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Divided stimulus control depends on global, but not local, reinforcement contingencies

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Abstract

Research suggests that divided stimulus control is graded according to the relative reinforcer probabilities associated with each stimulus, much like choice depends on reinforcer ratios. This experiment investigated whether parallels between divided stimulus control and choice extend to local levels of analysis. Six pigeons responded in a matching-to-sample procedure in which sample stimuli were composed of a color (blue or white) and frequency of color alternation (fast or slow) and subjects reported the identity of one dimension in each trial. In some conditions, the dimension to report in a trial signaled the dimension likely to be reinforced or to be reported in the following trial. Unlike choice—which favors the likely next-reinforcer location as signaled by last-reinforcer location—local probabilities had little effect on divided stimulus control. Instead, divided control depended on overall reinforcer probabilities associated with each stimulus dimension. Such global reinforcer effects were weaker when one dimension was less discriminable and were well described by a model asserting that divided control depends on differential and nondifferential reinforcement. These findings highlight the importance of the discriminated reinforcer differential in divided stimulus control and suggest that parallels between divided control and choice may not extend to local levels.

KEYWORDS
compound stimulus, divided stimulus control, pigeon, reinforcement

Stimuli that signal the contingencies for responding tend to gain control over the rate or probability of responding (Skinner, 1938; Terrace, 1966). Such *stimulus control* may be exclusive to one stimulus or divided between multiple stimuli. For example, if a pigeon's pecks are followed by food delivery in the presence of one compound stimulus (e.g., a vertical line on a red background) but not in the presence of another compound (e.g., a horizontal line on a green background), pecking may come to be controlled by one or both of the compound-stimulus dimensions. The division of control between stimulus dimensions depends on the extent to which each dimension predicts the contingencies for responding. Stimulus control tends to be selective (or near selective) when only one dimension is differentially or discriminably correlated with reinforcers (i.e., other dimensions are or appear to be irrelevant), whereas divided control typically occurs when multiple dimensions differentially signal reinforcer availability (e.g., Blough, 1969; Castro & Wasserman, 2014; Chase & Heinemann, 1972; Davison, 2018; Davison & Elliffe, 2010; Gomes-Ng et al., 2023; Leith & Maki, 1975; Reynolds, 1961; Shahan & Podlesnik, 2006, 2007; Wagner, 1969; Wagner et al., 1968).

For example, Shahan and Podlesnik (2006) showed that divided stimulus control (or divided attention[1]) is

[1]The term "divided attention" is sometimes used instead of "divided stimulus control." This is because attention and stimulus control are tightly linked in the sense that only those stimuli that are attended to can control behavior (see Skinner, 1953). Thus, the general consensus is that "any observation of stimulus control is [also] an observation of attention" (Johnson & Cumming, 1968, p. 157). Because of the connotations and assumptions that may be associated with the more cognitive term "attention," we have chosen to use the term "stimulus control" in this article.

graded according to the relative reinforcer probabilities associated with each stimulus dimension. In their experiment, pigeons responded in a matching-to-sample (MTS) procedure in which the sample stimulus was a vertical or horizontal line superimposed on a green or blue background and the comparison stimuli were either two colors (color trials) or two line orientations (line trials). Overall, accuracy in color trials was higher than accuracy in line trials, suggesting stronger control by the color dimension. Additionally, as the reinforcer probability for correct responses in color trials increased, so did the pigeons' accuracy of reporting the color of the sample, whereas accuracy in line trials decreased. Thus, control by a stimulus dimension increased as the relative reinforcer probability associated with that dimension increased. Subsequent research has extended these findings to different absolute and relative reinforcer probabilities (e.g., Gomes-Ng et al., 2023; Podlesnik et al., 2012), various stimulus dimensions (e.g., Davison, 2018; Davison & Elliffe, 2010; Gomes-Ng et al., 2023), stimuli trained separately and then presented together (Gomes-Ng et al., 2019; Thrailkill et al., 2025), and humans (e.g., Heyman et al., 2016; Heyman & Moncaleano, 2021).

The effects of relative reinforcer probabilities on divided stimulus control share similarities with the effects of reinforcer ratios on concurrent choice—stimulus dimensions associated with higher reinforcer probabilities exert stronger discriminative control in the same way that choice favors response alternatives that deliver more reinforcers (Davison, 2018; Davison & Elliffe, 2010; Gomes-Ng et al., 2023; Shahan & Podlesnik, 2006, 2007; Thrailkill et al., 2025). Indeed, Shahan and Podlesnik (2006, 2007) found that their data were well described by a quantitative model of choice, the generalized matching law (Baum, 1974), which asserts that choice (or in this case, divided stimulus control) depends on relative reinforcers and on other variables (e.g., subject-specific characteristics) that may bias responding (or stimulus control). Such parallels between divided stimulus control and choice suggest that findings from the choice literature may provide a useful framework for advancing our understanding of the processes that underlie divided stimulus control. In other words, attending to discriminative stimuli may be understood as a behavior maintained by reinforcers, much like (observable) operant responding (Davison & Elliffe, 2010; Shahan & Podlesnik, 2006, 2007).

In particular, growing evidence from choice studies shows that individual reinforcer deliveries are followed by systematic shifts in choice toward the alternative that is most likely to deliver the next reinforcer. For example, Krägeloh et al. (2005) found that pigeons' postreinforcer choice depended on the probability that another reinforcer would be delivered on the same alternative as the previous reinforcer; when this probability was low, the pigeons preferred the not-just-reinforced alternative, whereas they favored the just-reinforced alternative when the probability was high. Likewise, Cowie et al. (2011) arranged a concurrent schedule in which the likely next-reinforcer location shifted from one alternative to the other alternative during interreinforcer intervals and found that choice followed the change in reinforcer availability over time (see also Bensemann et al., 2015; Boutros, Elliffe, & Davison, 2011; Cowie et al., 2013, 2014, 2017, 2021; Gomes-Ng et al., 2024; Landon & Davison, 2001; Landon et al., 2002; Wood & Simon, 2023). By analogy, if divided stimulus control is governed by similar principles to concurrent choice, then local shifts in divided stimulus control (e.g., from trial to trial) may occur depending on which stimulus dimension is most likely to be relevant to a discrimination. For example, the dimension appearing as comparison stimuli in a trial (henceforth, for brevity, dimension to report) may signal which dimension is likely to be reinforced or relevant in the next trial—and thus shift divided control toward that dimension—just as the last-reinforcer location may signal the likely next-reinforcer location in a concurrent schedule. The purpose of the present experiment was to test this suggestion.

We arranged a symbolic MTS procedure in which the sample stimulus was either a blue or white light that alternated on and off at either a fast or slow rate and pigeons reported the color or alternation frequency in the comparison phase. That is, the sample stimulus was a compound of two dimensions, color and alternation frequency. In some conditions, we arranged contingencies analogous to Krägeloh et al.'s (2005) experiment in which the location of a reinforcer delivery signaled the likely next-reinforcer location. Specifically, we considered the stimulus dimensions in our experiment to be analogous to the reinforcer locations in Krägeloh et al.'s study because *stimulus control* may be divided between *dimensions* in the same way that *responding* is divided between *reinforcer locations*. Thus, in the present experiment, the dimension to report in a trial signaled either the probability of a reinforcer delivery for that same dimension in the next trial or the probability of that dimension appearing as comparison stimuli in the next trial. If divided stimulus control is indeed governed by similar principles to concurrent choice, then the signaled dimension should exert stronger control (just as choice favored the likely next-reinforcer location in Krägeloh et al.'s study).

We also arranged conditions in which the global reinforcer probabilities associated with each dimension varied and the alternation-frequency discrimination was easier (alternation every 0.1 s or 0.9 s) or harder (every 0.3 s or 0.5 s). This allowed us to test a quantitative model of divided stimulus control proposed by Davison (2018; see also Davison & Elliffe, 2010). Briefly, the model asserts that divided control depends on *discriminated* reinforcer rates, which may deviate from arranged rates due to errors in discrimination. To illustrate, if a subject does not observe or attend to the color of the

sample stimulus, they may respond randomly in a color trial. This response may occasionally be correct and thus reinforced, but the reinforcer would appear nondifferential with respect to color (because it was not observed or attended to). Likewise, some reinforcers may appear nondifferential if sample stimuli are perceptually similar (e.g., similar colors) and thus difficult to discriminate. Davison suggested that such nondifferential reinforcers could be modeled by redistributing obtained reinforcers from one stimulus or response to other stimuli or responses (e.g., reinforcers may generalize between two colors, two comparison responses, or two stimulus dimensions; see also Davison & Elliffe, 2010; Davison & Nevin, 1999). To date, only one study has tested this model, finding limited support (Gomes-Ng et al., 2023). However, Gomes-Ng et al. (2023) arranged reinforcers for incorrect responses, so their procedure differed from the typical procedure for studying divided stimulus control. Therefore, the present study tested Davison's model under typical experimental conditions.

METHOD

Subjects

Six pigeons, numbered 121 to 126, served as subjects. All pigeons had previous experience responding in concurrent schedules. Pigeon 124 was removed from the experiment due to old age after Phase 1 and was replaced with a new pigeon (labeled 124a) for subsequent phases. Pigeon 126 completed the first four phases of the experiment and was then removed due to old age.

Pigeons were kept at 85% ± 15 g of free-feeding body weight by supplementary feeding of mixed grain, when necessary, at 10 a.m. daily. Water and grit were freely available. The pigeons were housed in a colony room with a time-shifted environment (lights on at 12 a.m. and off at 4 p.m.).

Apparatus

Pigeons were housed individually in home cages, which also served as the experimental chambers. Each cage measured 375 mm high, 375 mm deep, and 370 mm wide. Two perpendicular wooden perches were mounted 60 mm above the cage floor; one perch was parallel to and 95 mm away from the right wall, and the other perch was parallel to and 95 mm away from the front wall. An operant panel containing three circular response keys was mounted on the right wall of the cage, 300 mm above the floor. Each response key measured 20 mm in diameter, and keys were centered 70 mm apart horizontally. The center key could be lit blue or white, and the side keys could be lit red or orange. Responses exceeding 0.1 N to illuminated keys were recorded. A magazine aperture measuring 50 mm by 50 mm was centered 90 mm below the response keys, and a hopper filled with wheat was located behind the magazine aperture. During a reinforcer delivery, the hopper was raised for 3 s, the magazine aperture was lit, and the keylights were extinguished. In an adjacent room, a computer running MED-PC IV software ran the experiment and recorded all experimental events.

Procedure

General trial structure

Sessions consisted of symbolic 0-s delayed MTS trials. Each session lasted for 80 trials or until 1 hr had elapsed, whichever occurred first. Sessions began at 3 a.m. each morning.

