upon sample duration. Pigeons responded on a delayed matching-to-sample procedure with compound samples (color + line orientation) and element comparison stimuli (two colors or two line orientations). Relative reinforcement for accurate matches on the two types of comparison trials varied across conditions. Sample duration was short (i.e., 0.75 sec) for half of the trials in a session and longer (i.e., 2.25 sec) for the other half. Sensitivity of accuracy to changes in relative reinforcement was greater with the longer sample than with the shorter sample, suggesting that differential reinforcement alters the allocation of attending to the elements of compound stimuli. Continued examination of the applicability of well-established theories of goal-directed behavior to the allocation of attention may provide further insights into what is variously referred to as goal-directed, voluntary, endogenous, or top-down control of attention.

The matching law states that the allocation of instrumental behavior to two options is proportional to the relative rate of reinforcement obtained from those options (Herrnstein, 1961). The generalized matching law provides an account of common deviations from the strict matching law and states that the ratio of behavior at two options is a power function of the ratio of reinforcers obtained from those options (Baum, 1974, 1979). In logarithmic form, this relation is

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

where B_1 and B_2 refer to Behaviors 1 and 2, respectively, and R_1 and R_2 refer to reinforcers for B_1 and B_2. The parameters a and $\log b$ represent sensitivity of changes in the behavior ratio to changes in the reinforcement ratio and bias for one response over the other, respectively. Equation 1 typically has been applied to simple instrumental responding of pigeons maintained by concurrent schedules of reinforcement, but it has been shown to have considerable generality across species and procedural variations (see Davison & McCarthy, 1988, for a review).

A recent experiment by Shahan and Podlesnik (2006) showed that changes in pigeons' performance on a divided-attention task produced by changes in the relative allocation of reinforcement were also well described by the generalized matching law. In that experiment, pigeons were presented with compound samples and element comparisons in a delayed matching-to-sample (DMTS)

procedure. Specifically, the subjects were exposed to 5-sec compound sample stimuli composed of one of two colors (i.e., blue or green) and one of two line orientations (i.e., vertical or horizontal). Following sample offset, two single-element comparison stimuli (i.e., two colors or two line orientations) were presented. Sample stimuli always included a color and a line; however, it was unpredictable whether the two colors (hereafter, *color trials*) or two line orientations (hereafter, *line trials*) would be presented as comparison stimuli. A correct response consisted of a peck to the side key with the color or line orientation that matched the color or line from the sample. Previous work with similar procedures has suggested that such compound sample stimuli produce lower accuracies than do single-element samples or require longer sample durations to maintain a constant level of accuracy because they require a division of attention between the two elements of the compound samples (e.g., Maki & Leuin, 1972; see Zentall, 2005, and Zentall & Riley, 2000, for reviews).

In Shahan and Podlesnik's (2006) experiment, accurate choices on the color and line trials were followed by probabilistic reinforcement. The ratio of reinforcement probabilities for accurate choices on color trials and line trials was varied across a ninefold range so that a version of Equation 1 modified for use with accuracy on the two trial types could be evaluated. Accuracy on each trial type was a direct function of the probability of reinforcement for that trial type and an inverse function of the probability of reinforcement on the other trial type. Furthermore,

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T. A. Shahan, tim.shahan@usu.edu

changes in relative accuracy on the two trial types with variations in the ratio of reinforcement obtained for those trial types were well described by a version of Equation 1 modified for application to changes in accuracy:

$$\log d_C - \log d_L = a \log\left(\frac{R_C}{R_L}\right) + \log b, \qquad (2)$$

where log d_C and log d_L refer to accuracy on color and line trials measured by log d.[1] The parameter a represents sensitivity of relative accuracy to variations in the ratio of reinforcers obtained on color (i.e., R_C) and line (i.e., R_L) trials. The parameter log b represents a bias in accuracy associated with proportionally higher accuracy on one type of trial than on the other, independent of variations in the reinforcement ratio.

The finding that variations in divided-attention performance with changes in relative reinforcement allocation were well described by Equation 2 may be interpreted to suggest that the allocation of attention to the elements of the compound samples was governed by the matching law. Thus, the distribution of attending to the two elements of the compound samples may be analogous to the distribution of responding to concurrent schedules of reinforcement. If this interpretation is correct, the generalized matching law could provide a useful framework for analyzing how variations in consequences affect the allocation of divided attention. For example, Shahan and Podlesnik (2006) suggested that the bias (i.e., log b) and sensitivity (i.e., a) parameters of Equation 2 may provide a way to quantify the impact of the sensory effects of stimuli (i.e., sensory activation or stimulus-driven control of attention) and the importance of the stimuli for the organism (i.e., pertinence or goal-directed control of attention; e.g., Egeth & Yantis, 1997; Norman, 1968), respectively, on the allocation of attention. However, Shahan and Podlesnik also noted that variations in relative reinforcement in their experiment may have affected relative accuracy by impacting some process at the comparison choice point. For example, the pigeons may have attended equally to both elements of the compound samples but may have been less motivated to choose the correct comparison when the low-reinforcement-rate comparison stimuli were presented.

