



Relative reinforcer rates determine pigeons' attention allocation when separately trained stimuli are presented together

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Abstract

Previous research suggests that organisms allocate more attention to stimuli associated with higher reinforcer rates. This finding has been replicated several times when stimuli are trained together as compounds, but not in other procedures. Thus, the generality of the relation between relative reinforcer rates and divided attention is not well established. Therefore, we investigated whether relative reinforcer rates determine attention allocation when stimuli are trained separately and then encountered together. Pigeons learned to associate two colors and two frequencies of key light on/off alternation with a left or right comparison key in a symbolic 0-s delayed matching-to-sample task. Across conditions, we varied the probability of reinforcement associated with each stimulus dimension during training. After training, we introduced test trials in which a color and flash-frequency stimulus were presented simultaneously. During sample-stimulus presentation in test trials, all pigeons preferred the stimulus associated with the higher reinforcer rate, suggesting that more attention was allocated to that stimulus. Interestingly, such attention allocation did not result in preference for the comparison that matched that stimulus. Instead, all pigeons preferred the comparison that was physically closer to the stimulus associated with the higher reinforcer rate, suggesting that comparison choice was controlled by the location of that stimulus. Nevertheless, overall, our results provide the first evidence that relative reinforcer rates determine divided attention between separately trained stimuli and thus demonstrate the generality of the relation between relative reinforcement and attention allocation. We suggest several avenues for future research to establish further the generality of this relation.

Keywords Attention · Pigeon · Matching to sample · Relative reinforcement · Compound stimulus

Attention is a limited resource (Broadbent, 1965; James, 1890; Pashler, 1998; Styles, 1997). Thus, when multiple stimuli are present, as is the case in natural environments, human and nonhuman animals must divide attention between the stimuli—attending to some and ignoring others. Elucidating the processes that control such divided attention has implications for understanding how stimuli exert control over behavior. Skinner (1953) suggested that attention is the “controlling relation” (p. 123) between a stimulus and behavior; that is, a stimulus will only control a subject’s behavior if the subject attended to it (see also Blough, 1996; Dinsmoor, 1985; Nevin, Davison, & Shahan, 2005; Ray, 1969, 1972; Reynolds, 1961). In support of this, the presence of multiple

stimuli correlated with reinforcement does not guarantee that all of those stimuli will control behavior, implying some mediating factor—perhaps attention—between stimulus and behavior (e.g., Born & Peterson, 1969; Dube et al., 2010; Dube & McIlvane, 1997; Spetch & Mondloch, 1993). Although there are difficulties with inferring attention from observable stimulus control—for example, subjects may attend to a stimulus, but this attention may not be expressed behaviorally (e.g., Born, Snow, & Herbert, 1969; Wilkie & Masson, 1976)—the generally accepted view is that “any observation of stimulus control is [also] an observation of attention” (Johnson & Cumming, 1968, p. 157). Thus, based on this view, variables that affect the allocation of attention between stimuli should also determine, to some extent, which stimuli control overt behavior (Davison & Elliffe, 2010; Nevin et al., 2005).

Shahan and Podlesnik (2006) suggested that attention allocation between stimuli depends on the relative reinforcer rate associated with each stimulus. They presented pigeons with a compound sample stimulus consisting of a vertical or

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horizontal line superimposed on a blue or green background, and then asked their pigeons to report either which of two colors or two line orientations had been presented (a 0-s delayed matching-to-sample [DMTS] task). In this task, the proportion of correct color and line-orientation choices provides an indication of attention allocation, because accurate responding on a dimension requires that pigeons attended to that dimension during sample presentation (Nevin et al., 2005; Zentall, 2005). Across conditions, Shahan and Podlesnik varied the probability of reinforcement for correct responses on each dimension. As the probability of reinforcement for one dimension increased, the proportion of correct responses on that dimension increased while the proportion of correct responses on the other dimension decreased. Thus, divided attention between the two stimulus dimensions varied systematically with the reinforcer rates associated with those dimensions.

Shahan and Podlesnik's (2006) findings have been replicated several times, using both identity and symbolic DMTS tasks, different stimulus dimensions (e.g., duration, response location), and a wide range of reinforcement probabilities (Davison, 2018a; Davison & Elliffe, 2010; Podlesnik, Thrailkill, & Shahan, 2012; Shahan & Podlesnik, 2007; see also Galloway, 1967; Galloway & Petre, 1968; Morey, Cowan, Morey, & Rouder, 2011). Additionally, Podlesnik et al. (2012) showed that the persistence of attending depends on overall reinforcer rates. They arranged the same procedure as Shahan and Podlesnik and found that when reinforcers were removed or the pigeons were fed before the experimental session, accuracy declined more slowly in a context associated with a higher overall reinforcer rate (signaled by a yellow stimulus) compared with a context associated with a lower overall reinforcer rate (signaled by a red stimulus). That is, attending to both stimulus dimensions was more persistent in the richer context. Taken together, these studies suggest that attention allocation is primarily controlled by relative reinforcer rates (see also Nevin et al., 2005; Shahan & Podlesnik, 2008).

Furthermore, Dube et al. (2010) demonstrated that differential reinforcement of attending may enhance control by relevant stimuli in behavior-modification procedures. They found that stimulus overselectivity (control by a small subset of stimuli) in individuals with intellectual disabilities was correlated with failures to observe all of the stimuli (measured by eye gaze), suggesting that participants had not attended to each stimulus (see also Dube et al., 1999; Dube et al., 2003). Dube et al. thus introduced an intervention in which participants earned more reinforcers if they observed each stimulus for at least 0.5 s. This intervention successfully reduced stimulus overselectivity and was more effective than other interventions (e.g., prompting). Therefore, differential reinforcement of attending may be a viable method to reduce stimulus overselectivity in applied behavior-analytic procedures.