Each trial began with the presentation of a compound sample stimulus on the center key. The sample stimulus was a blue or white keylight that alternated on and off at either a fast or slow frequency (every 0.1 s or 0.9 s in Phases 1, 2, and 5 or every 0.3 s or 0.5 s in Phases 3 and 4). Thus, there were four sample stimuli (blue-fast, blue-slow, white-fast, white-slow), and the alternation frequencies were either disparate (i.e., an easy discrimination in Phases 1, 2, and 5) or similar to each other (i.e., a hard discrimination in Phases 3 and 4). At the beginning of each trial, the experiment program chose a sample stimulus randomly ($p = .25$), with the constraint that each sample was presented no more than 20 times per session (to ensure equal presentation of each sample). The sample stimulus was presented for 5 s, after which a response to the sample resulted in its offset and the onset of the comparison stimuli.

The comparison stimuli were the two side keys, which were lit either red or orange depending on the dimension to report. If the dimension to report was color (henceforth, color trials), then the comparison assigned to match symbolically the color of the sample stimulus was the correct response. Similarly, if the dimension to report was alternation frequency (frequency trials), then the comparison assigned to match the alternation frequency of the sample was the correct response. The colors of the comparison keys and the comparison key matching each stimulus element were counterbalanced across pigeons (see Table 1). Thus, for example, for Pigeon 121, the comparison keys were lit red in color trials, and a left response was correct after a blue sample and a right response was correct after a white sample. For that same pigeon, the comparison keys were lit orange in frequency trials, and left and right responses were correct after fast and slow sample stimuli, respectively. A response to either comparison key resulted in the offset of the comparison stimuli. Correct responses were followed by a 3-s food delivery or equivalent-length blackout depending on whether a reinforcer was arranged. Incorrect responses

TABLE 1 Color of comparison keys, and key matching each stimulus element.

	Comparison key color		Stimuli matching comparisons in Phases 1 and 2		Stimuli matching comparisons in Phases 3 to 5	
Pigeon	**Color**	**Freq.**	**Match left**	**Match right**	**Match left**	**Match right**
121	Red	Orange	Blue, Fast	White, Slow	White, Slow	Blue, Fast
122	Red	Orange	White, Fast	Blue, Slow	White, Slow	Blue, Fast
123	Red	Orange	Blue, Slow	White, Fast	Blue, Slow	White, Fast
124/124a	Orange	Red	Blue, Fast	White, Slow	White, Slow	Blue, Fast
125	Orange	Red	White, Slow	Blue, Fast	Blue, Fast	White, Slow
126	Orange	Red	Blue, Slow	White, Fast	Blue, Fast	White, Slow

Note: Pigeon 124 completed Phase 1 and was replaced with Pigeon 124a for subsequent phases. Freq = alternation frequency.

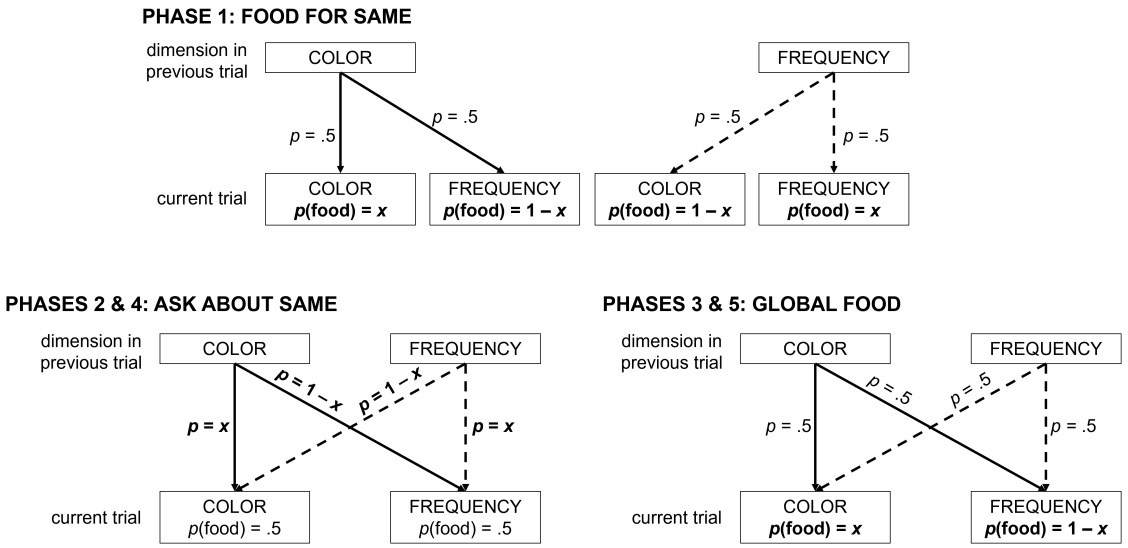

FIGURE 1 Contingencies arranged in each phase. Bolded probabilities indicate the manipulated probabilities (x and $1 - x$) in each phase. The probabilities next to each arrow indicate the probability of selecting the dimension to report (e.g., in Phase 1, the dimension to report was always selected with $p = .50$, whereas this probability varied in Phases 2 and 4).

were followed by a 3-s blackout. Trials were separated by a 3-s intertrial interval, during which the keys remained dark.

MTS pretraining

Before beginning the experiment, we arranged pretraining sessions with the procedure described above. The dimension to report was chosen randomly ($p = .50$) in these sessions, with the constraint that each dimension was selected up to a maximum of 10 times per sample stimulus (to ensure equal experience with each dimension). The purpose of pretraining was to reduce gradually the overall reinforcer probability to .50, which was the probability arranged in all phases of the experiment. Pretraining began with all correct responses reinforced for 26 sessions, after which the probability of food delivery for correct responding was reduced to .90 for two sessions and then reduced in increments of .10 every two sessions until it reached .70. Thereafter, the food probability was reduced in increments of .10 every three sessions until it reached .50. After five sessions with an overall food probability of .50, the experiment proper began.

Food-for-same conditions (Phase 1)

In Phase 1 (Conditions 1 to 7), we manipulated the conditional probability of a food delivery for a correct response to the same dimension as the previous trial. The contingencies are shown in the top panel of Figure 1, and Table 2 shows the sequence of conditions. In each trial, the dimension to report was chosen with a probability of .50, as in MTS pretraining. The probability of a food delivery for a correct response was .50 in the first trial of each session, and thereafter, food deliveries were arranged probabilistically depending on whether the dimension to report was the same as the previous trial. This probability ranged from 0 to 1, with higher probabilities corresponding to a greater likelihood of food

TABLE 2 Sequence of conditions.

	Arranged			Obtained *M*(*SEM*)		
Condition	***p*(food for same)**	***p*(ask abt same)**	***p*(food for color)**	***p*(food for same)**	***p*(ask abt same)**	***p*(food for color)**
Phase 1: Food-for-same conditions (easy frequency discrimination)						
1	.50	.50	.50	.50 (.00)	.50 (.01)	.49 (.01)
2	.75	.50	.50	.74 (.00)	.50 (.01)	.49 (.01)
3	.10	.50	.50	.09 (.00)	.49 (.01)	.49 (.00)
4	.90	.50	.50	.90 (.01)	.50 (.01)	.51 (.01)
5	0	.50	.50	0 (0)	.49 (.00)	.49 (.01)
6	1	.50	.50	1 (0)	.49 (.01)	.49 (.01)
7	.25	.50	.50	.25 (.01)	.50 (.01)	.50 (.00)
Phase 2: Ask-about-same conditions (easy frequency discrimination)						
8	.50	.75	.50	.45 (.02)	.75 (.01)	.46 (.03)
9	.50	.10	.50	.44 (.01)	.10 (.00)	.50 (.01)
10	.50	.35	.50	.49 (.02)	.35 (.01)	.49 (.01)
11	.50	.90	.50	.48 (.01)	.90 (.00)	.46 (.02)
12	.50	.50	.50	.46 (.02)	.50 (.00)	.47 (.01)
Phase 3: Global-food conditions (hard frequency discrimination)						
13	.50	.50	.50	.47 (.03)	.49 (.01)	.51 (.01)
14	.50	.50	.90	.48 (.02)	.50 (.00)	.89 (.01)
15	.50	.50	.10	.45 (.04)	.49 (.01)	.09 (.01)
16	.50	.50	.25	.47 (.04)	.50 (.01)	.26 (.01)
17	.50	.50	.75	.47 (.02)	.50 (.01)	.76 (.01)
18	.50	.50	0	.45 (.04)	.49 (.01)	0 (0)
19	.50	.50	.50	.47 (.02)	.50 (.00)	.50 (.01)
20	.50	.50	1	.49 (.01)	.50 (.01)	1 (0)
Phase 4: Ask-about-same conditions (hard frequency discrimination)						
21	.50	.90	.50	.36 (.01)	.90 (.00)	.63 (.01)
22	.50	.10	.50	.34 (.01)	.10 (.00)	.66 (.02)
23	.50	.35	.50	.38 (.02)	.25 (.01)	.68 (.01)
24	.50	.75	.50	.35 (.02)	.75 (.00)	.62 (.03)
25	.50	.50	.50	.36 (.01)	.49 (.00)	.67 (.02)
Phase 5: Global-food conditions (easy frequency discrimination)						
26	.50	.50	1	.48 (.01)	.49 (.00)	1 (0)
27	.50	.50	.50	.47 (.03)	.49 (.00)	.49 (.01)
28	.50	.50	.75	.47 (.02)	.50 (.01)	.75 (.00)
29	.50	.50	.10	.47 (.01)	.48 (.00)	.09 (.01)
30	.50	.50	.90	.49 (.02)	.50 (.01)	.89 (.00)
31	.50	.50	.25	.48 (.02)	.49 (.00)	.23 (.01)
32	.50	.50	0	.50 (.01)	.51 (.00)	0 (0)
33	.50	.50	.50	.48 (.01)	.50 (.00)	.51 (.01)
34	.50	.50	.95	.49 (.01)	.49 (.00)	.95 (.00)
35	.50	.50	.60	.48 (.00)	.49 (.00)	.61 (.01)

Note: *p*(food for same) = conditional probability of a reinforcer given that the previous dimension to report was the same as the current dimension to report; *p*(ask about same) = probability of asking about the same dimension as the previous trial; *p*(food for color) = probability of a reinforcer in color trials.

delivery for a correct response according to the same dimension. For example, in Condition 2, if the current trial was a color trial, then a correct response was reinforced with a probability of .75 if the previous trial was also a color trial and with a probability of .25 if the previous trial was a frequency trial.

To ensure that the obtained proportion of reinforcers approximated arranged probabilities, reinforcers were arranged dependently (Stubbs & Pliskoff, 1969). This meant, for example, that if a food delivery was arranged for a "same" trial (i.e., a trial in which the dimension to report was the same as the previous trial), that reinforcer was held and no further reinforcers could be arranged until a correct response was made in a "same" trial. Note that the reinforcer probability always depended on the dimension to report in the immediately preceding trial (regardless of whether that trial had ended in a reinforcer delivery) rather than on a specific dimension to report. That is, reinforcers were assigned to "same" or "different" trials, not to "color" or "frequency" trials. Thus, if a reinforcer was arranged for a "same" trial, then that reinforcer could be obtained following either a sequence of two color trials or a sequence of two frequency trials; likewise, if a reinforcer was arranged for a "different" trial, then it could be obtained in a color trial after a frequency trial, or vice versa. Thus, the local contingency was always defined over a two-trial sequence, ensuring that incorrect responses did not increase the memory demands of the task (if reinforcers had been assigned to color or frequency trials, incorrect responses would have delayed reinforcer delivery such that the obtained reinforcer would be contingent on the dimension to report several trials earlier). The right columns of Table 2 show that obtained reinforcer proportions closely approximated arranged proportions in these conditions. Each condition in Phase 1 lasted for 50 sessions.