The present experiment was an attempt to begin to assess whether differential reinforcement impacts divided-attention performance by affecting processing of the samples. The fact that the divided-attention task provides only a limited amount of time for processing the compound samples has been suggested as one of the most important features of the procedure. Thus, the time available for processing the sample has been a major variable of concern in previous experiments in which the divided-attention task has been used (see Zentall & Riley, 2000, for a review). A reliable finding in this previous research is that decreases in sample duration decrease accuracy on the task (e.g., Maki & Leith, 1973; Santi, Grossi, & Gibson, 1982; Zentall, Sherburne, & Zhang, 1997). Here, we ask whether the impact of variations in relative reinforcement on divided-attention performance (i.e., a in Equation 1)

depends on sample duration. If the effects of variations in relative reinforcement are mediated solely by differential motivation at the comparison choice point, sensitivity to the relative reinforcement allocation would not be expected to be dependent on sample duration. On the other hand, changes in sensitivity to relative reinforcement allocation with changes in sample duration would be consistent with the suggestion that the allocation of reinforcement impacts attending to the elements of the compound samples. In addition, to examine the potential impact of differential reinforcement on motivation at the comparison choice point, we also examined the effects of differential reinforcement on latency to choose a comparison stimulus.

METHOD

Subjects

The subjects were 8 homing pigeons obtained from Double-T farms, Glenwood, Iowa. The pigeons were maintained at approximately 80% of their free-feeding weights (± 15 g) by postsession supplemental feeding as necessary. The pigeons varied in age and had experience with procedures similar to those arranged in the present experiment. When not in the experimental sessions, the pigeons were housed in individual cages in a temperature-controlled colony with a 12:12-h light:dark cycle (lights on at 7:00 a.m.) and had free access to water.

Apparatus

The experiment was conducted in four Lehigh Valley Electronics pigeon chambers measuring 350 mm long, 350 mm high, and 300 mm wide. Three response keys were centered on the front panel 83 mm apart (center to center) and were 240 mm above the floor. The keys measured 25 mm in diameter and required about 0.1 N to operate. A projector could transilluminate each key with red, amber, blue, green, a white horizontal line on a black background, or a white vertical line on a black background. Compound stimuli composed of a color (blue or green) with a superimposed white line could be produced by simultaneously lighting a color and line stimulus. Reinforcers consisted of 1.8-sec presentations of pelleted pigeon food from a hopper. The hopper was accessible, when raised, through a 50-mm-wide $\times$ 55-mm-tall aperture located on the midline of the work panel, with its center 100 mm from the floor. A 28-V DC clear bulb illuminated the aperture, and all other lights were extinguished when the hopper was operated. General illumination was provided by a shielded 28-V DC clear bulb mounted 45 mm above the center key. A ventilation fan and white noise masked extraneous sounds. Control of experimental events and data recording were conducted with Med Associates programming and interfacing.

Procedure

General procedure. All the pigeons had experience with a similar divided-attention procedure and began the experiment on the final procedure. All DMTS trials throughout the experiment were preceded by the presentation of a red or amber trial-ready stimulus on the center key. Sample stimuli were presented following a single peck to the trial-ready stimulus. A red trial-ready stimulus signaled a 0.75-sec sample duration (hereafter, short trials), and an amber trial-ready stimulus signaled a 2.25-sec sample duration (hereafter, long trials) for Pigeons 936, 966, 144, and 1158. The trial-ready stimuli were reversed for the remaining pigeons. There were two blocks of 48 consecutive trials separated by a 6-sec blackout during which the keylights and houselight were off. Each block consisted of either all short or all long trials. The session started with the short- or long-sample block with $p = .5$.