Although investigating the effects of relative reinforcer rates on attention allocation has clear theoretical and applied relevance, few studies have done so, and those that have employ similar procedures (Davison, 2018b). Therefore, the generality of the relation between relative reinforcer rates and attention allocation across procedures is not well established. One situation in which the relation between relative reinforcer rates and attention allocation has not yet been thoroughly examined is when stimuli are trained separately and then encountered together. This situation is distinct from that arranged in studies such as Shahan and Podlesnik's (2006) because the stimulus dimensions are never encountered together during training in the former, whereas they are in the latter. This difference may mean that relative reinforcer rates have different effects on attention allocation in the two procedures.

Indeed, when stimuli are trained together in compound, as in Shahan and Podlesnik (2006), subjects must attend to both stimuli in order to maximize obtained reinforcers, and hence attention will likely be divided (see, e.g., Blough, 1969; Leith & Maki, 1975; Maki & Leith, 1973; Shahan & Podlesnik, 2006, 2007; Zentall, 2005). In contrast, when stimuli are trained separately, no division of attention is required because only one stimulus is presented at a time. Thus, when stimuli are later presented simultaneously, subjects may not actually divide their attention between the stimuli—instead, they may attend selectively to one stimulus (Du, McMillan, Madan, Spetch, & Mou, 2017; Yokoyama, Dailey, & Chase, 2006; see also Heinemann, Chase, & Mandell, 1968; Leith & Maki, 1975). If such selective attention occurs, whether it is controlled by the relative reinforcer rates previously associated with each stimulus is unknown. Alternatively, attention may be divided when separately trained stimuli are presented simultaneously. The question, then, is whether such division depends on relative reinforcer rates in the same way as when stimuli are trained together.

Additionally, relative reinforcer rates can only determine attention allocation if differences in reinforcer rates between stimuli are discriminated by the subject (see, e.g., Davison & Nevin, 1999; Lobb & Davison, 1975). Such discrimination is probably harder when stimuli are trained separately, compared with when they are trained together. In support of this, sensitivity to relative reinforcer rates is lower in multiple schedules, in which stimuli are presented separately, than in concurrent schedules, in which stimuli are presented simultaneously (Davison & Ferguson, 1978; Lander & Irwin, 1968; Lobb & Davison, 1977; McLean & White, 1983; McSweeney, Farmer, Dougan, & Whipple, 1986; Reynolds, 1963). Thus, sensitivity to the reinforcer rate associated with one stimulus *relative to* other stimuli may be lower when stimuli are trained separately, and hence relative reinforcer rates will have smaller effects on attention allocation, compared with when stimuli are trained together.

Nevertheless, a study by Dube and McIlvane (1997) tentatively suggests that relative reinforcer rates determine attention allocation when separately trained stimuli are presented together. They arranged a DMTS task, similar to Shahan and Podlesnik's (2006), with individuals diagnosed with developmental disabilities, except that the stimulus elements were associated with a high or low reinforcer rate before being presented simultaneously. Accuracy was higher in trials in which participants chose between two high-rate elements than in trials in which they chose between two low-rate elements, suggesting that greater attention was allocated to elements associated with higher reinforcer rates. However, in trials in which participants chose between elements associated with different reinforcer rates, they preferred the high-rate element regardless of whether their choice was correct or incorrect. This latter result implies that relative reinforcer rates affected processes during the choice phase, rather than attention allocation during sample presentation. For example, perhaps subjects were simply more motivated to choose high-rate elements (cf. Lamb, 1991; Wasserman & Miller, 1997). Thus, while some of Dube and McIlvane's findings suggest a systematic relation between relative reinforcer rates and attention allocation, other aspects of their findings do not.

In summary, divided attention between the dimensions of a compound stimulus depends on the relative reinforcer rate associated with each dimension (Davison & Elliffe, 2010; Podlesnik et al., 2012; Shahan & Podlesnik, 2006, 2007). Whether this is also the case when those dimensions are trained separately and then presented simultaneously is presently unclear. Thus, we investigated whether relative reinforcer rates determine attention allocation when separately trained stimuli are presented simultaneously. Pigeons learned to associate four visual stimuli—two colors (red and green) and two frequencies at which a white key light alternated on and off (fast and slow)—with either a left or right key in a symbolic 0-s DMTS procedure. Across conditions, we varied the relative reinforcer rate associated with the color and flash-frequency dimensions. After training, we introduced test trials, in which both a color and a flash-frequency stimulus were presented simultaneously.

To assess attention allocation in test trials, we analyzed both sample-key and comparison-key choice. Peck location provides a general indication of attention allocation in pigeons (Brown, Cook, Lamb, & Riley, 1984; Castro & Wasserman, 2014; Dittrich, Rose, Buschmann, Bourdonnais, & Güntürkün, 2010), and, hence, if our pigeons allocate more attention to stimuli associated with higher reinforcer rates, they should prefer the stimulus associated with the higher reinforcer rate during sample presentation. For comparison-key choice, if our pigeons attended to one stimulus more than the other, they should prefer the comparison key that matches that stimulus (see, e.g., Davison & Elliffe, 2010). Hence, in trials in which the color and flash-frequency stimuli match the

same comparison key (*compatible* trials), our pigeons should prefer that key if they attend to at least one stimulus. Therefore, compatible trials served as a control, as a high percentage of correct responses would suggest that our pigeons attended to at least one stimulus, and that they did not treat the simultaneous presentation of a color and flash-frequency as novel (otherwise, comparison-key preference should be indifferent). In test trials in which the stimuli match different comparison keys (*incompatible* trials), our pigeons should prefer whichever comparison key matches the stimulus associated with the higher reinforcer rate if reinforcer rates determine attention allocation when separately trained stimuli are presented simultaneously.