Ask-about-same conditions (Phases 2 and 4)

In Phases 2 and 4 (Conditions 8 to 12 and Conditions 21 to 25; see Table 2), we manipulated the conditional probability of asking about the same dimension as the previous trial (bottom-left panel of Figure 1). The dimension to report in the first trial of each session was selected with a probability of .50. In subsequent trials, the dimension was chosen probabilistically depending on the dimension to report in the previous trial. The probability of choosing the same dimension ranged from .10 to .90 across conditions, with higher probabilities corresponding to a greater likelihood of asking about the same dimension as the previous trial. For example, in Condition 8, there was a .75 probability that the dimension to report in the current trial would be the same as that in the previous trial and a .25 probability that the dimension would be different from that in the previous trial. In these conditions, correct responses were always reinforced with a probability of .50. The right columns of Table 2 show that the obtained proportion of asking about the same dimension approximated arranged probabilities.[2]

[2]In Phase 4, obtained p(food for same) and p(food for color) deviated from .50. This was because the alternation-frequency discrimination was harder in Phase 4, meaning that fewer reinforcers were obtained in frequency trials than in color trials.

Phases 2 and 4 were identical, except that the alternation-frequency discrimination was easier in Phase 2 and harder in Phase 4. Because visual inspection indicated that responding stabilized quickly, usually within the first few sessions of each condition, Phase 2 conditions lasted for 31 sessions each.

Global-food conditions (Phases 3 and 5)

In Phases 3 and 5 (Conditions 13 to 20 and Conditions 26 to 35; see Table 2 and bottom-right panel of Figure 1), the probability of a reinforcer delivery or of asking about the same dimension did not depend on the dimension to report in the previous trial. Instead, the dimension to report was always selected with a probability of .50, and we manipulated the probability of a food delivery in color trials from 0 to 1 (the probability of food delivery in frequency trials was the complement). Reinforcers were scheduled dependently such that a reinforcer arranged for a dimension was held until a correct response according to that dimension was made. As in ask-about-same conditions, Phases 3 and 5 differed only in the difficulty of the alternation-frequency discrimination (hard in Phase 3, easy in Phase 5). Each condition lasted for 31 sessions.

Data Analysis

Discriminative control and bias

Responses to the correct and incorrect comparison keys were separated according to the sample stimulus (blue-fast, blue-slow, white-fast, white-slow) and the dimension to report (color or alternation frequency) in each trial. We used these response counts to calculate a bias-free measure of conditional discrimination, log d_x, for each stimulus dimension (Davison & Nevin, 1999):

$$\log d_x = 0.5 \log\left(\frac{B_{correct\,|\,S1}}{B_{incorrect\,|\,S1}} \cdot \frac{B_{correct\,|\,S2}}{B_{incorrect\,|\,S2}}\right), \qquad (1)$$

where x is a placeholder representing the stimulus dimension and $S1$ and $S2$ represent the color elements (blue and white, respectively) or alternation-frequency elements (fast and slow, respectively). $B_{correct\,|\,Sy}$ and $B_{incorrect\,|\,Sy}$ represent the number of comparison responses that matched or did not match, respectively, element Sy. For example, $B_{correct\,|\,S1}$ represents the number of comparison responses matching the blue element (in color trials) or the fast element (in frequency trials), and $B_{incorrect\,|\,S1}$ represents the number of responses that did not match the blue or fast element in those trials. Because some response counts were zero, we added 0.5 to all

counts (Hautus, 1995). A log d_x value of zero indicates no discriminative control by stimulus dimension x, and more positive values reflect stronger control by that dimension.

We also calculated a related measure, log b_x, which quantifies bias toward one comparison key:

$$\log b_x = 0.5 \log\left(\frac{B_{left\,|\,S1}}{B_{right\,|\,S1}} \cdot \frac{B_{left\,|\,S2}}{B_{right\,|\,S2}}\right), \quad (2)$$

where the parameters are as in Equation 1, except that left and right response counts are used instead of correct and incorrect responses. A log b_x value of zero indicates no bias toward either comparison, and positive or negative values indicate a bias toward the left or right key, respectively.

In food-for-same and ask-about-same conditions, data were separated according to the dimension to report in both the current and previous trial for calculations of log d_x and log b_x (the first trial of each session was excluded from analysis because there was no previous trial). Thus, in these conditions, we calculated log d_x and log b_x for trials in which the dimension to report was the same as that in the previous trial (two color trials in a row or two frequency trials in a row; for brevity, "same-color" and "same-frequency" trials) and for trials in which the dimension to report differed from that in the previous trial (a color trial followed by a frequency trial or vice versa; "diff-color" and "diff-frequency" trials). In global-food conditions, data were only separated according to the dimension to report in the current trial. To assess changes in log d_x and log b_x across conditions, we used nonparametric trend tests (Elliffe & Elliffe, 2019; Kendall, 1955). Where replication conditions were conducted (e.g., Phase 3, in which Conditions 13 and 19 arranged the same global probability; see Table 2), we used the first of the replication conditions for trend tests.

Choice latencies

Another measure that may be sensitive to reinforcer probabilities in MTS procedures is the latency to respond during the comparison phase (e.g., Shahan & Podlesnik, 2007). Thus, we also examined the effects of local and global probabilities on latencies to respond to a comparison key. Comparison-key responses were separated based on the dimension to report in the current trial (and the dimension to report in the previous trial, in food-for-same and ask-about-same conditions), and we calculated the median time (in seconds) between the onset of the comparison keys and a response to either key. We used nonparametric trend tests to assess changes in latencies across conditions.

Modeling divided stimulus control

Finally, we fit a quantitative model of divided stimulus control (Davison, 2018) to log d_x values for each dimension. Figure 2 summarizes the model, which asserts that obtained reinforcers generalize between (1) the stimuli within a dimension (e.g., blue to white, fast to slow; dashed vertical arrows in Figure 2), (2) the comparison responses (e.g., left to right; solid black horizontal arrows in Figure 2), (3) the stimulus dimensions themselves (e.g., color to alternation frequency; thick gray vertical arrow in Figure 2), and (4) the stimuli signaling the dimension to report (e.g., red to orange comparisons; thick gray horizontal arrow in Figure 2). The first two sources of generalization involve the cells within a submatrix in Figure 2, whereas the latter two sources involve generalization between the submatrices.

Appendix A provides a detailed description of the model and its associated equations (see also Davison, 2018; Gomes-Ng et al., 2023, for detailed explanations). The general logic for calculating the effective (postgeneralization) reinforcer count in a particular cell of the matrix in Figure 2 is as follows:

> Effective Reinforcers R' = obtained reinforcers − (obtained reinforcers *lost* via generalization to other cells in submatrix) − (obtained reinforcers *lost* via generalization to the other matrix) + (obtained reinforcers *gained* via generalization from other cells in submatrix) + (obtained reinforcers *gained* via generalization from the other matrix).

The model contains five parameters quantifying reinforcer generalization between the color elements ($d_{sb\text{-}color}$), alternation-frequency elements ($d_{sb\text{-}freq}$), comparison keys (d_{br}), stimulus dimensions ($d_{DIMENSIONS}$), and comparison stimuli signaling the dimension to report ($d_{COMPARISONS}$). These parameters can take values ranging from 1 (maximum generalization, no discrimination) to ∞ (no generalization, perfect discrimination). Although the original model includes separate parameters quantifying generalization between dimensions and between comparison stimuli, these parameters are always multiplied together in the model terms that redistribute reinforcers between submatrices (see Appendix A). Thus, instead of fitting two separate parameters, we used a single parameter to capture generalization between the submatrices. Henceforth, we will term this parameter $d_{COLOR\text{-}FREQ}$.[3]

[3]We also fit the original model to our data. The proportion of data variance accounted for (VAC) for the full model was always the same as VAC for the model with one parameter capturing generalization between the submatrices. Thus, generalization between the submatrices was described just as well by a single $d_{\text{COLOR-FREQ}}$ parameter as it was by the two separate parameters proposed by Davison (2018). Moreover, the product of the two parameter estimates (i.e., $d_{DIMENSIONS} \times d_{COMPARISONS}$) equaled the $d_{COLOR\text{-}FREQ}$ estimates. Thus, a single parameter is more parsimonious.

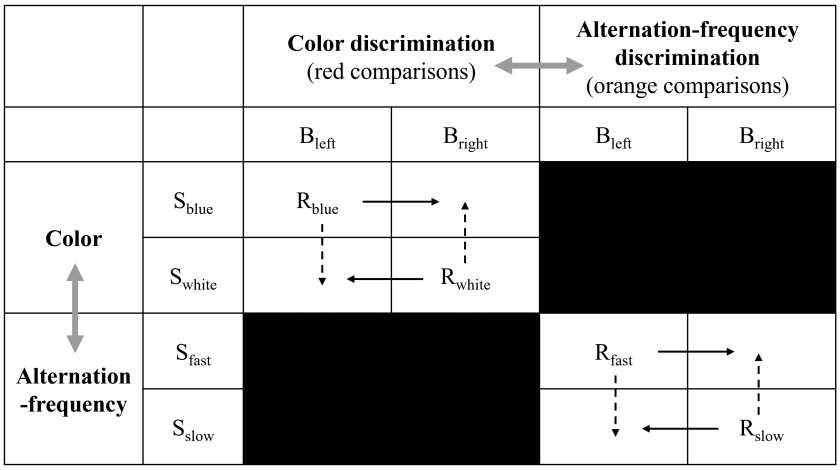

FIGURE 2 Summary of Davison's (2018) model of divided stimulus control. *S* represents the stimulus elements, *B* represents comparison-key responses, and *R* represents reinforcers obtained for correct responses. The arrows show reinforcer generalization.