All the sample stimuli consisted of one of two colors (i.e., blue or green) and one of two line orientations (i.e., horizontal or vertical) simultaneously presented on the center key. The four possible combinations of colors and line orientations were presented an equal number of times during each block (12 times each). Following the appropriate duration, the sample was removed, and the two colors or two lines were immediately presented as comparison stimuli on the side keys. Color or line trials and the location of the colors or lines on the side keys were selected from a list that presented an equal number of comparison stimuli combinations per sample stimulus. Thus, sample stimuli always included both a color and a line; however, it was unpredictable whether the two colors or two line orientations would be presented as comparison stimuli. A correct response was defined by a peck to the side key with the color or line orientation that matched the color or line from the sample. Reinforced correct responses resulted in 1.8-sec access to the food hopper. Nonreinforced correct responses and incorrect responses to the comparison that did not match the sample were followed by a 2-sec blackout during which all the stimuli were turned off. A 10-sec intertrial interval (ITI) followed each hopper delivery or blackout prior to the presentation of the next trial-ready stimulus. Only the houselight was illuminated during the ITI.

Procedure and variation in relative reinforcement rate. All the pigeons began the experiment with a 1:1 ratio of reinforcement. In this condition, each correct response on both color and line trials produced reinforcement with $p = .5$. After a minimum of 40 sessions and once performance showed no consistent trends or excessive day-to-day variability, the probability of reinforcement for correct choices on color and line trials varied across conditions for both the short and the long trials. Reinforcement probabilities for correct matches on color and line trials were varied to arrange ratios of reinforcement delivery of 1:9 ($p = .1$, $p = .9$), 1:1 ($p = .5$, $p = .5$), 3:1 ($p = .75$, $p = .25$), and 9:1 ($p = .9$, $p = .1$). Training on the initial 1:1 condition required an average of 91 sessions. All the subsequent conditions remained in effect for 40 sessions. Table 1 shows the order of conditions for each pigeon.

A generalized matching law analysis was conducted on relative accuracy, using log d (Davison & Tustin, 1978) as the measure of accuracy. Although log d theoretically ranges from zero at chance performance to infinity at perfect performance, it is undefined when one of its terms is zero. As a result, it is common to add a small number to each of the terms to avoid this problem (Hautus, 1995; see also Alsop, 2004). In the present experiment, log d was calculated in-

dividually for color and line trials totaled across the last 20 sessions in each condition. There were some cases in which there were no errors for one or more of the stimuli; thus, log d in all the conditions was calculated as follows:

$$\log d = 0.5 \log\left[\left(\frac{\text{Corr}_{S1} + 0.25}{\text{Incorr}_{S1} + 0.25}\right)\left(\frac{\text{Corr}_{S2} + 0.25}{\text{Incorr}_{S2} + 0.25}\right)\right], \quad (3)$$

where Corr_{S1} and Incorr_{S1} refer to correct and incorrect responses following Sample 1 (e.g., blue), and Corr_{S2} and Incorr_{S2} refer to correct and incorrect responses following Sample 2 (e.g., green). With this correction and 12 trials per stimulus per day (240 total trials per stimulus), the maximum calculable value of log d for both the color and the line trials was 2.98.

Equation 2, as described above, was applied separately to log d from short and long sample duration trials to obtain estimates of sensitivity of accuracy to variations in relative reinforcement allocation (i.e., a in Equation 2) and bias in accuracy for one trial type unrelated to variations in relative reinforcement allocation (i.e., log b in Equation 2). Although the value of a is somewhat constrained by the maximum calculable valuable of log d described above, simulations reveal that the value of a can exceed 2.0, a value far greater than the value of approximately 0.8 typically obtained with simple concurrent schedules of reinforcement (Baum, 1979).

Choice latencies were recorded as the time between presentation of the comparison stimuli and a response to one of the stimuli. Analyses of latencies were based on previous work with pigeons in attention experiments (Blough, 1991; Gibson, Juricevic, Shettleworth, Pratt, & Klein, 2005) and analyses of human choice latencies in a similar DMTS divided-attention task (Lamb, 1991). Accordingly, median latencies across trials were recorded for individual subjects, and the averages of these medians across subjects are presented. Prior to being subjected to an ANOVA, median latencies for individual subjects were log transformed (Gibson et al., 2005). The conclusions reached on the basis of the ANOVA are not changed if geometric means of latencies are used in the analysis. In addition, the effects of relative reinforcement allocation on latency to choose a comparison stimulus were examined with a generalized matching law analysis. For this analysis, median latencies for individual subjects were converted to response speeds (1/latency in seconds) and used as the behavior terms (i.e., B_1 and B_2) in Equation 1 above.

