Differential reinforcement and resistance to change of divided-attention performance

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Abstract Behavioral momentum theory provides a framework for understanding how conditions of reinforcement influence instrumental response strength under conditions of disruption (i.e., resistance to change). The present experiment examined resistance to change of divided-attention performance when different overall probabilities of reinforcement were arranged across two components of a multiple schedule. Pigeons responded in a delayed-matching-to-sample procedure with compound samples (color + line orientation) and element comparisons (two colors or two line orientations). Reinforcement ratios of 1:9, 1:1, and 9:1 for accurate matches on the two types of comparison trials were examined across conditions using reinforcement probabilities (color/lines) of .9/.1, .5/.5, and .1/.9 in the rich component and .18/.02, .1/.1, and .02/.18 in the lean component. Relative accuracy with color and line comparisons was an orderly function of relative reinforcement, but this relation did not depend on the overall rate of reinforcement between components. The resistance to change of divided-attention performance was greater for both trial types in the rich component with pre-session feeding and extinction, but not with decreases in sample duration. These findings suggest promise for the applicability of quantitative models of operant behavior to divided-attention performance, but they

highlight the need to further explore conditions impacting the resistance to change of attending.

Keywords Attention · Discrimination · Instrumental performance · Matching · Resistance to change · Pigeon

Attention is governed both by the features of exteroceptive stimuli and by the goals of the organism (see Yantis, 2000, for a review). Moreover, attending to stimuli is modifiable by experience (Gopher, 1992) and flexibly divisible as a function of the current reinforcement conditions (e.g., Morey, Cowan, Morey, & Rouder, 2011). These findings suggest that attention is governed by reinforcement principles in a manner akin to overt operant, or instrumental, behavior (see Shahan, 2011; Shahan & Podlesnik, 2008). On the basis of such considerations, we have explored the application of quantitative choice theories (i.e., the matching law) to the allocation of attending (Shahan & Podlesnik, 2006, 2007). The goal of the present study was to explore further how the conditions of reinforcement govern attending by asking whether the persistence of attending can be understood within the framework of behavioral momentum theory (see Nevin & Grace, 2000).

The matching law states that the allocation of instrumental responding is proportional to the relative reinforcement available for responding (Herrnstein, 1961). The generalized matching law accounts for systematic deviations in matching and states that the ratio of responses is a power function of the reinforcement ratio (Baum, 1974). In logarithmic form,

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

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 parameter α represents the sensitivity of changes in the behavior ratio to changes in the reinforcement ratio; the

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parameter $\log b$ represents bias for one response over the other, independent of changes in reinforcement ratios. 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).

Using a divided-attention task (Maki & Leuin, 1972), Shahan and Podlesnik (2006) found that the allocation of attention in pigeons was well described by the generalized-matching law. Specifically, in a modified delayed-matching-to-sample (DMTS) procedure, a compound sample consisting of a color (blue or green) and a line orientation (vertical or horizontal) was presented for 5 s on a center key. Following sample presentations, side keys presented comparison stimuli either of both colors (hereafter, *color trials*) or of both line types (hereafter, *line trials*) with $p = .5$. Choosing the comparison element appearing in the sample produced food reinforcement on a probabilistic basis. The required division of attention between the two elements of the compound-sample stimulus produces lower accuracies than do single-element samples and requires longer sample durations to maintain a constant level of accuracy (e.g., Maki & Leuin, 1972; see Zentall, 2005, and Zentall & Riley, 2000, for reviews).

With changes in the relative reinforcement probabilities during color and line trials from 9:1 to 1:9, the relative accuracy between the color and line trials was described well by a version of Eq. 1 modified to account for accuracy:

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

where $\log d_C$ and $\log d_L$ refer to the accuracy on color and line trials measured by $\log d$.¹ The parameter α represents the 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 bias parameter $\log b$ indicates proportionally higher accuracy on one type of trial than on the other, independent of variations in the reinforcement ratio. Because relative reinforcement rates impacted the relative allocation of attention in a manner consistent with the matching law, we interpret these findings as suggesting that 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 (see also Shahan & Podlesnik, 2007). As such, the division of attention may be considered an instance of instrumental behavior obeying the same processes as overt choice behavior.