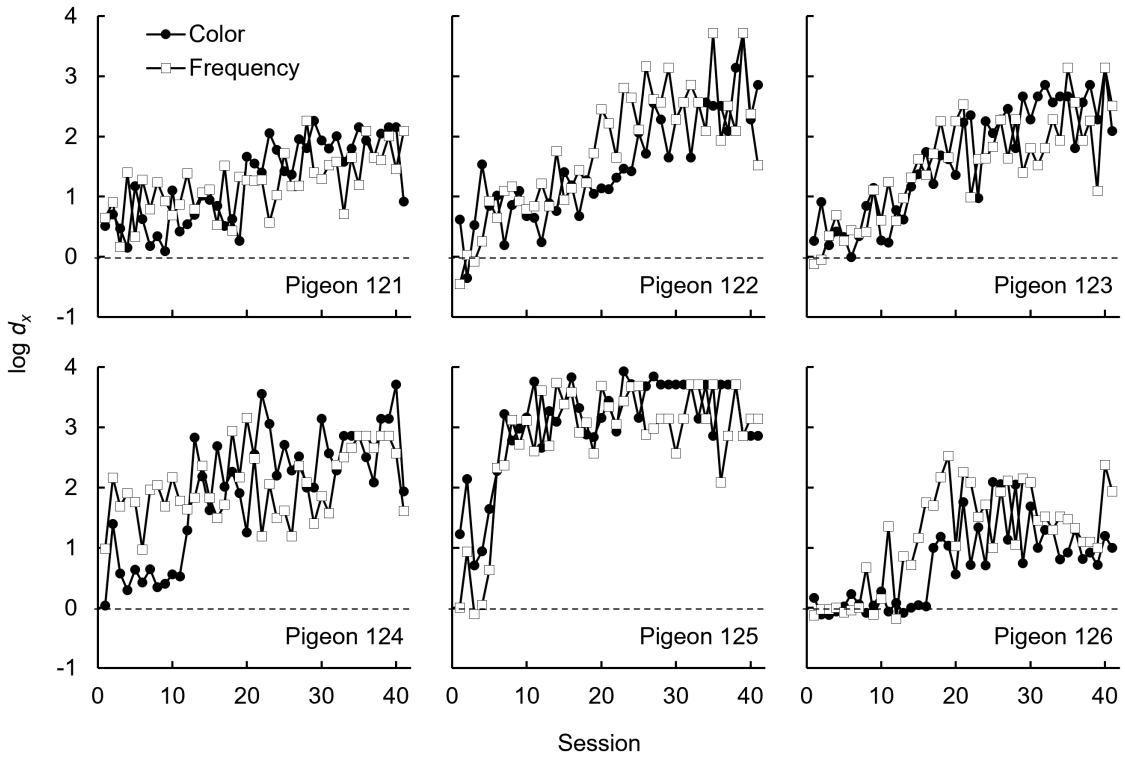

FIGURE 3 Log d_x values across sessions during pretraining. Each panel shows data from an individual pigeon. Filled circles show log d_{color} values, and unfilled squares show log d_{freq} values.

RESULTS

Acquisition during pretraining

Figure 3 shows log d_x values (Equation 1) in pretraining sessions, during which correct responses according to both dimensions were reinforced with equal probabilities. Log d_x values were close to zero at the start of pretraining and gradually increased across sessions. By the end of pretraining, log d_x stabilized at above-zero levels for all pigeons, indicating that they had learned the discrimination. There were no systematic differences between stimulus dimensions; thus, discriminative control by color and alternation frequency was similar before the experiment proper began.

Visual inspection of log d_x values across sessions in all conditions indicated that performance had stabilized by the last 15 sessions of each condition for all pigeons and that any fluctuations in performance between sessions were not systematic (see Supplementary Materials for log

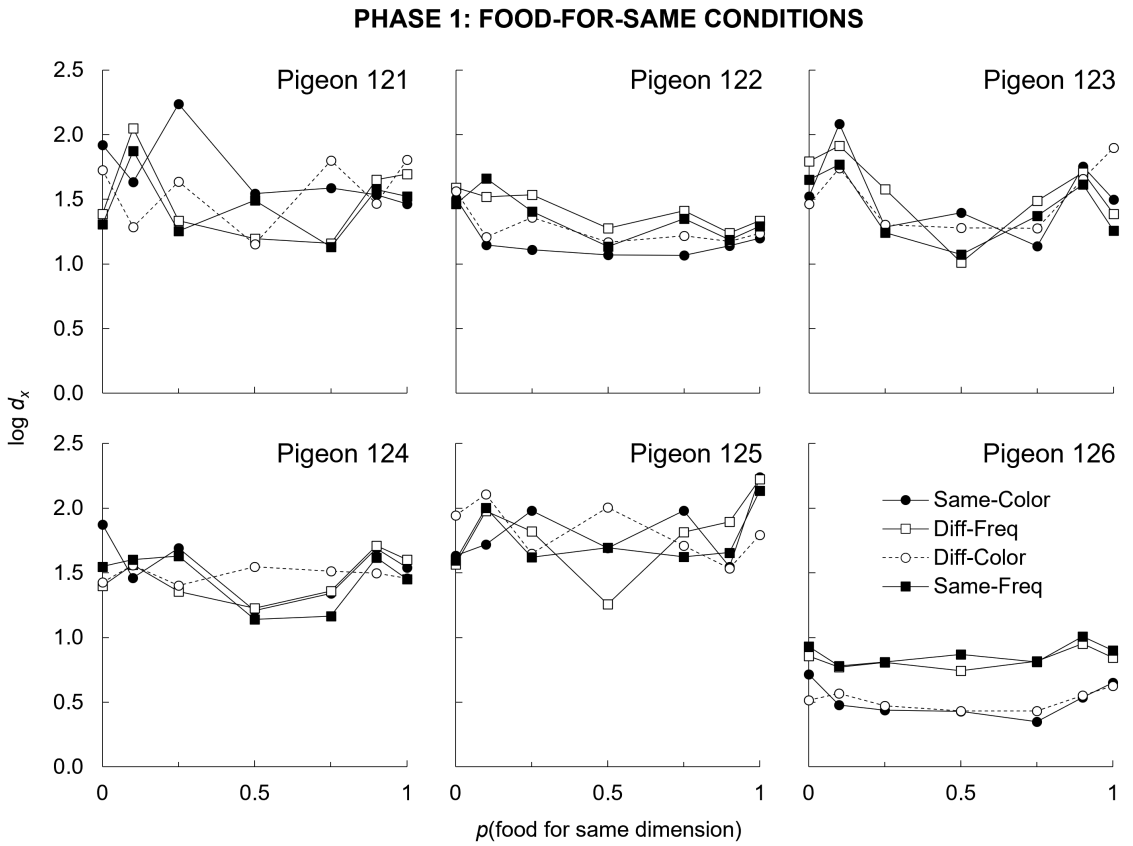

FIGURE 4 Log d_x values in food-for-same (Phase 1) conditions. Each panel shows data for an individual pigeon. Same and Diff refer to trials in which the dimension to report was the same as or different from the previous trial, respectively. -Color and -Freq indicate the dimension to report in the current trial. For example, log d_x values for Diff-Color trials were calculated using data from color trials when the previous dimension to report was alternation frequency.

d_x across sessions in each condition). Thus, all subsequent analyses used data from the last 15 sessions of each condition.

Effects of local probabilities on divided stimulus control

In food-for-same (Phase 1) and ask-about-same (Phases 2 and 4, easy and hard alternation-frequency discriminations, respectively) conditions, the dimension to report in a trial signaled the dimension that was likely to be reinforced or to appear as comparison stimuli in the following trial. If such local probabilities determined divided stimulus control, then log d_x in same-color and same-frequency trials should increase and log d_x in diff-color and diff-frequency trials should decrease as the probability of a reinforcer delivery for same or of asking about the same dimension increased.

Figure 4 shows log d_x values in food-for-same conditions, and Figures 5 and 6 show log d_x values in ask-about-same conditions. Log d_x values were above zero for all pigeons, reflecting control by the color and alternation-frequency dimensions. The only exception was Phase 4, in which log d_{freq} values were close to zero, reflecting the more difficult alternation-frequency discrimination (Figure 6). There were no systematic changes in log d_x across food-for-same conditions (Figure 4; one-tailed nonparametric trend tests: $\Sigma S = -24$, -2, -6, and -6 for same-color, same-freq, diff-color, and diff-freq trials, respectively; all ps > .07). Likewise, there was little systematic change in log d_x in ask-about-same conditions (Figures 5 and 6; Phase 2: $\Sigma S = 0$, 12, -8, -12, and -8 for same-color, same-freq, diff-color, and diff-freq trials, respectively; Phase 4: $\Sigma S = -6$, 14, -4, and 8 for same-color, same-freq, diff-color, and diff-freq trials, respectively; all ps > .09).

There were also no systematic changes in bias (log b_x, Equation 2; figures shown in Supplementary Materials) across food-for-same and ask-about-same conditions; this is unsurprising, as we did not manipulate reinforcer probabilities for left and right comparison responses. Therefore, varying the local probability of a reinforcer delivery for, or of asking about, the same dimension had little effect on divided stimulus control.

The contingencies in food-for-same and ask-about-same conditions were arranged such that local probabilities were contingent on the dimension to report

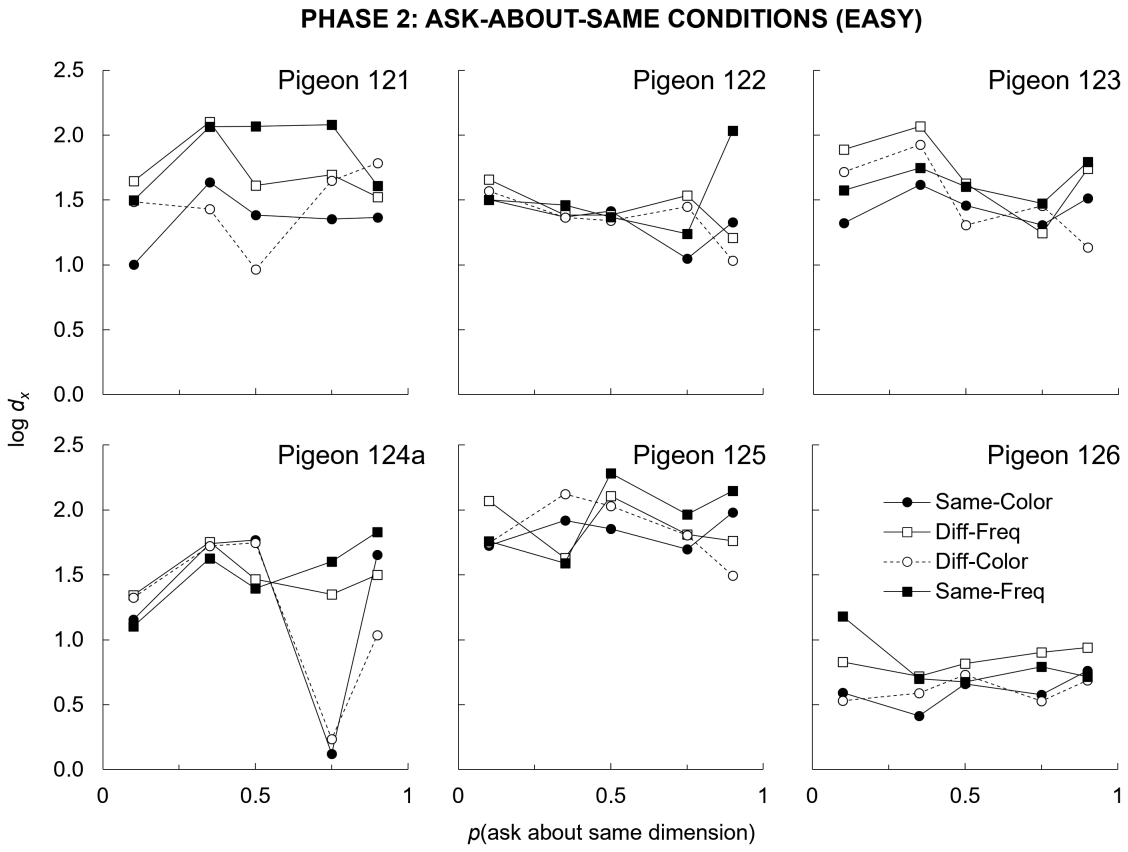

FIGURE 5 Log d_x values in ask-about-same (Phase 2) conditions with an easy alternation-frequency discrimination. Each panel shows data for an individual pigeon. Same and Diff refer to trials in which the dimension to report was the same as or different from the previous trial respectively. -Color and -Freq indicate the dimension to report in the current trial (Color or Frequency, respectively).

in the immediately preceding trial. However, not every correct response was reinforced (as reinforcers were arranged probabilistically; see Figure 1), and this may have made it more difficult to discriminate the contingencies. Figure 7 shows the mean proportion of trials in which a correct response was followed by a reinforcer, by no reinforcer, or in which an incorrect response was followed by a blackout. While the pigeons made few incorrect responses overall, about 50% of correct responses in food-for-same conditions and just over 25% of correct responses in ask-about-same conditions were unreinforced. This may have made it more difficult to discriminate local probabilities, particularly in food-for-same conditions, in which the local reinforcer probability varied across conditions (in ask-about-same conditions, this probability was always .50, and it was the dimension to report that varied across conditions).