RESULTS

Figure 1 shows accuracy with short and long sample durations on color and line trials as a function of the probability of reinforcement for color trials. The probability of reinforcement for line trials was always the complement of the value for color trials. A repeated measures ANOVA revealed that accuracy was greater with the longer sample duration [$F(1,7) = 101.66$, $p < .0001$] and with color than with line trials [$F(1,7) = 11.02$, $p = .013$]. In addition, there was a significant interaction between type of trial (i.e., color vs. line) and probability of reinforcement [$F(3,21) = 10.20$, $p < .001$]. This interaction resulted from the fact that accuracy on color trials increased but accuracy on line trials decreased with increases in the probability of reinforcement for color trials. Finally, the degree to which accuracy changed with changes in the probability of reinforcement for the two types of elements was dependent upon the sample duration. Accordingly, there was a significant three-way interaction between sample duration, type of trial, and probability of reinforcement [$F(3,21) = 4.60$, $p = .013$]. There were no other significant main effects or interactions.

Table 1
Order of Conditions for Each Pigeon

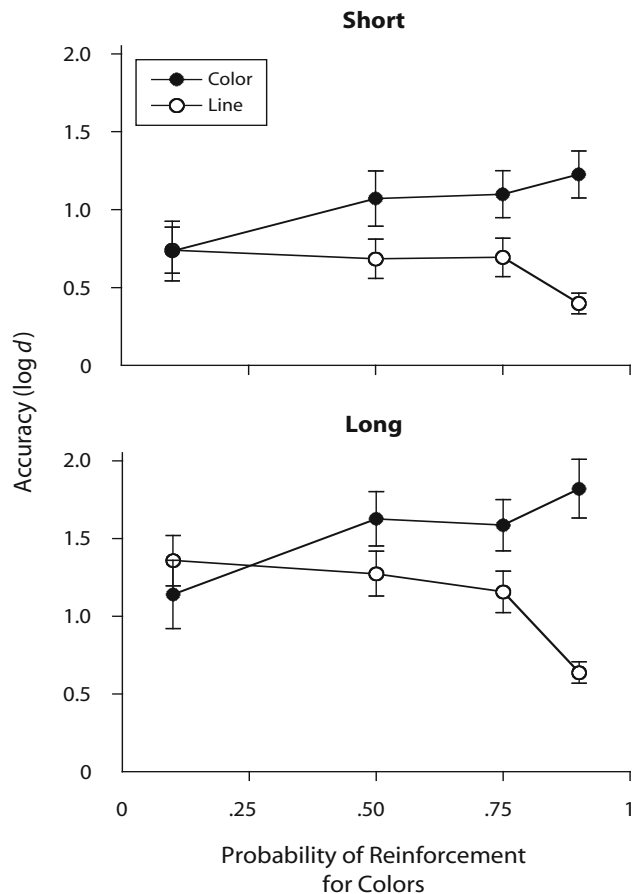| Pigeon	Condition	Pigeon	Condition
936	1:1	144	1:1
	9:1		1:9
	1:1		1:1
	1:9		9:1
	3:1		3:1
966	1:1	1158	1:1
	1:9		9:1
	9:1		1:9
	1:1		1:1
	3:1		3:1
956	1:1	232	1:1
	9:1		9:1
	1:9		1:1
	1:1		1:9
	3:1		3:1
957	1:1	222	1:1
	1:9		1:9
	1:1		9:1
	9:1		1:1
	3:1		3:1

Figure 1. Mean accuracy for the color and line trials as a function of the probability of reinforcement for the color trials. The probability of reinforcement for the line trials was always the complement of that arranged for the color trials. The top panel shows data from the short sample trials, and the bottom panel shows data from the long sample trials.

Figure 2 shows estimates of sensitivity of relative accuracy to relative reinforcement (i.e., *a*) and bias in accuracy for one trial type (i.e., log *b*) derived from fits of Equation 2. The proportion of variance accounted for (VAC) by Equation 2 ranged from .04 to .94 and is presented for each subject and trial duration in Table 2. With the exception of

the very low VAC for the 2 pigeons that showed nearly no sensitivity to relative reinforcement with the short trials (i.e., Pigeons 956 and 1158), the VAC for both trial types is within the range reported by Shahan and Podlesnik (2006). When fitted to the data averaged across subjects, VAC was .93 for short trials and .92 for long trials. The top panel shows that sensitivity to relative reinforcement was greater with the long sample duration than with the short sample duration for each of the pigeons except 222. The difference in sensitivity between the two sample durations across pigeons was significant [$t(7) = -3.43, p = .011$]. Although sensitivity was lower with the shorter sample duration, sensitivities for both the long [$M = 0.64; t(7) = 5.26, p = .001$] and the short [$M = 0.38; t(7) = 3.69, p = .009$] samples were significantly greater than zero. Thus, relative accuracy on the color and line trials was sensitive to changes in relative reinforcement for both sample durations, but sensitivity was greater with the longer sample duration. The bottom panel shows that there was no consistent difference in bias with the two sample durations [$t(7) = -0.03$, n.s.]. However, bias in accuracy for the color trials was significantly greater than zero with both the long [$M = 0.35; t(7) = 2.77, p = .028$] and the short [$M = 0.34; t(7) = 2.48, p = .042$] sample durations. Thus, unlike with sensitivity to relative reinforcement, bias in accuracy unrelated to reinforcement was not dependent upon sample duration.