Method

Subjects

Six pigeons, numbered 71 to 76, served as subjects. All pigeons were maintained at $85\% \pm 10$ g of free-feeding body weight by supplementary feeding of mixed grain at around 10:00 a.m. daily. Pigeons were housed in a colony room with a time-shifted environment (lights on from 12:00 a.m. until 4:00 p.m.). All pigeons had previous experience in a DMTS task similar to that arranged here (see Procedure section). Analyses (not shown here) suggested that there were no systematic carryover effects from this previous experience.

Apparatus

Pigeons were housed individually in home cages (375 mm high \times 375 mm deep \times 370 mm wide), which also served as the experimental chambers. Each cage contained two wooden perches, spaced 135 mm apart, and parallel to the back wall. The back perch was 110 mm away from the back wall. An operant panel was mounted on the back wall, 115 mm above the cage floor. The operant panel contained five circular response keys, each 20 mm in diameter, arranged in three rows. The top and bottom rows each contained two keys spaced 113 mm apart horizontally from center to center. The middle row contained one response key, which was centered horizontally between the keys in the top and bottom rows. The perpendicular distance from the bottom of the keys in one row and the top of the keys in the row below was 25 mm. Only the top and bottom keys were used; these could be illuminated red, green, or white. Responses exceeding about 0.1 N to illuminated keys were recorded. Centered on the back wall and 53 mm below the operant panel was a magazine aperture measuring 40 mm \times 40 mm. A hopper, filled with wheat, was located behind the magazine aperture. During a reinforcer delivery, the hopper was raised for 2 s, the magazine aperture was illuminated, and the key lights were extinguished. In an

adjacent room, a computer running MED-PC®-IV software ran the experiment and recorded all experimental events.

Procedure

Experimental sessions were run daily, beginning at 1 a.m. The pigeons were run successively and in numerical order. Each session lasted until 136 trials or 65 min had elapsed, whichever occurred first. All pigeons completed all 136 trials in every session.

Training The pigeons were trained to associate four sample stimuli with either a left or right comparison key using a symbolic 0-s DMTS task. The sample stimuli were a red key light, a green key light, and a white key light that alternated on and off every 0.1 s or every 0.5 s (hereafter, for brevity, these stimuli are termed *red*, *green*, *fast*, and *slow*, respectively). There were thus two stimulus dimensions—color and flash frequency.

The left panel of Fig. 1 depicts an example of a training trial. Each trial began with the illumination of the sample stimulus, which was displayed on the top-left and top-right keys (hereafter, collectively termed the *sample keys*). The sample stimulus was chosen probabilistically ($p = .25$), with the constraints that there were an equal number of trials per sample in each session and the same stimulus could not occur more than twice consecutively. The sample stimulus was presented for at least 5 s, after which a response to either sample key resulted in the offset of the sample stimulus and the onset of the comparison keys. This fixed-interval (FI) 5-s requirement ensured that the pigeons observed the sample in each trial. The comparison keys were the bottom-left and bottom-

right keys, which were illuminated white. Depending on the previously presented sample, one of the comparisons was defined as correct, and the other as incorrect. If the program arranged a reinforcer, a response to the correct comparison was immediately reinforced. If no reinforcer was arranged, a correct response turned off the comparison keys and started the intertrial interval (ITI), which was a 3-s blackout period. An incorrect response resulted in a 4-s blackout followed by the ITI, after which the same trial repeated except that only the correct comparison was illuminated during the comparison phase (i.e., a correction procedure). Correction trials did not count toward the 136 total trials per session.

The sample-comparison association was counterbalanced across pigeons. For Pigeons 71 and 72, the red and fast stimuli matched the left key; for Pigeons 73 and 74, the green and fast stimuli matched the left key; for Pigeon 75, the green and slow stimuli matched the left key; and for Pigeon 76, the red and slow stimuli matched the left key. The other stimuli matched the right key.

Across conditions, we varied the relative probability of a reinforcer delivery associated with each stimulus dimension. The probabilities of reinforcer deliveries for each dimension were always complementary, in order to keep the overall reinforcer rate the same in all conditions (arranging such complementary probabilities also replicates previous work examining the relation between relative reinforcer rates and attention allocation; e.g., Shahan & Podlesnik, 2006). Table 1 shows the sequence of conditions, which was the same for all pigeons. In Condition 1, the probability of a reinforcer delivery was .2 for color stimuli and .8 for flash-frequency stimuli. Condition 2 arranged the reverse probabilities. In Condition 3, the probability of reinforcer deliveries was .5

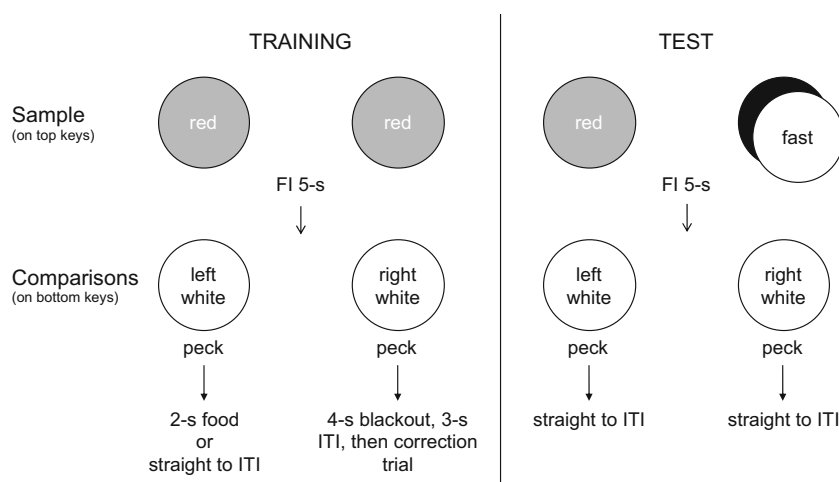


Fig. 1 Diagram showing examples of a red training trial (left panel) and a red-fast test trial (right panel). In this example, the red stimulus matches the left comparison key during training. For both trial types, the sample stimulus was presented on a fixed interval (FI) 5-s schedule, and its offset was immediately followed by the onset of the comparison keys. One peck

to either comparison resulted in food delivery, blackout, or the start of the intertrial interval (ITI). In test trials, the location of the color and flash-frequency stimulus during sample-stimulus presentation was counterbalanced. See text for further details