In food-for-same conditions, reinforcers were arranged dependently so that a reinforcer arranged for one type of trial sequence (i.e., same or different) was held until a correct response in such a trial occurred. This meant that the pigeons may have experienced sequences of unreinforced trials if they made many incorrect responses. If so, then this would have also reduced the discriminability of the contingencies in food-for-same conditions. To examine the extent to which unreinforced trials may have affected discriminability, we analyzed the distribution of unreinforced trial sequences. In Phases 1 (food-for-same conditions) and 2 (ask-about-same conditions with easy alternation-frequency discrimination), at least 90% of reinforcers were obtained on consecutive reinforced trials (i.e., no unreinforced trial occurred between successive reinforcers), pooled across pigeons in each condition. Thus, sequences of unreinforced trials were rare, occurring in fewer than 10% of cases. In Phase 4 (ask-about-same conditions with hard alternation-frequency discrimination), the pigeons made more incorrect responses (Figure 6); nevertheless, longer unreinforced trial sequences remained uncommon, with at least 60% of reinforcers obtained either in consecutive trials or after a single unreinforced trial.

Effects of global probabilities on divided stimulus control

In global-food conditions (Phases 3 and 5, hard and easy alternation-frequency discriminations, respectively), we manipulated the overall reinforcer probability associated with each stimulus dimension. Thus, in these conditions,

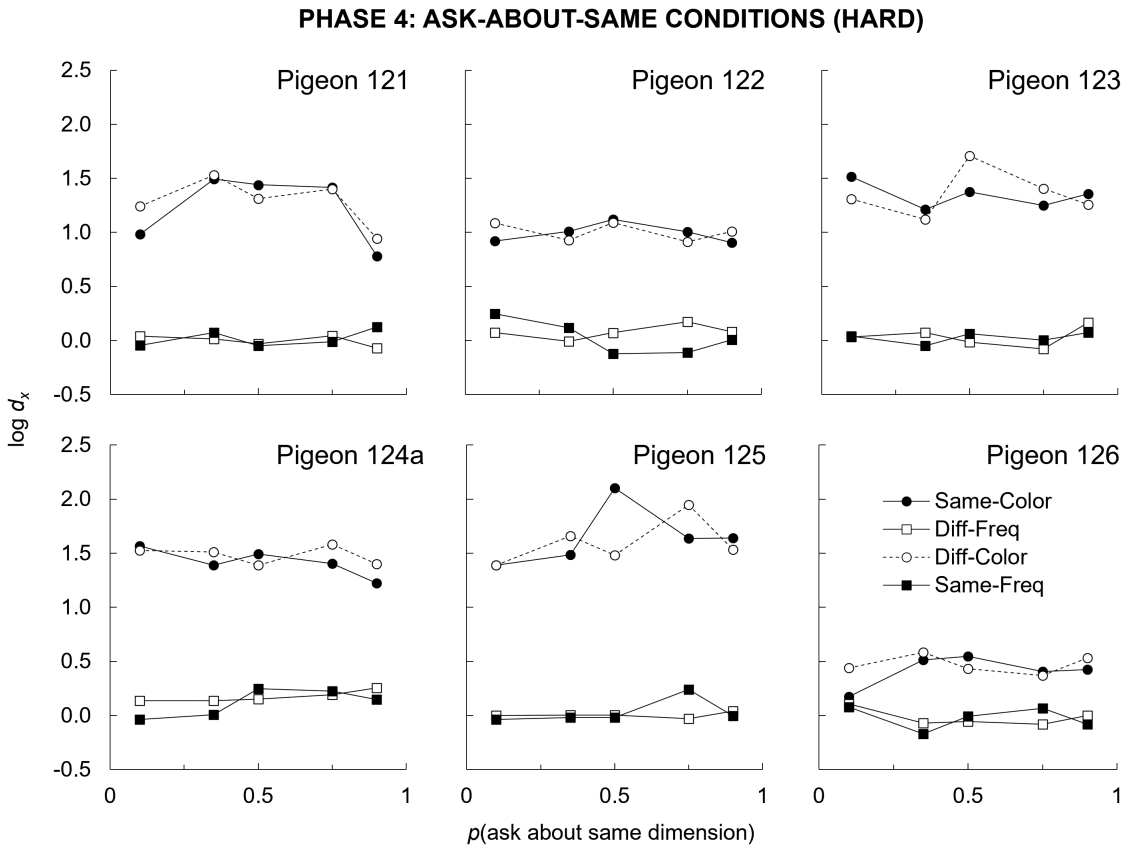

FIGURE 6 Log d_x values in ask-about-same (Phase 4) conditions with a hard alternation-frequency discrimination. Each panel shows data for an individual pigeon. Same and Diff refer to trials in which the dimension to report was the same as or different from the previous trial, respectively. -Color and -Freq indicate the dimension to report in the current trial (Color or Frequency, respectively).

the reinforcer probability in a trial only depended on the dimension to report in that trial. Figures 8 and 9 show log d_x in Phases 3 and 5, respectively. Overall, control by the color dimension was stronger, as evidenced by larger log d_{color} relative to log d_{freq} values even when the reinforcer probabilities for both dimensions were equal. There was some carryover between conditions, as log d_x in a condition changed relative to the previous condition. As a result, changes in log d_x as the reinforcer probability for a dimension increased were not always monotonic and log d_x values in replication conditions differed. For example, the low log d_{freq} values when p(food for color) was .50 in Phase 5 (Condition 27; unfilled squares in Figure 9) reflect carryover from the previous condition in which log d_{freq} values were close to zero because correct responses in frequency trials were never reinforced (Condition 26; p[food for color] = 1).

Despite this carryover, changes in log d_x between conditions followed changes in the reinforcer probabilities for each dimension (Figures 8 and 9). Thus, control by the reinforcer contingencies was still evident. Log d_{color} increased as the reinforcer probability for the color dimension increased in both phases ($\Sigma S = 66$ and 102 in Phases 3 and 5, respectively, both ps < .001). Concomitant decreases in log d_{freq} were evident when the alternation-frequency discrimination was easy (Phase 5; $\Sigma S = -94$, $p < .001$), whereas log d_{freq} remained close to zero when the discrimination was hard (Phase 3; $\Sigma S = 10$, $p = .292$). Therefore, control by a stimulus dimension depended on its discriminability and on the global reinforcer probability for that dimension. As in other phases, there were no systematic changes in bias across conditions in global-food conditions (see Supplementary Materials).

Choice latencies

To examine further the effects of local and global probabilities on divided stimulus control, we analyzed latencies to respond to a comparison key. Because local and global probabilities had similar effects on behavior across pigeons (see Figures 4–9), we present the group average of the median choice latencies here. Figure 10 shows average latencies in each phase, which are representative of individual-pigeon latencies.

The patterns in Figure 10 are largely similar to those in Figures 4–9. In food-for-same and ask-about-same conditions, latencies changed little across conditions, and one-tailed nonparametric trend tests were not significant

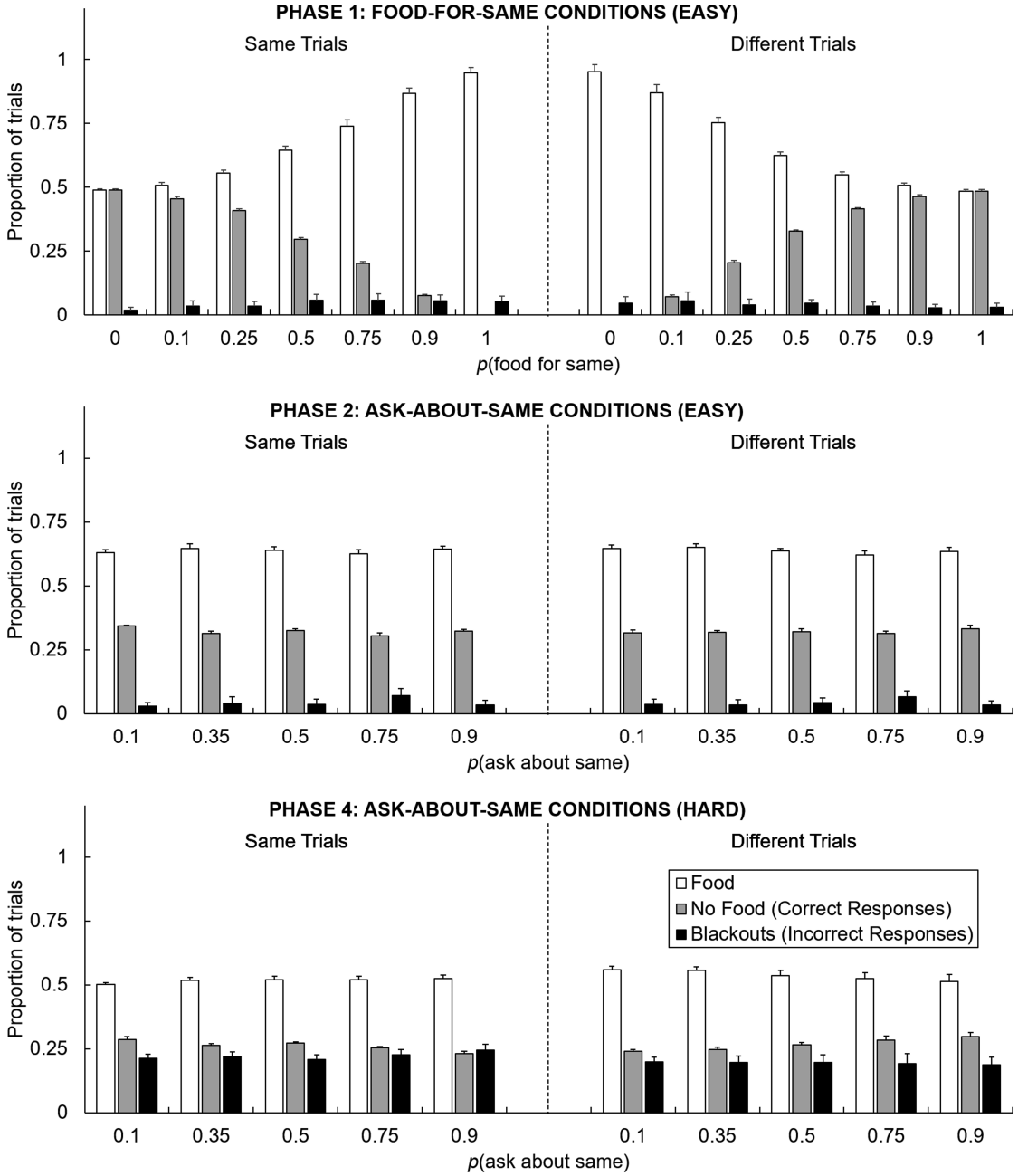

FIGURE 7 Mean proportion of reinforced and unreinforced trials in food-for-same (Phase 1) and ask-about-same (Phases 2 and 4) conditions. Data from Same trials (same-color and same-freq) are shown on the left, and data from different trials (diff-color and diff-freq) are shown on the right. White bars show trials ending in food, gray bars show trials in which a correct response occurred but no food was delivered, and black bars show trials in which an incorrect response and blackout occurred.