Whether the same behavioral processes govern overt behavior and attention can be investigated further by examining whether the conditions of reinforcement also mediate the persistence of attending. According to behavioral momentum theory (Nevin & Grace, 2000), the persistence, or resistance to change, of instrumental responding is mediated by the Pavlovian relation between a discriminative stimulus context and the rate of reinforcement obtained in that context (i.e., the stimulus–reinforcer relation). This relation was most clearly revealed by Nevin, Tota, Torquato, and Shull (1990) with pigeons pecking for food reinforcement in a multiple schedule of reinforcement. In both components, separate but equal variable-interval (VI) 60-s schedules of reinforcement were presented. In one component, additional food was presented according to a variable-time (VT) 15-s schedule. The added food degraded the relation between responding and reinforcement (i.e., response–reinforcer relation) but enhanced the Pavlovian stimulus–reinforcer relation. Although the added food decreased the baseline response rates in that component, the resistance to disruption by satiation and extinction, relative to baseline response rates, was greater in the component with added food. These findings suggest that stimulus–reinforcer relations govern resistance to change independently of the response–reinforcer relations governing stable baseline response rates (see Podlesnik & Shahan, 2008, for a discussion of exceptions).

As the allocation of instrumental responding is well described by generalized matching, the resistance to change of instrumental responding is well described by behavioral momentum theory (Nevin, 1992). According to behavioral momentum theory, resistance to disruption of instrumental responding is a power function of the relative reinforcement rate in a discriminative stimulus context:

$$\log \left(\frac{Bx_1}{Bo_1} \right) - \log \left(\frac{Bx_2}{Bo_2} \right) = \alpha_r \log \left(\frac{R_1}{R_2} \right) + \log b, \quad (3)$$

in which Bx is responding during disruption relative to baseline response rates, Bo , in the presence of two discriminative stimuli (i.e., Components 1 and 2). R_1 and R_2 are the rates of reinforcement delivered in the presence of those stimuli. The α_r parameter reflects the sensitivity of the relative resistance to change to variations in relative reinforcement rate. $\log b$ indicates greater resistance to change on one trial type, independent of variations in the reinforcement ratio. Like the matching law, findings

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, it theoretically ranges from zero (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.

supporting behavioral momentum theory have shown considerable generality across experimental preparations and species, ranging from fish to humans (e.g., Ahearn, Clark, Gardenier, Chung, & Dube, 2003; Harper, 1999; Igaki & Sakagami, 2004; Nevin et al., 1990; Pyszczyński & Shahan, 2011).

In addition to the persistence of free-operant responding, resistance to change of accuracy in DMTS tasks is also governed by the rate of reinforcement in a stimulus context (Nevin, Milo, Odum, & Shahan, 2003; Nevin, Ward, Jimenez-Gomez, Odum, & Shahan, 2009; Odum, Shahan, & Nevin, 2005). In a two-component multiple schedule with pigeons, Nevin et al. (2003) arranged equal VI 30-s schedules signaled by different keylight colors immediately preceding DMTS trials with different line orientations during the sample. Accurate matches during comparisons produced food reinforcement with $p = .8$ in the rich component and $p = .2$ in the lean component. Baseline accuracy and the resistance to disruption of accuracy by pre-session feeding, free food during intercomponent intervals (ICI), and extinction were greater in the rich component. Therefore, the findings that the persistence of DMTS performance is governed by Pavlovian stimulus–reinforcer relations extend the generality of the assertions of behavioral momentum theory from free-operant responding to more covert processes, such as remembering and attending (see Nevin, Davison, Odum, & Shahan, 2007; Nevin, Davison, & Shahan, 2005).

To assess more directly whether stimulus–reinforcer relations govern the resistance to change of divided-attention performance, we arranged a two-component multiple schedule of divided-attention tasks arranging different overall rates of food reinforcement for accurate performance. Components were signaled by different colored trial-ready stimuli—red or yellow—and a peck to the trial-ready stimuli initiated 2.25-s compound samples consisting of one color and one line. In both components, reinforcement ratios of 1:9, 1:1, and 9:1 for accurate matches on the two types of comparison trials were examined across conditions. Specifically, reinforcement probabilities (color/lines) were, in the rich component, .9/.1, .5/.5, and .1/.9, and in the lean component, .18/.02, .1/.1, and .02/.18. Finally, we assessed resistance to disruption in all conditions. We arranged two disrupters traditionally used in behavioral momentum research—satiation by pre-session feeding, and extinction. To more directly disrupt attending, we also assessed resistance to disruption with decreases in sample duration. Decreasing sample duration reliably decreases the accuracy of divided-attention performance by reducing processing time at the sample (e.g., Maki & Leith, 1973; Santi, Grossi, & Gibson, 1982; Shahan & Podlesnik, 2007; Zentall, Sherburne, & Zhang, 1997).