Table 1 Sequence of conditions

Condition	$p(\text{food} \mid \text{color})$	$p(\text{food} \mid \text{flash frequency})$
1	.2	.8
2	.8	.2
3	.5	.5
4	.8	.2

for both stimulus dimensions. To determine if results were replicable, Condition 4 arranged the same probabilities as Condition 2.

Training sessions in each condition ran for at least 31 sessions and until accuracy for each sample stimulus was above 80% for five consecutive sessions. All pigeons reached the latter criterion within 31 sessions.

Testing After training, four test sessions were conducted. Test sessions were identical to training sessions, except that 16 unreinforced training trials (taken equally from the four sample stimuli) were replaced by unreinforced test trials. Test trials were distributed randomly throughout the session and never occurred consecutively. In test trials, one stimulus from each dimension was presented on each sample key. That is, a red or green stimulus was presented on one sample key, and a fast or slow stimulus on the other key. There were thus four types of test trials: red-fast, red-slow, green-fast, and green-slow. The right panel of Fig. 1 depicts an example of a red-fast test trial. Four trials of each type occurred in each session. The location of the color and flash-frequency stimuli was counterbalanced so that the color element was presented on the top-left key in half of test trials and on the top-right key in the other half of test trials. For two of the test-trial types, both stimuli matched the same comparison key (*compatible* trials), whereas for the other two trial types, the stimuli matched opposite keys (*incompatible* trials).

Data analysis

We calculated the proportion of correct responses following each sample stimulus (*matching accuracy*) in training trials across the last five training sessions, and matching accuracy in training and compatible test trials across all four test sessions. Correction trials were excluded from analyses. There was no systematic difference between accuracy in training trials during the last five training sessions and across all four test sessions; a binomial sign test on accuracy in training trials during training versus test sessions in all conditions was not significant ($p > .2$). Sign tests for individual conditions were also not significant (all $ps > .05$). Hence, introducing test trials did not affect accuracy in training trials. We also investigated whether our pigeons learned that test trials were unreinforced by analyzing comparison-key choice in individual test trials

across test sessions for each condition (analysis not shown here). Preference in test trials varied unsystematically across individual trials and sessions, suggesting that the absence of reinforcer deliveries had little effect on behavior in test trials. Thus, in the Results section we present only data from all four test sessions. Hereafter, *training trials* always refers to training trials during test sessions.

We conducted several analyses on test-trial data. First, we wanted to see if there were systematic differences between matching accuracy in compatible test trials and accuracy in training trials. Thus, we compared the proportion of correct responses in compatible test trials with the proportion of correct responses in training trials using nonparametric Friedman analyses of variance by ranks ($N = 6$, $df = 4$). Because the flash-frequency stimulus in compatible test trials depended on the sample-comparison association (e.g., for some pigeons, the red and fast stimuli matched the same comparison, whereas for other pigeons, the red and slow stimuli matched the same comparison), data from flash-frequency training trials were separated according to whether the flash-frequency stimulus matched the same comparison as the red or green stimulus for the Friedman ANOVAs.

Second, to assess attention allocation between the color and flash-frequency stimuli in test trials, we calculated three bias-free measures of preference (Davison & Tustin, 1978; see also Davison & Nevin, 1999): one that quantified preference for each stimulus during sample presentation ($\log d_{\text{samples}}$); one that quantified preference for the comparison key matching the color or flash-frequency stimulus ($\log d_{\text{matching}}$); and, to assess whether the location of the color and flash-frequency stimuli controlled comparison-key choice, a measure that quantified preference for the comparison key that was on the same *side* as the color or flash-frequency stimulus ($\log d_{\text{comparison-side}}$). We used the following general equation to calculate these measures of preference:

$$\log d = 0.5 \log \left(\frac{B_{\text{color} \mid S1} \cdot B_{\text{color} \mid S2}}{B_{\text{flash-freq} \mid S1} \cdot B_{\text{flash-freq} \mid S2}} \right). \quad (1)$$

In Eq. 1, $S1$ and $S2$ represent either the two compatible test trial types or the two incompatible test trial types. $B_{X=\text{color or flash-freq} \mid Y=S1 \text{ or } S2}$ represents the number of responses made to Stimulus X ($\log d_{\text{samples}}$), the number of responses made to the comparison key matching Stimulus X ($\log d_{\text{matching}}$), or the number of responses made to the comparison key below Stimulus X ($\log d_{\text{comparison-side}}$) in Trial Type Y . Positive values of Eq. 1 indicate stronger preference for the color stimulus or for the comparison key matching or on the same side as the color stimulus, and negative values indicate stronger preference for the flash-frequency stimulus or for the comparison key matching or on the same side as the flash-frequency stimulus. Thus, for $\log d_{\text{samples}}$ and $\log d_{\text{matching}}$, positive values indicate greater attention allocated to the color stimulus and

negative values indicate greater attention to the flash-frequency stimulus. For $\log d_{comparison-sides}$, the extent of deviation from zero indicates the extent to which the location of the color and flash-frequency stimulus controlled comparison-key choice.