for food-for-same conditions (ΣS = 3, 1, −10, −12 for same-color, same-freq, diff-color, and diff-freq trials, respectively; all ps > .20) or ask-about-same conditions (Phase 2: ΣS = 2, −1, 0, −12 for same-color, same-freq, diff-color, and diff-freq trials, respectively; Phase 4: ΣS = 5, −3, 12, 12 for same-color, same-freq, diff-color, and diff-freq trials, respectively; all ps > .10). In contrast, in global-food conditions, choice latencies in color trials decreased and latencies in frequency trials increased as the reinforcer probability in color trials increased. These trends were statistically significant when the alternation-frequency discrimination was hard (Phase 3; ΣS = −46 and 37 for color and frequency trials, respectively; both ps < .005) and when it was easy (Phase 5: ΣS = −81 and 98 for color and frequency trials, respectively; both ps < .001). In sum, like discriminative control (log d_x; Figures 4–9), choice latencies depended on global reinforcer probabilities but not local probabilities (Figure 10). This suggests that the pigeons may not have discriminated changes in local

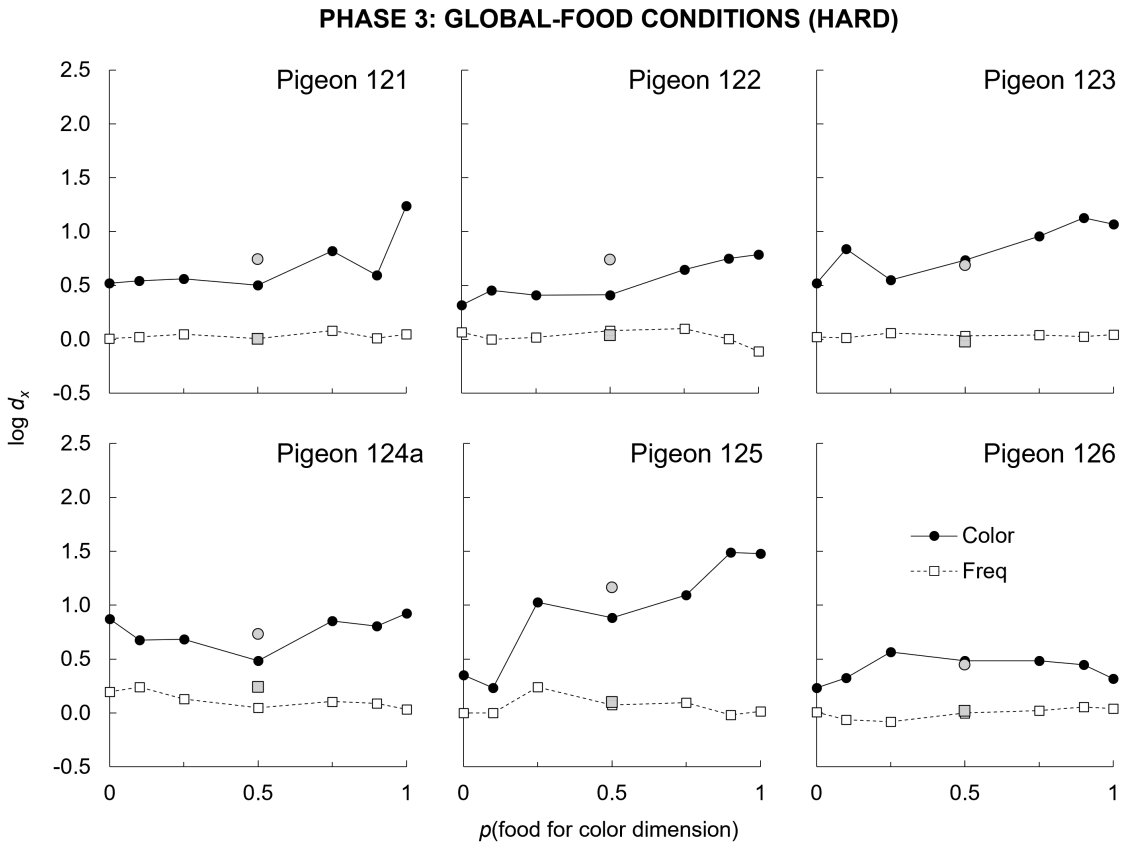

FIGURE 8 Log d_x values in global-food (Phase 3) conditions with a hard alternation-frequency discrimination. Each panel shows data for an individual pigeon. Color and Freq (frequency) refer to the dimension to report in the current trial. The shaded gray symbols show data from replication conditions.

probabilities across conditions in food-for-same and ask-about-same conditions.

Modeling divided stimulus control

Table 3 shows the results of fits of Davison's (2018) model of divided stimulus control (Figure 2) to overall log d_{color} and log d_{freq} values. The model contained five parameters quantifying generalization between the color elements ($d_{sb\text{-}color}$), between the alternation-frequency elements when the discrimination was easy ($d_{sb\text{-}freq\text{-}easy}$) and hard ($d_{sb\text{-}freq\text{-}hard}$), between the comparison keys (d_{br}), and between the color and alternation-frequency discriminations themselves ($d_{COLOR\text{-}FREQ}$). In general, model fits were excellent, with VAC exceeding .85 for all pigeons.

Although there were individual differences in parameter estimates between pigeons (Table 3), similar patterns were evident across most or all pigeons. Overall, d_{br} values were higher than d_{sb} values, suggesting that the degree of reinforcer generalization between the left and right comparison keys was smaller than generalization between the elements within a stimulus dimension. Log d_{sb} values were highest for the easy alternation-frequency discrimination ($d_{sb\text{-}freq\text{-}easy}$), slightly lower for the color discrimination ($d_{sb\text{-}color}$), and lowest for the hard alternation-frequency discrimination ($d_{sb\text{-}freq\text{-}hard}$). Thus, more reinforcer generalization between the stimulus elements occurred when the discrimination was harder. Finally, $d_{COLOR\text{-}FREQ}$ values—which measure the degree of generalization between the color and alternation-frequency discriminations—were generally similar to or larger than d_{sb} values, suggesting that generalization between dimensions was similar to or weaker than between the elements within a stimulus dimension. In summary, the parameter estimates suggest that less reinforcer generalization occurred with easier discriminations (e.g., left vs. right comparison keys, color vs. alternation-frequency discrimination), whereas greater generalization occurred with harder discriminations (hard alternation-frequency discrimination).

DISCUSSION

The present experiment investigated local and global shifts in divided stimulus control. Pigeons reported either the keylight color (blue or white) or frequency of color

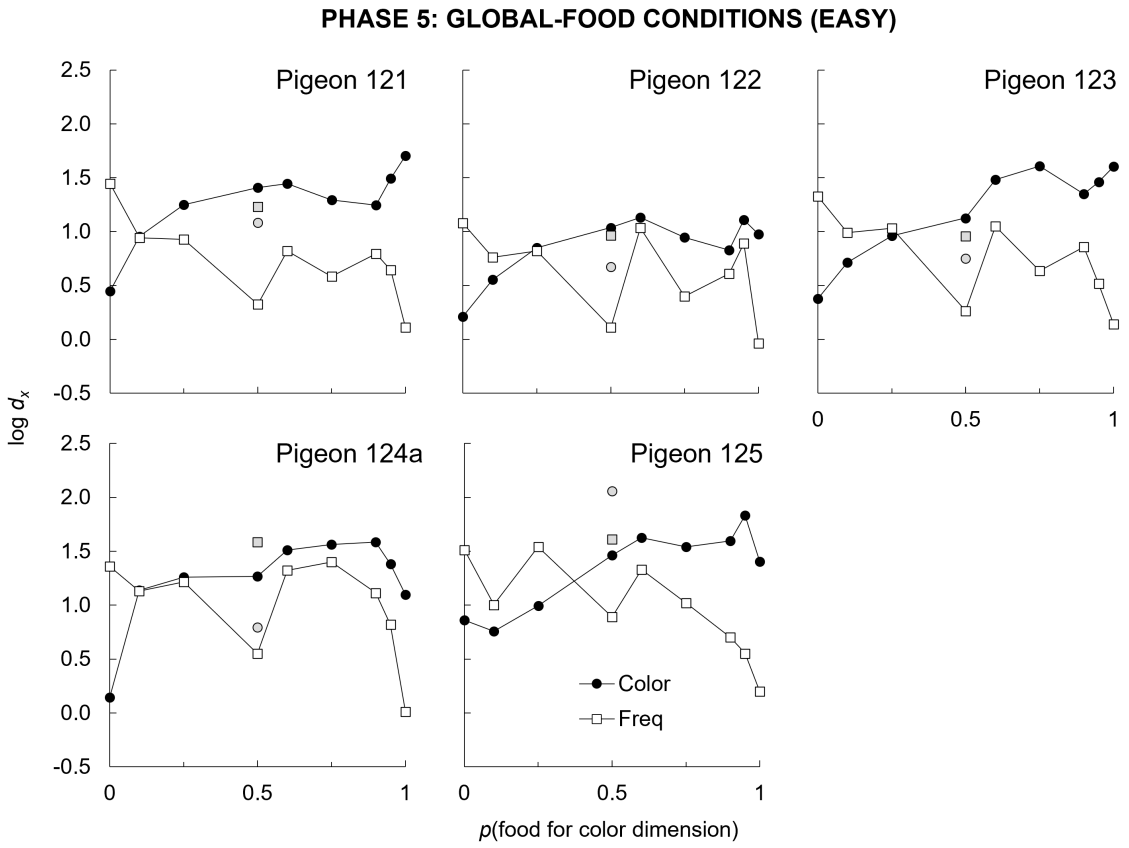

FIGURE 9 Log d_x values in global-food (Phase 3) conditions with a hard alternation-frequency discrimination. Each panel shows data for an individual pigeon. Color and Freq (frequency) refer to the dimension to report in the current trial. The shaded gray symbols show data from replication conditions.

alternation (fast or slow) of a compound sample stimulus in a symbolic MTS procedure. In some conditions, the dimension to report in a trial signaled the dimension that was likely to be reinforced (food-for-same conditions) or to appear as comparison stimuli (ask-about-same conditions) in the next trial. Such local probabilities had little to no effect on divided stimulus control (Figures 4–6, and Figure 10). In contrast, when we manipulated the overall reinforcer probabilities in color and frequency trials (global-food conditions), control by a stimulus dimension increased as the reinforcer probability associated with that dimension increased (Figures 8–10). These effects of global reinforcer probabilities were stronger when both dimensions were discriminable (Phase 5) than when the alternation-frequency dimension was less discriminable (Phase 3). Additionally, global reinforcer effects were well described by a quantitative model (Davison, 2018), suggesting that obtained reinforcers generalize between the elements within a stimulus dimension, between comparison responses, and between the color and frequency discriminations. Our findings highlight the importance of the discriminated reinforcer differential in divided stimulus control and suggest that reinforcer effects occur at global but not necessarily local levels.