Method

Subjects

The subjects were 5 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 a line stimulus. Reinforcers consisted of 1.8-s presentations of pelleted pigeon food from a hopper. The hopper was accessible, when raised, through a 50-mm-wide by 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 during all conditions except hopper presentations. A ventilation fan and white noise masked extraneous sounds. Control of experimental events and data recording was conducted with Med Associates programming and interfacing.

Procedure

General procedure All pigeons had experience with a similar DMTS divided-attention procedure and began the experiment on the final procedure. A single peck to a trial-ready stimulus initiated a 2.25-s presentation of the compound sample stimulus. All 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. Following the sample, 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. All food presentations for accurate responses were arranged probabilistically. Reinforced correct responses resulted in 1.8-s 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-s blackout during which all stimuli were turned off. A 10-s intertrial interval (ITI) followed each hopper delivery and blackout prior to the presentation of the next trial-ready stimulus. Only the houselight was illuminated during the ITI.

Signaled trial blocks Blocks of DMTS trials arranged different overall probabilities of food reinforcement. Across all conditions, a yellow trial-ready stimulus signaled an overall higher probability of reinforcement for correct responses to comparisons ($p = .5$; hereafter, the rich component), and a red trial-ready stimulus signaled a lower probability ($p = .1$; hereafter, the lean component). Within both components, the relative probability of reinforcement for accurate matches on color versus line trials was manipulated across conditions. In the rich component, the color-to-line reinforcement probability ratios were 1:9 ($p = .1, p = .9$), 1:1 ($p = .5, p = .5$), and 9:1 ($p = .9, p = .1$). In the lean component, color-to-line reinforcement probability ratios were 1:9 ($p = .02, p = .18$), 1:1 ($p = .1, p = .1$), and 9:1 ($p = .18, p = .02$). The color-to-line reinforcement ratios in the rich and lean components were equal in all conditions and were arranged from 9:1, 1:1, to 1:9 for Pigeons 353, 284, and 232; the order was reversed for Pigeons 222 and 175.

All components consisted of 12 trials, with each of the four possible combinations of color and line orientations being presented an equal number of times during each component, resulting in a total of 96 trials per session. The rich and lean components initiated sessions with $p = .5$ and alternated strictly thereafter. Components were separated by 10-s ICIs, during which the keylights and houselight were turned off.

Disruption All disrupters occurred for 10 consecutive sessions. All conditions with a particular reinforcement ratio were conducted for 40 sessions prior to the first disruption with pre-session feeding. Pre-session feeding consisted of

providing access to 12% of the pigeons' running weight 1 h prior to the session. Baseline was reestablished for 20 sessions prior to the next disrupter, which consisted of decreasing the sample duration to 0.5 s. Finally, baseline was reestablished for another 20 sessions prior to the final disruption via extinction, in which food presentations were discontinued for accurate responses. Instead, 2-s blackouts followed all responses, as described above.

Data analysis Across baseline and disruption conditions, generalized-matching-law analyses were conducted on relative accuracy using $\log d$ (Davison & Tustin, 1978) as the measure of accuracy for both components. 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 individually for color and line trials by summing data across the last 10 sessions of each condition. In some cases, there were no errors for one or more of the stimuli, and thus $\log d$ in all conditions was calculated as follows:

$$\log d = 0.5 \log \left[\left(\frac{\text{Corr}_{S1} + 0.25}{\text{Incorr}_{S1} + 0.25} \right) \left(\frac{\text{Corr}_{S2} + 0.25}{\text{Incorr}_{S2} + 0.25} \right) \right], \quad (4)$$

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 in each component per session (120 total trials per stimulus), the maximum calculable value of $\log d$ for both color and line trials was 2.68.

Equation 2, as described above, was applied separately to $\log d$ from the rich and lean components to obtain estimates of the sensitivity of accuracy to variations in relative reinforcement allocation (i.e., a in Eq. 2) and of the bias in accuracy for one trial type unrelated to variations in relative reinforcement allocation (i.e., $\log b$ in Eq. 2). Although the value of a is somewhat constrained by the maximum calculable value of $\log d$ described above, simulations revealed 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).