For all three measures of $\log d$ (Eq. 1), $B_{X|Y}$ sometimes equaled zero (i.e., all responses were made to one key), so we added 0.5 to all response counts (Hautus, 1995; see also Davison & Nevin, 1999). Additionally, for all three measures, we conducted one-tailed nonparametric trend tests (Kendall, 1955) to determine whether attention allocation to the color stimulus increased systematically as the probability of reinforcer deliveries associated with color stimuli increased. Trend tests were conducted separately for compatible and incompatible test trials. All trend tests were conducted with $N = 6$, $k = 3$, and $\alpha = .05$. Conditions 2 and 4 arranged the same reinforcer probabilities (see Table 1); hence, we averaged data from those two conditions together for nonparametric trend tests.

Results

In the analyses that follow, data from Condition 4 are shown separately from data from Conditions 1 to 3, because Condition 4 was a replication of Condition 2 (see Table 1). All pigeons behaved similarly in Conditions 2 and 4 (see Figs. 2, 3, and 4).

Obtained reinforcer rates

In all conditions, the obtained proportion of reinforced trials for each sample stimulus was always within .01 of its arranged value (see Table 1 for arranged reinforcer probabilities). Thus, obtained and arranged reinforcer rates were equal for all pigeons and in all conditions.

Proportion correct in training and compatible test trials

Table 2 shows the proportion of correct comparison-key responses following each sample stimulus (matching accuracy) in training trials for each condition. Data shown in Table 2 are averaged across pigeons because accuracy was similarly high for all pigeons. In all conditions, matching accuracy in training trials was close to 100% for all stimuli, and relative reinforcer rates had no effect on accuracy.

The rightmost two columns of Table 2 show the proportion of correct comparison-key responses in compatible test trials, in which both stimuli matched the same comparison key. These trials served as control trials: If our pigeons treated the simultaneous presentation of a color and a flash-frequency stimulus as novel, then preference between the comparison keys should have been around indifference (i.e.,

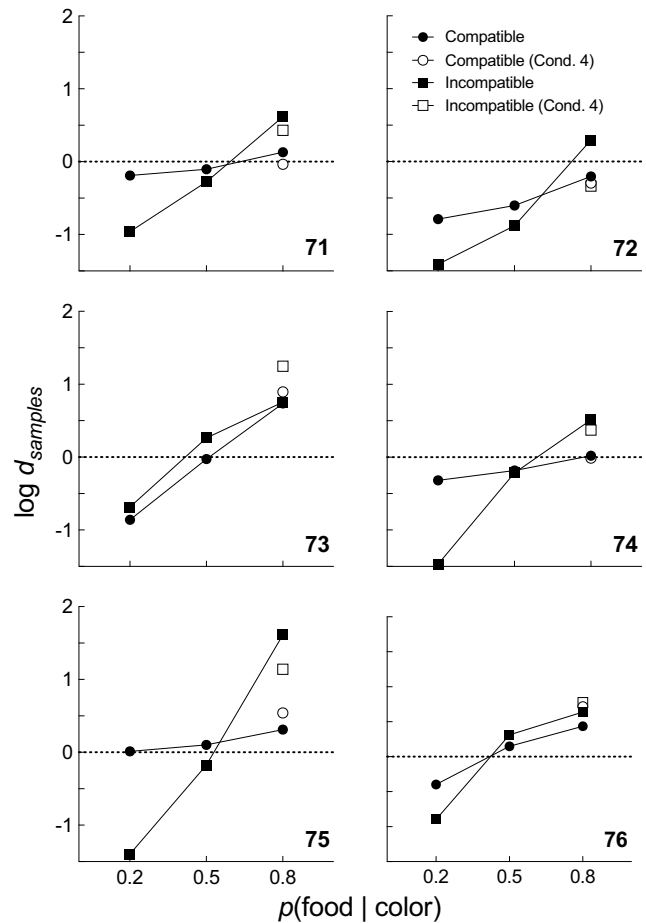


Fig. 2 $\log d_{samples}$ values (Eq. 1) as a function of the probability of reinforcer deliveries associated with color stimuli in compatible (circles) and incompatible (squares) trials. Data from Condition 4 (unfilled symbols) are shown separately from data from Conditions 1 to 3 (filled symbols)

proportion correct = .5) in compatible test trials. Accuracy was similar in compatible test trials and training trials; Friedman tests comparing accuracy in compatible test trials with accuracy in training trials were not significant ($p > .05$), although the comparison between green-compatible trials and training trials approached significance in Condition 2 ($\chi^2 = 8.63$, $p \approx .07$). Relative reinforcer rates had little effect on accuracy in compatible test trials. Thus, our pigeons appeared not to treat the simultaneous presentation of a color and a flash-frequency stimulus in test trials as novel. The high matching accuracies in compatible test trials (see Table 2) also show that our pigeons did not learn that test trials were always unreinforced; if they had, accuracy in compatible test trials would have been lower than in training trials.

Preference for color or flash-frequency stimulus during sample-stimulus presentation ($\log d_{samples}$)

The distribution of responses between the color and flash-frequency stimuli during sample-stimulus presentation