Figure 3 shows choice latencies for the color and line trials as a function of the probability of reinforcement for the color trials. Data are presented separately for trials following short and long sample durations. Latencies were significantly shorter for the line trials than for the color trials [$F(1,7) = 10.31, p = .015$]. In addition, there was a significant interaction between trial type (i.e., color vs. line) and probability of reinforcement [$F(3,21) = 6.40, p = .003$]. This interaction resulted from the fact that latencies tended to decrease for the color trials but increase somewhat for the line trials as the probability of reinforcement for the color trials increased. Sample duration had no effect on the relation between latencies and probability of reinforcement. There were no other significant main effects or interactions.

Figure 4 shows estimates of sensitivity of relative choice response speed to relative reinforcement (i.e., *a*)

Table 2
Sensitivity (i.e., *a*) and Bias (i.e., Log *b*) Parameter Values and Variance Accounted For (VAC) From the Fits of the Generalized Matching Law to Relative Accuracies and Response Speeds (Equations 2 and 1, Respectively) Based on Fits to the Data From Individual Subjects and to the Average Across Subjects

|	Accuracy (Equation 2)						Response Speed (Equation 1)					
	Short Sample			Long Sample			Short Sample			Long Sample		
Pigeon	*a*	log *b*	VAC	*a*	log *b*	VAC	*a*	log *b*	VAC	*a*	log *b*	VAC
936	0.81	0.36	0.80	1.30	0.49	0.84	0.13	−0.01	0.78	0.11	−0.03	0.67
956	0.06	−0.12	0.04	0.65	0.04	0.91	0.03	−0.22	0.27	0.02	−0.15	0.69
144	0.40	0.09	0.70	0.55	0.04	0.35	0.02	−0.15	0.30	0.04	−0.16	0.53
232	0.43	0.26	0.91	0.52	−0.12	0.63	0.14	−0.12	0.77	0.13	−0.11	0.82
966	0.21	1.20	0.32	0.47	0.96	0.54	0.02	−0.03	0.48	0.00	−0.03	0.05
957	0.46	0.34	0.74	0.82	0.56	0.85	0.08	−0.23	0.82	0.04	−0.23	0.25
1158	−0.03	0.46	0.11	0.12	0.48	0.27	0.01	−0.15	0.34	0.00	−0.14	0.00
222	0.70	0.15	0.86	0.67	0.30	0.94	0.17	0.00	0.77	0.17	−0.01	0.88
Mean	0.39	0.33	0.93	0.64	0.34	0.92	0.08	−0.12	0.94	0.07	−0.11	0.87
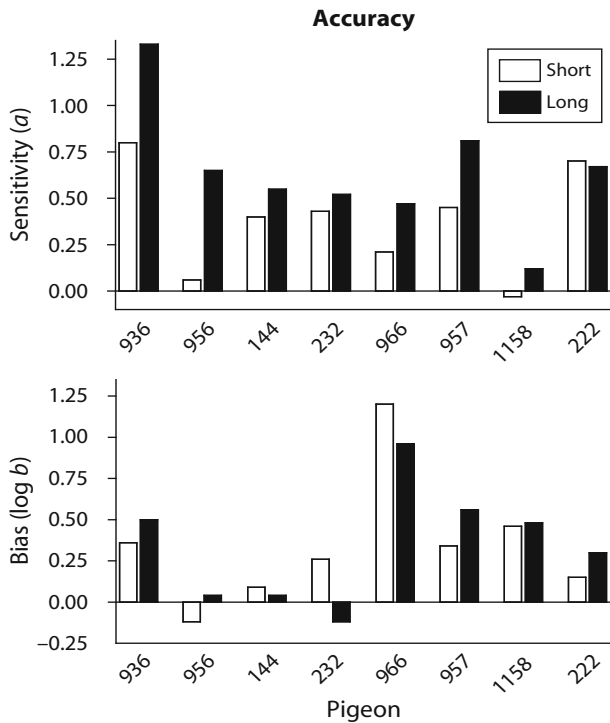
Accuracy

Figure 2. Parameters derived from fits of Equation 2 to the accuracy data for the individual subjects. The top panel shows sensitivity of relative accuracy on the color and line trials to variations in relative reinforcement on those trials (i.e., *a* in Equation 2). The bottom panel shows bias in accuracy on one trial type over the other independent of variations in relative reinforcement (i.e., log *b* in Equation 2). A bias greater than zero represents a bias for higher accuracy on the color trials.