The resistance to disruption of accuracy was assessed individually for all disrupters as a proportion of baseline $\log d$ (see Nevin et al., 2003). Specifically, $\log d$ was calculated from the 10 sessions of disruption and divided by $\log d$ from 10 baseline sessions immediately prior to disruption.

Results

Table 1 shows the food presentations obtained per session and the log food-presentation ratios from color and line trials in the rich and lean components. The log food-presentation ratios within and between components approximated the programmed ratios.

Figure 1 shows accuracy (log d) in the rich and lean components on color and line trials as a function of the probability of reinforcement for color trials. The probability of reinforcement for line trials always was the complement of the value for color trials. A three-way repeated measures ANOVA revealed a significant interaction between the type of trial (i.e., color vs. line) and the probability of reinforcement [$F(2, 3) = 30.67, p < .001$]. This interaction resulted from accuracy increasing with the probability of reinforcement on color trials, and accuracy decreasing with the probability of reinforcement on line trials. No other significant main effects or interactions were found.

Figure 2 shows the sensitivity (i.e., a) and bias in accuracy for one trial type (i.e., log b) derived from fits of Eq. 2. The black bars show sensitivity and bias estimates during baseline, and grey bars show estimates during disruption. In the baseline, estimates of sensitivity for the rich component (mean $a_R = 0.36$) and the lean component (mean $a_L = 0.44$) did not differ statistically, according to a paired t test [$t(4) = 1.21, n.s.$]. Estimates of bias in the rich component (mean log $b_R = 0.23$) and the lean component (mean log $b_L = 0.10$) also did not differ statistically [$t(4) =$

1.04, n.s.]. The proportions of variance accounted for (VAC) by Eq. 2 ranged from .83 to 1.00 (see Table 2) and were similar to previous reports of matching of divided-attention performance (Shahan & Podlesnik, 2006, 2007). The fits to individual subjects are shown in Table 2. Sensitivity was greater in the lean component for 4 out of the 5 pigeons (the exception was Pigeon 284). Table 2 also shows that bias in accuracy for color trials was greater in the rich component for 4 out of the 5 pigeons (again, the exception was Pigeon 284). The lack of statistical significance in sensitivity and bias was due to the fairly large intersubject variability in these measures.

The grey bars in Fig. 2 show estimates of sensitivity and bias in the rich and lean components during conditions of disruption. One-way repeated measures ANOVAs revealed a significant decrease in sensitivity during disruption in the rich [$F(3, 12) = 3.67, p = .048$] and the lean [$F(3, 12) = 7.26, p = .005$] components. Using baseline sensitivity as the control, Dunnett's multiple-comparisons test revealed lower sensitivity only during extinction in the rich ($p < .05$) and lean ($p < .01$) components. One-way repeated measures ANOVAs revealed that bias did not differ when compared to baseline estimates in the rich [$F(3, 12) = 1.12, n.s.$] or the lean [$F(3, 12) = 1.73, n.s.$] component.

Figure 3 shows resistance to disruption of accuracy (i.e., log d) as a proportion of baseline accuracy for pre-session feeding, extinction, and decreases in sample duration. In each panel, proportions of baseline are shown as mean values during color and line trials across the 1:9, 1:1, and

Table 1 Food presentations obtained per session for color and line trials in the rich and lean components and within- and between-component log food-presentation ratios

Pigeon	Overall		Rich			Lean		
	Log Ratio	Condition	Log Ratio	Color	Line	Log Ratio	Color	Line
353	0.71	9:1	1.03	20.03	1.87	1.12	3.93	0.30
	0.68	1:1	-0.04	10.23	11.13	0.02	2.27	2.17
	0.68	1:9	-0.93	2.40	20.30	-1.04	0.40	4.37
284	0.75	9:1	0.95	20.93	2.37	0.89	3.63	0.47
	0.69	1:1	-0.05	10.67	11.87	-0.11	2.03	2.60
	0.75	1:9	-0.92	2.33	19.60	-1.03	0.33	3.60
232	0.70	9:1	1.08	21.33	1.77	0.92	4.13	0.50
	0.71	1:1	0.01	11.40	11.27	0.00	2.23	2.23
	0.73	1:9	-0.95	2.27	20.37	-0.98	0.40	3.80
222	0.68	9:1	1.12	19.40	1.47	1.14	4.10	0.30
	0.70	1:1	0.10	10.50	8.40	0.06	2.03	1.77
	0.60	1:9	-0.87	2.17	16.00	-1.01	0.40	4.13
175	0.68	9:1	1.02	17.97	1.70	0.79	3.50	0.57
	0.60	1:1	-0.04	9.83	10.67	0.01	2.57	2.53
	0.60	1:9	-0.91	1.83	14.93	-1.06	0.33	3.83
Mean	0.71	9:1	1.04	19.93	1.83	0.97	3.86	0.43
	0.68	1:1	0.00	10.53	10.67	0.00	2.23	2.26
	0.67	1:9	-0.92	2.20	18.24	-1.02	0.37	3.95