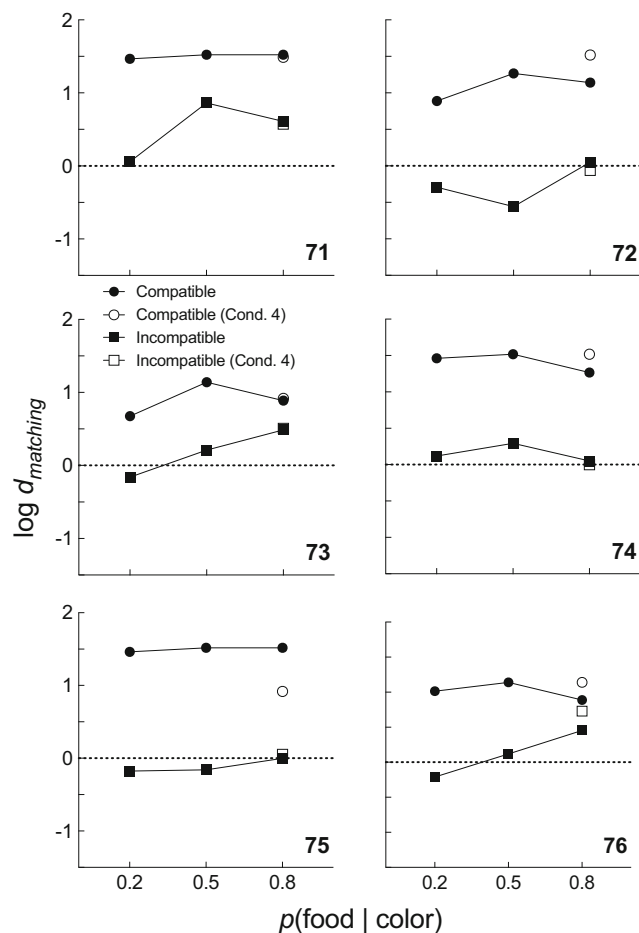


Fig. 3 $\log d_{\text{matching}}$ values (Eq. 1) as a function of the probability of reinforcer deliveries associated with color stimuli in compatible (circles) and incompatible (squares) trials. Data from Condition 4 (unfilled symbols) are shown separately from data from Conditions 1 to 3 (filled symbols)

provides a measure of attention allocation (see, e.g., Brown et al., 1984; Castro & Wasserman, 2014; Dittrich et al., 2010). Figure 2 shows $\log d_{\text{samples}}$ values (Eq. 1), which provide a measure of preference for the color or flash-frequency stimulus, as a function of the probability of reinforcer deliveries associated with color stimuli. If relative reinforcer rates determine attention allocation, then preference for the color stimulus should increase (i.e., $\log d_{\text{samples}}$ values should increase) as the relative reinforcer rate associated with color stimuli increases. This was clearly the case in both compatible and incompatible test trials (see Fig. 2), and one-tailed nonparametric trend tests on $\log d_{\text{samples}}$ values for compatible and incompatible test trials were significant (both Kendall's $\Sigma S = 18$, $z = 3.62$, $p < .001$). Thus, as the probability of reinforcer deliveries associated with color stimuli increased, so did preference for the sample key displaying the color stimulus, strongly suggesting that relative reinforcer rates determined attention allocation in test trials.

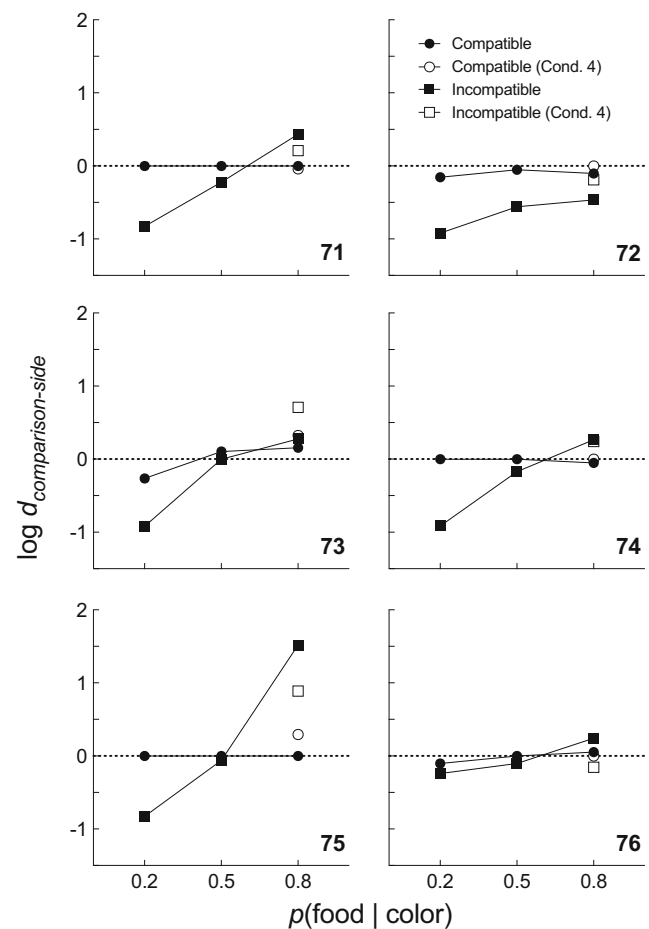


Fig. 4 $\log d_{\text{comparison-side}}$ values (Eq. 1) as a function of the probability of reinforcer deliveries associated with color stimuli in compatible (circles) and incompatible (squares) trials. Data from Condition 4 (unfilled symbols) are shown separately from data from Conditions 1 to 3 (filled symbols)

The effects of relative reinforcer rates on sample-key preference varied between pigeons, and also between compatible and incompatible test trials. For some pigeons (e.g., Pigeons 73 and 76), changes in preference were much larger than for other pigeons (e.g., Pigeons 71 and 74). More importantly, changes in preference between the color and flash-frequency stimuli were much larger in incompatible test trials than in compatible test trials for all pigeons except Pigeon 73, for whom changes in preference were comparable in both trial types. Thus, relative reinforcer rates appeared to exert stronger control over attention allocation when the color and flash-frequency stimuli matched opposite comparisons (incompatible test trials) compared with when both stimuli matched the same comparison (compatible test trials).