Global effects of differential and nondifferential reinforcers on divided control

This study adds to the growing body of evidence showing that overall reinforcer rates determine divided stimulus control or divided attention (e.g., Davison, 2018; Davison & Elliffe, 2010; Gomes-Ng et al., 2019, 2023; Heyman et al., 2016; Heyman & Moncaleano, 2021; Podlesnik et al., 2012; Shahan & Podlesnik, 2006, 2007; Thrailkill et al., 2025). The present findings extend the existing literature by showing that stimulus discriminability moderates the effects of global reinforcer probabilities on divided stimulus control; changes in divided control across conditions were larger when both dimensions were discriminable (Phase 5; Figure 9) than when the fast and slow elements were less disparate and thus harder to discriminate (Phase 3; Figure 8). This is similar to Shahan and Podlesnik's (2007) finding of greater sensitivity to relative reinforcer probabilities with longer compound sample presentations (which may have made it easier to discriminate the stimulus dimensions; see also Thrailkill et al., 2025). The effects of stimulus discriminability on divided stimulus control are also consistent with findings showing that sensitivity to reinforcer ratios in concurrent

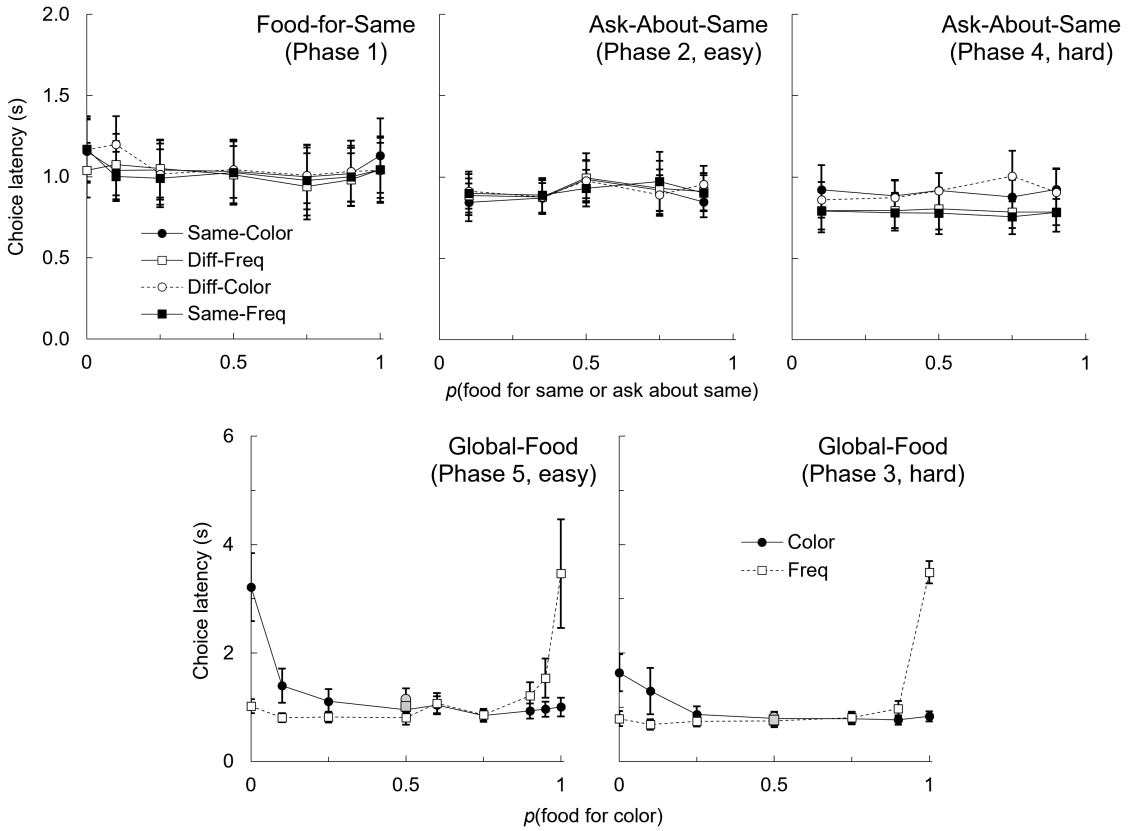

FIGURE 10 Mean (across pigeons) choice latencies. The top row shows data from conditions in which local probabilities were manipulated (food-for-same and ask-about-same conditions), and the bottom row shows data from conditions in which global probabilities were manipulated (global-food conditions). Error bars show the SEM.

TABLE 3 Model fits to individual pigeon data.

	Pigeon					
	121	**122**	**123**	**124a***	**125**	**126***
log $d_{sb\text{-}color}$	1.59	1.25	1.65	1.28	1.72	0.73
log $d_{sb\text{-}freq\text{-}easy}$	1.76	1.58	1.73	1.43	1.84	1.08
log $d_{sb\text{-}freq\text{-}hard}$	0.34	0.36	0.34	0.40	0.38	0.34
log d_{br}	1.88	1.63	1.86	6.92	3.40	1.44
log $d_{COLOR\text{-}FREQ}$	1.60	1.61	1.57	1.90	1.76	1.59
VAC	.87	.88	.89	.89	.92	.97

Note: *Pigeon 124a joined the experiment in Phase 2, so model fits for that pigeon exclude Phase 1 data. Pigeon 126 was removed from the experiment after Phase 4, so its model fits exclude Phase 5 data.

schedules is greater when the stimuli signaling the response alternatives are easier to discriminate (e.g., Alsop & Davison, 1991, 1992; Everly, 2016; Davison & Cowie, 2022; Godfrey & Davison, 1998; Miller et al., 1980). Thus, our global-food conditions provide further evidence that overall relative reinforcer probabilities divide stimulus control in the same way as they govern concurrent choice.

Our findings also join a small number of studies demonstrating that the effects of global reinforcer probabilities on divided stimulus control can be understood in terms of differential and nondifferential reinforcement (Davison, 2018; Davison & Elliffe, 2010; Gomes-Ng et al., 2023). Even when reinforcers are arranged to be differential with respect to a stimulus dimension, they may not necessarily be discriminated as such due to errors in discrimination (e.g., because of forgetting or when environmental conditions make it harder to discriminate the contingencies). Davison (2018; see also Davison & Elliffe, 2010; Davison & Nevin, 1999) suggested that differential and nondifferential reinforcer effects could be described by a model that redistributes obtained reinforcers between the elements within a stimulus dimension (e.g., blue and white), comparison responses (e.g., left and right), stimulus dimensions (e.g., color and alternation frequency), and comparison stimuli (e.g., red and orange comparison keys). The present study is the first to apply this model to divided stimulus control under typical experimental conditions (see Gomes-Ng et al., 2023, for a test of the model under less typical conditions, i.e., with reinforcers for errors). Our findings provide empirical support for the model, albeit a simpler version capturing reinforcer generalization between stimulus dimensions and comparison stimuli with a single parameter (rather than Davison's two separate parameters). Furthermore, we also show that the parameter estimates vary appropriately with changes in

discriminability (i.e., greater reinforcer generalization with harder discriminations). Therefore, divided stimulus control is graded according to relative discriminated rates of differential and nondifferential reinforcers; higher rates of differential reinforcers and lower nondifferential reinforcer rates engender stronger control by a dimension.

Effects of local contingencies on divided control

In food-for-same and ask-about-same conditions, the dimension to report in a trial signaled the likely next-reinforced or next-relevant dimension in the following trial. These conditions were effectively analogous to those arranged by Krägeloh et al. (2005), in which the location of each reinforcer delivery in a concurrent schedule signaled the likely next-reinforcer location. However, unlike Krägeloh et al., who found that choice after reinforcer deliveries favored the likely next-reinforcer location, local shifts in divided stimulus control toward the signaled dimension were not apparent in our food-for-same and ask-about-same conditions. Therefore, in contrast to global reinforcer probabilities, local contingencies had little to no effect on divided stimulus control. Instead, control by each stimulus dimension was similar to global-food conditions arranging equal reinforcer probabilities in color and frequency trials (i.e., p[food for color] = .50; Figures 4–9). Thus, divided stimulus control appeared to depend on global probabilities (which were always arranged to be equal in food-for-same and ask-about-same conditions; Table 2), even though the likely next-reinforced or next-relevant dimension in a trial could be predicted based on the dimension to report in the previous trial.

The present experiment shares similarities with studies that have investigated local shifts in stimulus control when priming cues signal the relevant dimension to report in a trial (Fremouw et al., 2002) or when most trials arrange the same dimension to report (Fremouw et al., 1998). Fremouw et al. (2002) arranged an MTS procedure in which a pretrial red or green cue signaled the likely dimension to report in the current trial and found that pigeons' accuracy was higher and reaction times were faster—indicating stronger discriminative control—when the dimension to report was consistent with the cued dimension (compared with when it was inconsistent with the cue, which occurred in 15% of trials). In Fremouw et al. (1998), 85% of trials within a session arranged the same dimension to report, resulting in stimulus control shifting toward that dimension and away from the other dimension. These past results appear at odds with our study in which local shifts in divided stimulus control did not occur. This discrepancy may reflect two important procedural differences between Fremouw et al. (1998, 2002) and the current study. First, in Fremouw et al.'s studies, the compound stimuli always contained one relevant element and one irrelevant element. This meant that the dimension to report (and thus the correct comparison response) could be predicted as soon as the sample was presented. In contrast, in the present experiment, both compound-stimulus dimensions were relevant in a trial and the dimension to report was selected probabilistically (i.e., was unpredictable, depending on this probability). This may explain why divided stimulus control shifted toward the relevant dimension in past studies, whereas control by both dimensions was evident across conditions in the present study. Second, in Fremouw et al.'s procedure, the dimension to report in a trial was always independent of the previous trial, whereas in the present experiment it was selected relative to the previous dimension to report. As a result, Fremouw et al.'s contingencies may have been easier to discriminate compared with those in the present experiment, in which memory of and control by the previous dimension to report was required to accurately discriminate local contingencies.