Fig. 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 rich component, and the bottom panel shows data from the lean component. Error bars represent SEMs

9:1 conditions. Therefore, each pair of black and white bars shows the proportions of baseline for rich and lean on a particular dimension (i.e., color or line) at a given relative reinforcement ratio (i.e., 1:9, 1:1, or 9:1). For instance, the top left two bars under pre-session feeding indicate proportions of baseline accuracy for color trials in the rich and lean components when the color-to-line reinforcement ratio was set at 1:9.

The top panel of Fig. 3 shows that accuracy was more resistant to pre-session feeding in the rich component during both color and line trials. When comparing color versus line trials within each component, no effect of differences in the probability of reinforcement for color versus line trials was observed. These conclusions were supported in a three-way repeated measures ANOVA revealing a significant main effect of component [$F(1, 4) = 8.573, p = .043$], with no other significant main effects or interactions.

The middle panel of Fig. 3 shows that accuracy also was more resistant to extinction in the rich component across all conditions. However, the resistance to extinction of accuracy was also a function of the probabilities of reinforcement for color versus line trials. Specifically, in the 1:9 and 9:1 conditions, resistance to extinction was greater for the trial type (color or line) reinforced with the lower probability within both the rich and lean components. These conclusions were supported by a three-way repeated measures ANOVA revealing a significant main effect of component [$F(1, 4) = 13.927, p = .020$] and a significant interaction between trial type (i.e., color or line) and probability of reinforcement [$F(2, 8) = 11.262, p = .005$]. There were no other significant main effects or interactions.

The bottom panel of Fig. 3 showed no systematic resistance to disruption by decreases in sample duration as a function of either the component or the probability of reinforcement within components. According to a three-way repeated measures ANOVA, however, there was a significant interaction between component and trial type (i.e., color or line), $F(1, 4) = 9.685, p = .036$, suggesting that resistance to decrease in the sample duration between components changed with trial type. There were no other significant main effects or interactions.

To compare directly the magnitudes of disruption of accuracy across the three disrupter types, proportions of baseline log d were calculated for each disrupter type by collapsing across trial types (i.e., color and line), components, and reinforcement ratios. The proportions of baseline accuracy were impacted to similar extents by pre-session feeding ($M = .77, SEM = .10$), extinction ($M = .64, SEM = .06$), and decreased sample duration ($M = .57, SEM = .11$). This conclusion was supported by a lack of statistical significance when tested in a one-way repeated measures ANOVA [$F(2, 8) = 2.812, p = .119$]. In addition, we compared the log proportions of baseline log d values collapsed across trial types, components, and reinforcer ratios to the null hypothesis that responding was not disrupted (i.e., proportion of baseline log $d = 1.0$) in a one-sample t test. The proportion of baseline did not differ statistically from 1.0 for pre-session feeding [$t(4) = 2.319, p = .081$], despite 4 out of 5 pigeons' values falling below 1.0. The proportions of baseline log d values were significantly different from 1.0 for decreased sample duration [$t(4) = 3.974, p = .016$] and extinction [$t(4) = 5.788, p = .004$].