Preference for comparison-key matching color or flash-frequency stimulus ($\log d_{\text{matching}}$)

Figure 3 shows preference for the comparison key that matched the color or flash-frequency stimulus in

Table 2 Proportion of correct comparison-key responses, averaged across pigeons, for each sample stimulus in training trials and for compatible test trials. Standard deviations are shown in parentheses

Condition	Red	Green	Fast	Slow	Red compatible	Green compatible
1	.99 (.03)	.97 (.04)	.97 (.02)	.99 (.01)	.94 (.07)	.97 (.06)
2	.99 (.02)	.99 (.03)	.94 (.10)	.98 (.02)	.96 (.06)	.95 (.05)
3	.99 (.01)	.99 (.01)	.98 (.02)	.99 (.01)	.98 (.05)	.97 (.05)
4	.99 (.01)	.99 (.01)	.98 (.02)	.98 (.02)	.90 (.16)	.98 (.05)

Note. Red compatible and green compatible refer to compatible test trials in which the color stimulus was red or green, respectively

compatible and incompatible test trials as a function of the probability of reinforcer deliveries associated with color stimuli. Such preference was calculated using Eq. 1 ($\log d_{\text{matching}}$). For compatible test trials, $\log d_{\text{matching}}$ is akin to matching accuracy (i.e., proportion correct; see Table 2). Thus, like Table 2, Fig. 3 shows that preference for the comparison key matching the color and flash-frequency stimuli changed little across conditions in compatible test trials (Kendall's $\Sigma S = 5$, $z = .85$, $p > .10$).

Data from incompatible test trials provide a better indication of attention allocation than data from compatible test trials. This is because both stimuli matched the same comparison in compatible test trials, and hence our pigeons probably preferred that comparison regardless of how they allocated their attention between the stimuli (see Table 2 and Fig. 3). In contrast, in incompatible test trials, the color and flash-frequency stimuli matched opposite comparisons, and, hence, if relative reinforcer rates determined attention allocation, then preference for the comparison key matching the color stimulus (i.e., $\log d_{\text{matching}}$ values) should have increased as the probability of reinforcer deliveries associated with color stimuli increased. A one-tailed nonparametric test on $\log d_{\text{matching}}$ values in incompatible test trials (see Fig. 3) was significant (Kendall's $\Sigma S = 10$, $z = 1.92$, $p < .03$), suggesting that our pigeons indeed allocated more attention to the color stimulus and less to the flash-frequency stimulus as the probability of reinforcer deliveries associated with color stimuli increased. However, a clear, monotonic increase in $\log d_{\text{matching}}$ values was only apparent for Pigeons 73 and 76. For the remaining pigeons, $\log d_{\text{matching}}$ values increased nonmonotonically (Pigeons 71 and 72) or hardly changed (Pigeons 74 and 75) as the relative reinforcer rate associated with color stimuli increased. Thus, even though preference for the comparison key matching the color stimulus was higher overall when the probability of reinforcer deliveries associated with color stimuli was .8 compared with when it was .2, changes in preference as relative reinforcer rates changed were fairly unsystematic across pigeons.

Preference for comparison key below color or flash-frequency stimulus ($\log d_{\text{comparison-side}}$)

One possible reason why relative reinforcer rates had fairly unsystematic effects on preference for the comparison key matching the stimuli ($\log d_{\text{matching}}$; see Fig. 3) is that comparison-key choice may have also been controlled by the location of the color and flash-frequency stimuli. Thus, we analyzed preference for the comparison key that was below the color or flash-frequency stimulus in test trials ($\log d_{\text{comparison-side}}$; Eq. 1). Figure 4 shows such preference, plotted as a function of the probability of reinforcer deliveries associated with color stimuli. In compatible test trials, $\log d_{\text{comparison-side}}$ values were at or close to zero and did not change as relative reinforcer rates changed (Kendall's $\Sigma S = 7$, $z = 1.28$, $p > .1$). This result is unsurprising, because our pigeons preferred whichever comparison key matched the sample stimuli (see Table 2) in compatible test trials. That comparison would have been below the color stimulus in half of test trials and below the flash-frequency stimulus in the remaining half, resulting in $\log d_{\text{comparison-side}}$ values close to zero.

In contrast, in incompatible test trials, $\log d_{\text{comparison-side}}$ values (see Fig. 4) increased as the probability of reinforcer deliveries associated with color stimuli increased (Kendall's $\Sigma S = 18$, $z = 3.62$, $p < .001$). This suggests that all pigeons preferred whichever comparison key was below the stimulus that was associated with the higher reinforcer rate, regardless of whether that comparison key matched that stimulus. For example, when the probability of reinforcer deliveries associated with color stimuli was .8, our pigeons preferred the left comparison key when the color was presented on the left sample key, and the right comparison when the color was presented on the right sample key. Compared with $\log d_{\text{matching}}$ values (see Fig. 3), relative reinforcer rates had larger effects on $\log d_{\text{comparison-side}}$ values (see Fig. 4). Thus, rather than preferring the comparison key that matched the stimulus associated with the higher reinforcer rate, all pigeons simply preferred the comparison that was on the same *side* as that stimulus.

Taken together, analyses of sample-key and comparison-key choice (see Figs. 2, 3, and 4) suggest that comparison-key

choice was controlled by the location of the sample key that pigeons most recently pecked. This is apparent in incompatible test trials, as our pigeons preferred the sample key that displayed the stimulus associated with the higher reinforcer rate (see Fig. 2) and also preferred the comparison below that sample (see Fig. 4). To determine more conclusively whether comparison-key choice depended on the location of the last-pecked sample, we calculated the proportion of responses made to the comparison key below the last-pecked sample key (see Table 3). These values were similar across all trial types and pigeons, and so Table 3 shows these values averaged across pigeons and also across training trials, compatible test trials, or incompatible test trials. Evidently, our pigeons indeed preferred the comparison key below the last-pecked sample key, suggesting that comparison-key choice was strongly controlled by the location of that sample.