and bias in response speed for one trial type (i.e., log *b*) derived from fits of Equation 1. Table 2 shows that VAC by Equation 1 ranged from .00 to .88. When fitted to the data averaged across subjects, VAC was .94 for short trials and .87 for long trials. The top panel of Figure 4 shows that sensitivity (i.e., *a*) of response speeds to relative reinforcement allocation on color and line trials was slightly but significantly greater than zero following both short [$M = 0.08$; $t(7) = 3.36$, $p = .01$] and long [$M = 0.07$; $t(7) = 2.90$, $p = .023$] sample durations. Sensitivity to relative reinforcement did not differ significantly for short and long samples [$t(7) = 1.5$, n.s.]. Thus, although there was some tendency for relative response speeds to increase with increases in relative reinforcement, these changes were small and independent of sample duration. The bottom panel of Figure 4 shows bias in response speed unrelated to relative reinforcement (i.e., log *b*) for short and long sample durations. There were significant biases for higher response speeds on the line trials than on the color trials for both short [$M = -0.12$; $t(7) = -3.58$, $p = .009$] and long [$M = -0.11$; $t(7) = -3.9$, $p = .006$] sample durations. There was no significant difference in bias for short and long sample durations [$t(7) = -0.67$, n.s.]. Results nearly identical to those reported in Figures 3 and 4 are obtained if response speeds from only correct trials are used in the analysis.

DISCUSSION

The present experiment showed that changes in accuracy with variations in relative reinforcement on a divided-attention task were well described by the generalized matching law. This finding is consistent with the findings of Shahan and Podlesnik (2006). In addition, overall accuracy on the divided-attention task was lower with a shorter sample duration than with a longer sample duration. This finding is consistent with a number of previous experiments in which sample duration has been manipulated within similar tasks (e.g., Maki & Leith, 1973; Santi et al., 1982; Zentall et al., 1997). Most important, sensitivity of accuracy to changes in relative reinforcement was greater with a longer sample than with a shorter sample. Although choice response speeds on color and line trials were also somewhat sensitive to changes in relative reinforcement, choice speeds were not impacted by sample duration. These findings suggest that variations in relative reinforcement may impact both attending to the elements of the compound samples and motivation to respond at the choice point. However, the fact that sensi-
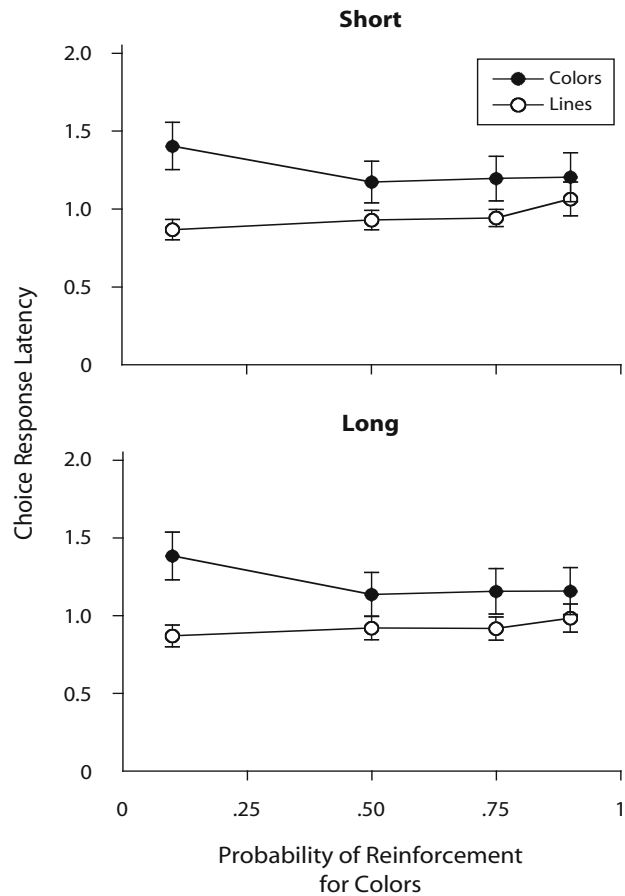