We assessed resistance to disruption of responding during sample presentations across pre-session feeding, extinction, and decreased sample duration. We reasoned that resistance to disruption of sample responding might provide a measure that converged with accuracy among the disrupters. Figure 4 shows the resistance to disruption of responding during sample presentations across pre-session feeding, extinction, and decreased sample duration. Resistance to disruption of

Fig. 2 Mean sensitivity (a) and bias ($\log b$) from a generalized-matching-law analysis (Eq. 2) of relative accuracy on color and line trials (i.e., $\log d_C - \log d_L$) as a function of the relative reinforcements obtained for accurate matches on color and line trials [i.e., $\log (R_C/R_L)$]. The black bars show parameter values during baseline, and grey bars show parameter values during disruption. Table 1 shows parameter values for individual pigeons. Error bars represent *SEMs*

sample responding was calculated by comparing mean response rates (in responses per second) during the 10 disruption sessions to mean response rates during the 10 previous baseline sessions for the rich and lean components. Resistance to disruption for both components was averaged across all conditions in which relative reinforcement rates were manipulated within the components. Response rates during the baseline conditions did not differ between the rich ($M = .49$, $SEM = .21$) and lean ($M = .45$, $SEM = .12$) components, as supported statistically by a paired t test [$t(4) = 0.46$, n.s.]. Sample responding in the rich component was more resistant to pre-session feeding [$t(4) = 3.176$, $p = .034$] and extinction [$t(4) = 5.80$, $p = .004$], but not to decreases in sample duration [$t(4) = 1.52$, n.s.], as compared to sample responding in the lean component.

Table 2 Sensitivity (i.e., a) and bias (i.e., $\log b$) parameter values and the variance accounted for (VAC) from fits of the generalized-matching law (GML) to relative accuracies (Eq. 2)

Pigeon	Rich		Lean	
	GML Plots	VAC	GML Plots	VAC
353	$y = 0.53x + 0.06$	.94	$y = 0.65x + 0.04$	.88
284	$y = 0.42x - 0.23$	.91	$y = 0.27x - 0.10$	1.00
232	$y = 0.40x + 0.71$	.98	$y = 0.44x + 0.08$	.83
222	$y = 0.19x + 0.49$	.91	$y = 0.43x + 0.41$	.99
175	$y = 0.28x + 0.15$	.93	$y = 0.42x + 0.06$	1.00
Mean	$y = 0.36x + 0.23$	.93	$y = 0.44x + 0.10$	.94

To determine whether the different trial-ready stimuli signaling the rich and lean components differentially controlled responding, we examined whether the proportions of trials in which a response did not occur to the trial-ready stimuli differed between the rich and lean components. Figure 5 (top panel) shows that a smaller proportion of responses occurred to trial-ready stimuli in the lean component during baseline and during all three disrupters. However, the proportions of trial-ready stimuli without a response were greater in both components during pre-session feeding and extinction as compared to baseline and decreased sample duration. These findings were supported in a two-way repeated measures ANOVA by a significant main effect of condition [$F(3, 12) = 24.346$, $p < .001$], a main effect of component [$F(1, 4) = 12.735$, $p = .023$], and a significant interaction between condition and component [$F(3, 12) = 7.878$, $p = .004$].

Finally, we assessed the log median latencies to respond to comparisons for each trial type (color and line) in the rich and lean components. Figure 5 (bottom panel) shows that latencies in both components were longer during pre-session feeding and extinction as compared to baseline and decreased sample duration. Moreover, latencies were shorter in the rich component than in the lean component during pre-session feeding and extinction, but they were similar during baseline and decreased sample duration. These findings were supported in a two-way repeated measures ANOVA by a significant main effect of condition [$F(3, 12) = 17.482$, $p = .0001$] and a significant component $\times$ condition interaction [$F(3, 12) = 4.500$, $p = .025$].

Fig. 3 Resistance to disruption by pre-session feeding (top panel), extinction (middle panel), and decreased sample duration (bottom panel) in the rich and lean components across the 1:9, 1:1, and 9:1 relative reinforcement probabilities within components. Data are shown as mean $\log d$ values during disruption as a proportion of baseline $\log d$ values. Black bars show responding in the rich component, and white bars show responding in the lean component during both color and line trials. Error bars represent *SEMs*

Discussion

The present study examined relative accuracy and the resistance to disruption of divided-attention performance. Between components of a multiple schedule, we arranged a 5:1 difference in probability of food reinforcement for accurate performance on color and line trials with pigeons. Within those components, we manipulated the relative probability of reinforcement from 1:9 to 9:1 for accurate performance on color and line trials. Accuracy was

sensitive to changes in relative probability of reinforcement and was described well by the generalized-matching law (Eq. 2). Sensitivity to changes in relative reinforcement fell within the range of previous studies examining matching of divided-attention performance (Shahan & Podlesnik, 2006, 2007).