Indeed, when past stimuli are relevant to a present discrimination, control by past stimuli depends on the extent to which they are remembered by the subject (e.g., Cowie et al., 2011, 2017, 2020). If past stimuli are forgotten, then behavior will depend on other available stimuli that are or appear to be relevant to the present discrimination. In our procedure, the comparison phases in consecutive trials were separated by several events (a 3-s food delivery or blackout, 3-s intertrial interval, and a minimum 5-s sample-stimulus presentation), and these events may have retroactively interfered with memory for the dimension to report in the previous trial (see, e.g., Davison, 2018; Grant, 1988; Grant & Roberts, 1976; Roberts & Grant, 1978; Tranberg & Rilling, 1980; Zentall, 1973). If so, then our pigeons would not have been able to discriminate that the events in a trial depended on the previous dimension to report in food-for-same and ask-about-same conditions. This may explain why global probabilities—which could be discriminated without remembering the previous dimension to report—but not local probabilities—determined divided stimulus control in those conditions.

A memory-based explanation can also account for differences between our findings and those of past choice studies (e.g., Cowie et al., 2011, 2017; Krägeloh et al., 2005). In concurrent schedules, reinforcer deliveries are separated by empty interreinforcer intervals, so it may be easier to remember the last-reinforcer location (compared with the dimension to report in the present experiment) because no interfering events occur between reinforcers. Furthermore, egocentric stimuli—such as enduring differences in body positioning (e.g., orienting toward one side of the operant panel)—may help to bridge the gap between successive reinforcer deliveries and thus maintain control by the last-reinforcer location (e.g., Cowie et al., 2020; Davison, 2018; Gomes-Ng et al., 2019, 2022; McMillan & Roberts, 2015;

Rayburn-Reeves et al., 2018). Such mediating behaviors or behavioral mnemonics were not possible in the present experiment because response locations did not differentially predict the likely next-reinforced or next-relevant dimension.

Therefore, the absence of local shifts in divided stimulus control in food-for-same and ask-about-same conditions here may reflect forgetting of the previous dimension to report, which would have reduced the discriminability of the contingencies. To test this, future research could replicate our experiment and include a reminder stimulus signaling the previous dimension to report at the start of each trial. In concurrent schedules, such reminder stimuli (which signal the last-reinforcer location) enhance control by last-reinforcer location (Cowie et al., 2011, 2017); similarly, if a memory-based account of our results is correct, we would expect divided stimulus control to favor the likely next-reinforced or next-relevant dimension when reminder stimuli signal the previous dimension to report.

Alternatively, it may be the case that unlike the last-reinforcer location in a concurrent schedule, the dimension to report in a divided-stimulus-control procedure does not function as a discriminative stimulus. An important difference between the last-reinforcer location and the dimension to report is that the former is inextricably linked to subjects' behavior (they must respond to that location) and a reinforcer delivery, whereas this is not the case for the dimension to report. Instead, in the typical divided-stimulus-control procedure, the dimension to report in each trial is chosen probabilistically and independently of subjects' behavior and trial outcomes. Prior work suggests that reinforcer deliveries may be more salient, and thus more effective discriminative stimuli, than nonreinforced stimuli. For example, Davison and Baum (2006) found that changes in choice after food deliveries were larger than after nonfood stimuli, even when both food deliveries and nonfood stimuli signaled the same local contingencies (see also Boutros, Davison, & Elliffe, 2011; Davison & Baum, 2010; Fox & Kyonka, 2014, 2016). The subject's own behavior may also exert strong discriminative control, sometimes even at the expense of control by more reliable stimuli (e.g., Cowie et al., 2020; Gomes-Ng et al., 2019, 2022; Jones & Davison, 1998; Killeen, 1978; Urcuioli, 1984, 1985). Therefore, one possibility is that reinforcer locations, but not the dimension to report, are effective discriminative stimuli because they depend on the subjects' behavior and the delivery of a reinforcer. Given that these properties are inherent to last-reinforcer location and not to the dimension to report (i.e., these are fundamental differences between reinforcer locations and the dimension to report), this line of reasoning suggests a potential limit to the parallels between concurrent choice and divided stimulus control.

CONCLUSION

What do the present findings suggest about the variables that influence the division of control between multiple stimulus dimensions? First, our findings provide additional evidence that the overall division of stimulus control is graded according to relative reinforcer probabilities, at least to the extent that the stimuli and reinforcer probabilities are accurately discriminated by the organism. When errors in discrimination occur—for example, because of memory or perceptual failures (e.g., Cowie & Davison, 2022; Davison & Nevin, 1999)—these degrade the reinforcer differential such that some reinforcers may *appear* nondifferential with respect to a stimulus dimension. The present study joins just two others (Davison & Elliffe, 2010; Gomes-Ng et al., 2023) showing that the effects of differential and nondifferential reinforcers on divided stimulus control can be described by a model that redistributes obtained reinforcers between stimuli or responses. We provide the first empirical support for Davison's (2018) extended version of this model, which contains a parameter reflecting reinforcer generalization between the discriminations themselves (i.e., between stimulus dimensions). Furthermore, this study is the first to show that the model's parameters vary appropriately with changes in stimulus discriminability.

Second, we are the first to ask whether local (trial-to-trial) shifts in divided stimulus control occur when the dimension to report in a trial signals the likely next-reinforced or next-relevant dimension. Given that global reinforcer probabilities divide stimulus control just as they divide responding in concurrent schedules, we expected that the dimension to report would function as a discriminative stimulus in the same way as the last-reinforcer location does in concurrent schedules. However, we found little support for such discriminative effects of the dimension to report on local divided stimulus control. This may reflect fundamental differences in the nature of divided stimulus control compared with concurrent choice; specifically, divided control is typically examined in a discrete-trials MTS procedure in which the dimension to report is selected independently of subjects' behavior and trial outcomes, whereas choice is typically examined in a free-operant procedure and the last-reinforcer location depends on subjects' behavior and a reinforcer delivery. These differences—particularly in the dependence on behavior and reinforcer delivery—suggest that parallels between divided stimulus control and choice may not extend to local levels of analysis. Our findings thus raise an important question about the extent to which divided stimulus control can (and should) be conceptualized as similar to concurrent choice.

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AUTHOR CONTRIBUTIONS

Stephanie Gomes-Ng: conceptualization, methodology, formal analysis, investigation, writing original draft, review, editing, visualization, project administration.

Douglas Elliffe: conceptualization, writing, review, editing, resources, supervision.

Sarah Cowie: conceptualization, methodology, resources, writing, review, editing, supervision.

CONFLICT OF INTEREST STATEMENT

No conflicts of interest.

ETHICS APPROVAL

This experiment was conducted under Approval 2657, granted by The University of Auckland Animal Ethics Committee.

DATA AVAILABILITY STATEMENT

Data will be made available upon request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX A

A.1 | Modeling divided stimulus control

This appendix provides a detailed description of Davison's (2018) model of divided stimulus control. The model that we fit to the data contained five parameters quantifying reinforcer generalization. For generalization between the color elements, we used one parameter ($d_{sb\text{-}color}$) for all conditions because these elements were the same in all conditions. For generalization between the alternation-frequency elements, we used separate parameters to quantify generalization when the discrimination was easy ($d_{sb\text{-}freq\text{-}easy}$) and when it was hard ($d_{sb\text{-}freq\text{-}hard}$). We used one parameter for generalization between the comparison keys (i.e., left and right) because they remained the same across conditions (d_{br}) and one parameter to quantify generalization between the dimensions themselves ($d_{COLOR\text{-}FREQ}$).

We calculated the effective (postgeneralization) reinforcer counts for each cell of the matrix shown in Figure 2. When the dimension to report was color, the effective reinforcers (R') for a correct and incorrect response following a blue sample stimulus were calculated using the following equations:

$$R'_{blue\,|\,correct} = R_{blue} - \frac{R_{blue}}{d_{sb-color}} - \frac{R_{blue}}{d_{br}} - \frac{R_{blue}}{d_{sb-color}d_{br}} - \left(\frac{R_{blue}}{d_{COLOR-FREQ}}\right) + \frac{R_{white}}{d_{sb-color}d_{br}} + \frac{1}{4}\left(\frac{R_{fast}+R_{slow}}{d_{COLOR-FREQ}}\right); \quad \text{(A1)}$$

$$R'_{blue\,|\,incorrect} = \frac{R_{blue}}{d_{br}} + \frac{R_{white}}{d_{sb-color}} + \frac{1}{4}\left(\frac{R_{fast}+R_{slow}}{d_{COLOR-FREQ}}\right), \quad \text{(A2)}$$

where R_{blue} and R_{white} represent the number of obtained reinforcers for correct responses when the sample stimulus was blue or white, respectively. In Equation A1, which quantifies effective reinforcers for a correct response following a blue sample stimulus, the second to fourth terms on the right-hand side represent reinforcers *lost* (thus the subtraction) via generalization to the other color element, comparison key, and stimulus dimension. The last two terms represent reinforcers *gained* (thus the addition) via generalization from the other color element (white) and the other dimension (alternation-frequency). The last term is divided by four because generalization from the other dimension is assumed to be equally divided between all four cells in the color submatrix in Figure 2. In Equation A2, which quantifies effective reinforcers for an incorrect response following a blue sample stimulus, the terms represent reinforcers gained via generalization from correct responses in color trials and from the other dimension.

The same logic can be applied to calculate the effective reinforcers for correct responses following a white sample stimulus:

$$R'_{white\,|\,correct} = R_{white} - \frac{R_{white}}{d_{sb-color}} - \frac{R_{white}}{d_{br}} - \frac{R_{white}}{d_{sb-color}d_{br}} - \left(\frac{R_{white}}{d_{COLOR-FREQ}}\right) + \frac{R_{blue}}{d_{sb-color}d_{br}} + \frac{1}{4}\left(\frac{R_{fast}+R_{slow}}{d_{COLOR-FREQ}}\right). \quad \text{(A3)}$$

$$R'_{white\,|\,incorrect} = \frac{R_{white}}{d_{br}} + \frac{R_{blue}}{d_{sb-color}} + \frac{1}{4}\left(\frac{R_{fast}+R_{slow}}{d_{COLOR-FREQ}}\right). \quad \text{(A4)}$$

The predicted value of log d_{color} is then

$$Predicted \log d_{color} = 0.5 \log\left(\frac{R'_{blue\,|\,correct}}{R'_{blue\,|\,incorrect}} \times \frac{R'_{white\,|\,correct}}{R'_{white\,|\,incorrect}}\right). \quad \text{(A5)}$$

To calculate the effective reinforcer counts and predicted log d values for the alternation-frequency dimension, the equations are the same, except that "blue" and "white" are replaced with "fast" and "slow," and vice versa.