Figure 3. Average median choice response latencies for the color and line trials as a function of the probability of reinforcement for the color trials. The probability of reinforcement for line trials was always the complement of that arranged for color trials. The top panel shows data from the short sample trials, and the bottom panel shows data from the long sample trials.
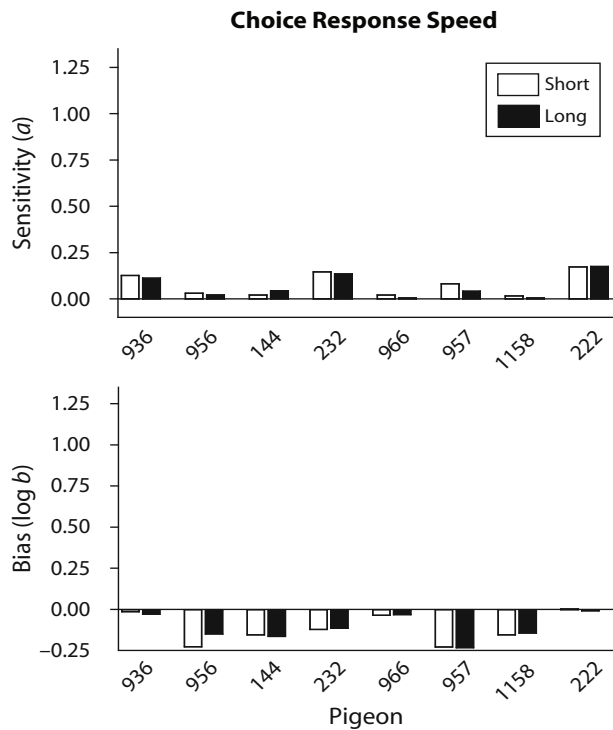
Choice Response Speed

Figure 4. Parameters derived from fits of Equation 1 to the choice response speed data (i.e., 1/latency in seconds) for the individual subjects. The top panel shows sensitivity of response speeds on the color and line trials to variations in relative reinforcement on those trials (i.e., *a* in Equation 1). The bottom panel shows bias in response speeds on one trial type independent of variations in relative reinforcement (i.e., log *b* in Equation 1). A bias greater than zero represents a bias for higher response speeds on the color trials.

tivity of accuracy was dependent upon sample duration but choice speeds were not suggests that changes in motivation at the choice point likely did not mediate the effects of relative reinforcement on accuracy. Thus, the impact of relative reinforcement on divided-attention performance appears to be attributable to changes in the processing of the compound sample stimuli.

Before the conclusion above is accepted, it is important to rule out the possibility that the sample-duration-dependent differences in sensitivity to relative reinforcement could be an artifact of the overall lower accuracies with the shorter sample (see Figure 1). The question is whether it was mathematically possible to obtain comparable sensitivities with the short and the long samples, given the lower and more restricted range of accuracies produced by the shorter sample. The answer to this question is yes, it was possible to obtain similar estimates of sensitivity with the two sample durations. To understand how, assume that accuracies for the color and line trials were at their highest possible values with the short sample duration when the probability of reinforcement for those elements was highest (i.e., *p* = .9). Even given this restrictive assumption about the highest possible accuracies, sensitivities similar to those obtained with the long sample duration could have resulted from *decreases* in accuracy

for the element with the lower probability of reinforcement. For example, accuracy on the color and line trials was nearly identical with the short sample when the probability of reinforcement for color trials was .1 (i.e., probability of reinforcement for line trials = .9; see Figure 1). Sensitivity similar to that obtained with the long sample duration could have been obtained if accuracy (i.e., log *d*) had been 0.4 on the color trials when the probability of reinforcement was .1 for the color trials and if accuracy had been 0.2 on the line trials when the probability of reinforcement for the line trials was .1. In short, the lower sensitivity with the short sample duration can be understood as resulting from accuracy's being *too high* for the element with the lower probability of reinforcement. Thus, the lower sensitivity with the short sample duration may have resulted from the pigeons' attending to the element with the lower reinforcement probability too much, rather than from a restriction imposed by the lower overall accuracies obtained with the short sample.

In addition to helping rule out lower overall accuracies as the source of the lower sensitivity with the short sample, the discussion above suggests a potential mechanism for the lower sensitivity obtained with the shorter sample duration. Roberts (1998) noted that the division of attention required with compound sample stimuli may result in the repeated switching of attention between the two elements. Because it is unpredictable which dimension of the compound sample will be queried at the comparison choice point, the animal must attend somewhat to both elements of the sample or completely ignore one of the elements and forgo the potential reinforcement associated with that element (presumably the one associated with the lower reinforcement probability). Put another way, at least "one look" to each element is required. Assuming that one look takes a relatively constant amount of time, the amount of extra time available for the allocation of attention to the element with the higher reinforcement probability decreases with decreases in the sample duration. As a result, the amount of time allocated to the two elements and, presumably, accuracy on the two trial types would be expected to approach equality as the sample duration decreases. Such an equalization of accuracy on the two trial types for the shorter sample *is* the lower sensitivity reported with the shorter sample in the present experiment. One perhaps counterintuitive prediction of this one-look hypothesis is that sensitivity to relative reinforcement might be expected to *increase* at very short sample durations. The reason is that near-exclusive attending to the higher probability reinforcement element (i.e., very high sensitivity values) might be expected if the sample duration were shorter than the time required for a look at both elements.