Sensitivity to changes in the relative probability of reinforcement did not differ with differences in overall reinforcement rate arranged between components. These findings are consistent with the predictions of the

Fig. 4 Resistance to disruption during sample presentations by presession feeding (left), extinction (middle), and decreased sample duration (right) in the rich and lean components. Data are shown as mean response rates (responses per second) during disruption as proportions of the baseline response rates, averaged across the 1:9, 1:1, and 9:1 relative reinforcement probabilities within components. Error bars represent *SEMs*

generalized-matching law that sensitivity should be controlled by the distribution of reinforcement rather than by overall frequency (see Alsop & Elliffe, 1988, for a discussion). Elliffe and Alsop (1996) found that matching of concurrent-choice performance with differences in overall rates of reinforcement depended on the distribution of reinforcers within concurrent VI schedules. Given the differences in procedures and scheduling of reinforcers between the present study and concurrent-choice studies, making general conclusions about how overall reinforcement rate influences the sensitivity of divided-attention performance is premature.

Fig. 5 Proportions of trial-ready stimulus presentations without a response in the rich and lean components during baseline, presession feeding, extinction, and decreased sample duration (top panel). Log median latency (in seconds) to respond to comparison stimuli in the rich and lean components during baseline, presession feeding, extinction, and decreased sample duration (bottom panel). Error bars represent *SEMs*

Although differences in overall reinforcement rate between components did not impact the sensitivity of baseline accuracy, differences in overall reinforcement rate impacted the resistance to disruption by presession feeding and extinction. Specifically, when comparing accuracy on color and line trials between the rich and lean components, resistance to presession feeding and extinction was greater for both trial types in the rich component. These findings, in which stimulus context mediated the resistance to change of divided attention, are consistent with the persistence of free-operant performance (e.g., Nevin et al., 1990) and accuracy in discrete-trial conditional discriminations (e.g., Nevin et al., 2003). Moreover, these findings are the first to show that the persistence of divided-attention performance is consistent with the assertions of behavioral momentum theory: Resistance to disruption of divided attention is a function of the overall rate of reinforcement obtained in the context in which attending occurs (see Nevin & Grace, 2000).

Although the resistances to presession feeding and to extinction of divided attention and sample responding were consistent with the assertions of behavioral momentum theory, decreasing sample duration produced no differential resistance to disruption between components. It is unlikely that decreases in sample duration eliminated stimulus control by the trial-ready stimuli. Responding to the trial-ready stimuli during the decreased sample duration remained differential between components and similar to baseline levels. Conversely, responding to trial-ready stimuli during presession feeding and extinction decreased relative to baseline. At this point, we can only conjecture that the persistence of divided-attention performance might involve different processes when assessing different disrupters. For instance, decreasing sample duration might disrupt integration of the contextual stimuli signaling differential reinforcement between the components (i.e., trial-ready stimuli) and the sample stimuli. Future studies might arrange different sample stimuli between components, as well as explore a larger battery of disrupters, including those targeting attending to the sample (e.g., Nevin et al., 2009). At this point, the present findings reveal differences in the resistance to change of divided-attention performance when attending is disrupted by altering reinforcement conditions (presession feeding and extinction) versus when attending to the sample is disrupted more directly (decreased sample duration).

Examining resistance to disruption within each component as a function of relative reinforcement probability for colors versus lines also resulted in different effects, depending on the disrupter type. In no case did higher relative reinforcer probabilities for a given trial type (color or line) produce greater resistance to disruption for that trial type. Resistance to presession feeding and decreased

sample duration were similar between trial types, whereas resistance to extinction was greater for the leaner trial type during the 1:9 and 9:1 conditions. Although they are inconsistent with sensitivity of baseline accuracy, these findings are consistent with previous findings in concurrent-choice situations that have shown no clear pattern of resistance to disruption as a function of different reinforcement rates between two alternatives (e.g., Bell & Williams, 2002; McLean & Blampied, 1995; McLean, Campbell-Tie, & Nevin, 1996; Nevin et al., 1990). While they resembled the present findings with presession feeding and extinction, however, these previous studies nevertheless revealed greater overall resistance to disruption of responding on both alternatives in components arranging higher reinforcement rates. Therefore, as with concurrent-choice performance, the persistence of divided attention is a function of the overall rate of reinforcement in a discriminative stimulus context, with all sources of reinforcement within a context contributing to the persistence of behavior in that context (see McLean et al., 1996, for a discussion).