Two findings from previous research on the matching law in which concurrent schedules of reinforcement were used also could be related to the differences in sensitivity with the two sample durations. First, Alsop and Elliffe (1988) showed that sensitivity to variations in relative reinforcement increases with increases in overall rates of reinforcement. Given the lower overall accuracies with the shorter sample duration in the present experiment, one

might suspect that overall reinforcement rates were lower with the shorter sample. If so, the lower sensitivity values with the shorter sample duration might reflect only the lower reinforcement rate associated with those trials. Despite the fact that the average number of reinforcers was somewhat lower for the short than for the long sample duration trials (20.7 vs. 22.6), the rate of reinforcement was slightly *higher* for the short than for the long sample trials (2.17 vs. 2.12 reinforcers/min). The lower reinforcement rate for the long sample duration trials resulted from the additional time contributed by the threefold longer sample. Thus, the greater sensitivity of accuracy to changes in relative reinforcement with the long sample duration cannot be attributed to overall greater rates of reinforcement with the long sample. Second, when the stimuli defining the choice alternatives in concurrent schedules are made less discriminable, sensitivity to variations in relative reinforcement decreases (e.g., Miller, Saunders, & Bourland, 1980). The shorter sample duration in the present experiment could have made the elements of the compound samples less discriminable, and thus sensitivity of attending to the elements might have been decreased. Further work will be needed to understand how discriminability of the elements of compound samples may interact with relative reinforcement rates in the allocation of attending to those elements.

Shahan and Podlesnik (2006) suggested that the generalized matching law may provide a useful framework within which to consider the joint contribution of stimulus-driven and goal-driven (i.e., consequential) control of divided attention. They noted that changes in performance produced by changes in relative reinforcement and indexed by the sensitivity parameter of Equation 2 (i.e., *a*) appear to capture the impact of the importance of a stimulus to the organism, or what Norman (1968) has called *pertinence*. In addition, they suggested that the bias term of Equation 2 (i.e., log *b*) may capture the impact of the sensory properties of a stimulus, or what Norman has called *sensory activation*. The fact that, unlike sensitivity to reinforcement, the bias term of Equation 2 was not sample duration dependent suggests caution in interpreting that term as a measure of stimulus-driven-related bias in attending to one of the elements of the compound stimulus. It should be noted, however, that the influence of stimulus-driven features would be expected to be apparent within a shorter time frame than would that of goal-directed control of attention (see Egeth & Yantis, 1997; Johnston, McCann, & Remington, 1995). Both sample durations used in the present experiment may have been sufficiently long to allow a stimulus-driven-based bias of attention to the color stimuli. Thus, bias as measured by Equation 2 also could be sample duration dependent at shorter sample durations than those used here.

Regardless, the sample-duration-dependent changes in sensitivity to the allocation of reinforcement obtained in this experiment suggest that differential reinforcement alters the allocation of attending to the elements of compound stimuli. We suggest that such changes in performance are also analogous to and may provide a useful animal model of similar changes produced by instructional

sets in human experiments on what is variously called voluntary, top-down, endogenous, or goal-directed attentional control in humans (see Yantis, 2000, for a review). In addition, the allocation of attention in the natural environment also likely varies with differential consequences encountered in a manner consistent with simple processes of goal-directed action (cf. Lacourse & Blough, 1998; McIlvane, Dube, & Callahan, 1996). Thus, further examination of the applicability of well-established theories of goal-directed behavior to the allocation of attention may provide alternatives to relatively ambiguous constructs such as central executive and supervisory attentional systems, which are often postulated to be responsible for goal-directed attention (see Styles, 1997, for a review and criticism).

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NOTE

1. Log *d* is the log of the geometric mean of the ratios of correct to incorrect choices for each stimulus (e.g., blue and green for color trials). This measure of discriminative performance is used extensively in applications of the matching law to conditional discrimination performance (Davison & Tustin, 1978; see Davison & Nevin, 1999, for a review) and is useful because it is bias free and, like response rates, theoretically ranges from 0 (i.e., chance performance) to infinity (i.e., perfect performance). These metric properties of log *d* are similar to those of response rates and make it appropriate for use in generalized matching law analyses. The equation for calculating log *d* is provided in the Method section.