Extinction of divided-attention performance within each component was impacted inversely by the relative probability of reinforcement for accurate performance to that trial type. Such findings are consistent with the partial reinforcement extinction effect (PREE), in which more responding occurs in extinction following intermittent reinforcement than following continuous reinforcement (see Nevin, 1988, for a review). Such findings can be understood by assuming that extinction involves two processes (Mackintosh, 1974): (1) termination of the contingency between responding and reinforcement, and (2) a change in stimulus conditions by eliminating reinforcers from the experimental context (i.e., generalization decrement). The generalization decrement is greater following continuous reinforcement than following intermittent reinforcement, because the removal of reinforcement is more discriminable following continuous reinforcement (i.e., the change in reinforcement rate is greater in extinction following continuous reinforcement).

According to behavioral momentum theory, contingency termination and a generalization decrement function as disrupters, with generalization decrement having a larger impact with richer reinforcement schedules (Nevin, McLean, & Grace, 2001):

$$\log\left(\frac{B_x}{B_o}\right) = \frac{-x(c + d\Delta r)}{r^b} \quad (5)$$

The impact of extinction is a function of reinforcement rate (r), the time in extinction (x), termination of the contingency (c), and the generalization decrement (d). The b parameter scales sensitivity to baseline reinforcement rate. Most importantly, the parameter d accounts for the

decremental effect of decreasing reinforcer rate from r in baseline to zero during extinction (Δr). Equation 5 explains the present within-component extinction findings as a greater disruptive effect of omitting reinforcers during extinction (i.e., $d\Delta r$) in trial types arranging the currently greater reinforcement probability.

One interesting finding is that PREE was obtained between trial types (color vs. line) but not between components. This likely is due to the differences in the arranged absolute and relative reinforcement probabilities within and between components. Specifically, the ninefold difference within components likely produced a more discriminable change during extinction (i.e., $d\Delta r$) than did the fivefold difference between components. One test of this account would be to systematically manipulate the relative and absolute reinforcement rates within and between components, followed by tests of resistance to extinction (see Nevin & Grace, 1999, for related findings). Presumably, PREE would be obtained within components, between components, or both, depending on the prevailing conditions of reinforcement.

Previous studies have shown that arranging differential outcomes for accurate performance at comparison stimuli in DMTS tasks engenders more accurate performance than when identical outcomes are arranged (e.g., Jones, White, & Alsop, 1995; Nevin et al., 2009). The conditions of reinforcement in the present study during the 1:9 and 9:1 ratios of reinforcement between color and line trial types arranged differential outcomes for accurate performance. The 1:1 ratio of reinforcement, conversely, arranged equivalent outcomes for accurate performance between color and line trials. Inconsistent with previous findings of differential outcomes on accuracy, overall levels of accuracy in the present study did not differ between the 1:9 and 9:1 reinforcement ratios versus the 1:1 reinforcement ratio. Upon closer examination of the findings of Nevin et al. (2009), greater accuracy was observed only when delays were interposed between accurate comparison responses and food presentation. Thus, under the 0-s DMTS trials most analogous to the present study, Nevin et al. (2009) found no effect of differential outcomes on accuracy. Future studies should examine the role of differential outcomes on divided-attention performance at different reinforcement delays.

In conclusion, the present study further explored the applicability of quantitative models of operant behavior to divided-attention performance (see also Davison & Elliffe, 2010; Shahan & Podlesnik, 2006, 2007). Shahan and Podlesnik (2006, 2007) suggested that the generalized-matching law could provide a useful framework for analyzing how variations in consequences affect the allocation of divided attention. The bias (i.e., $\log b$) and sensitivity (i.e., a) parameters of Eq. 2 might provide a way to quantify the independent influences of environmental

factors on the allocation of attention. Specifically, the bias parameter indicates the sensory effects of stimuli (i.e., sensory activation or stimulus-driven control of attention), whereas sensitivity indicates the importance of the stimuli for the organism (i.e., pertinence or goal-directed control of attention; e.g., Egeth & Yantis, 1997; Norman, 1968). Although the effects with decreases in sample duration require further study, the present findings suggest that behavioral momentum theory could provide a useful framework within which to begin an analysis of how differential reinforcement affects the persistence of divided attention (see Nevin & Grace, 2000).

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