Discussion

Previous research suggests that the division of attention between the dimensions of a compound stimulus depends on the relative reinforcer rates associated with each dimension (Davison, 2018a; Davison & Elliffe, 2010; Podlesnik et al., 2012; Shahan & Podlesnik, 2006, 2007). We investigated whether this was also the case when the stimulus dimensions were trained separately before being presented simultaneously with pigeons. Our results suggest that attention allocation does indeed depend on relative reinforcer rates under such conditions. During sample-stimulus presentation, all pigeons preferred to peck the stimulus associated with the higher reinforcer rate, suggesting that they attended more to that stimulus (see Fig. 2). Although pigeons weakly preferred the comparison key that matched the stimulus associated with the higher reinforcer rate (see Fig. 3), this was because most pigeons strongly preferred the comparison that was on the same *side* as the stimulus associated with the higher reinforcer rate (see Fig. 4). Thus, overall, the present findings replicate previous research demonstrating a systematic relation between relative reinforcer rates and divided attention.

Table 3 Mean proportion of responses made to the comparison key below the sample key that pigeons most recently pecked. Data are averaged across pigeons and trial types. Standard deviations are shown in parentheses

Condition	Training	Compatible	Incompatible
1	.86 (.29)	.88 (.18)	.82 (.20)
2	.80 (.36)	.83 (.25)	.78 (.27)
3	.81 (.33)	.86 (.24)	.77 (.23)
4	.81 (.33)	.85 (.23)	.76 (.28)

Unlike past research demonstrating the relation between relative reinforcement and attention allocation, in which the stimulus dimensions were always encountered together in the form of a compound stimulus (e.g., Davison & Elliffe, 2010; Shahan & Podlesnik, 2006), stimuli were never encountered together during training in the present experiment. We speculated that our training procedure might (1) reduce sensitivity to relative reinforcer rates and (2) not facilitate divided attention when the stimuli are later presented simultaneously. Our findings show that training stimuli separately did not reduce sensitivity to reinforcement; relative reinforcer rates clearly determined attention allocation, particularly during sample-stimulus presentation (see Fig. 2).

The differences between our pigeons' behavior in compatible and incompatible test trials suggest that our pigeons divided their attention despite stimuli being trained separately. Preference for the stimulus associated with the higher reinforcer rate was stronger in incompatible trials than in compatible trials (see Fig. 2), and our pigeons always preferred the correct comparison key in compatible trials (see Table 2 and Fig. 3), whereas they preferred the comparison that was on the same side as the stimulus associated with the higher reinforcer rate regardless of whether that comparison matched that stimulus in incompatible trials (see Figs. 3 and 4). Such differential behavior in compatible and incompatible test trials must be related to whether the stimuli provided redundant (compatible) or conflicting (incompatible) information—a discrimination that is only possible if our pigeons attended to both stimuli. Therefore, relative reinforcer rates appear to determine attention allocation regardless of whether the stimuli are trained together or separately.

Another procedural difference between the present experiment and past experiments is the configuration of the stimuli. In past research, the stimulus dimensions were compounded together into a single stimulus (e.g., a line superimposed on a colored background). In contrast, in the present experiment, the color and flash-frequency stimuli were presented separately in test trials. That our findings replicate past findings appears to suggest that relative reinforcer rates control divided attention with different stimulus configurations. However, our findings from a preliminary experiment suggest that this conclusion is premature. In a similar procedure to that arranged here, we found no systematic effect of relative reinforcer rates on attention allocation when the stimulus dimensions were compounded together in compatible and incompatible test trials. This was not because the pigeons treated compound stimuli as novel, nor because of a generalization decrement from training to test trials, nor because compounding the dimensions together made them more difficult to discriminate (see Zentall, 2005), as accuracy in compatible test trials was high. Rather, it seems that when separately trained stimuli are presented together, the configuration of those stimuli determines whether a systematic relation between relative reinforcer rates

and divided attention is observed: Such a relation is observed if the stimuli are presented separately, but not when they are compounded together. Why this is the case remains unanswered; presently, not enough is known about how relative reinforcer rates determine divided attention with different stimulus configurations.

Although we found that relative reinforcer rates determine divided attention, one aspect of our results differs substantially from past research: In past research, pigeons preferred the comparison matching the stimulus associated with the higher reinforcer rate (Davison & Elliffe, 2010; Podlesnik et al., 2012; Shahan & Podlesnik, 2006, 2007), whereas such preference was weak in the present experiment (see Fig. 3). This discrepancy is probably related to differences in how the sample stimuli were presented. In the present experiment, sample stimuli were always presented on the top-left and top-right keys. As a result, our pigeons developed differential sample behavior—they pecked one sample key, and then the comparison below that sample—in training trials, and this probably helped to maintain the high accuracies in training (see Table 3). Such differential sample behavior generalized to test trials, as subjects tended to choose the comparison below the last-pecked sample in test trials (see Table 3). In contrast, in past experiments, the sample stimulus was presented on a single key centered between the comparisons, and hence differential sample behavior was probably much less likely to have occurred.

Our pigeons' strong tendency to peck the comparison below the last-pecked sample (see Table 3) suggests that comparison-key choice was more strongly controlled by differential sample behavior than by the sample stimulus itself. Indeed, previous research has shown that control by differential sample behavior can overshadow control by the sample stimulus in DMTS tasks (Urcuioli, 1984, 1985; Urcuioli & Honig, 1980; Weaver, Dorrance, & Zentall, 1999). Although such differential sample behavior was not explicitly required or reinforced in the present experiment, it may have been maintained by the reinforcers obtained for choosing the correct comparison (i.e., by adventitious reinforcement; see e.g., Blough, 1959), especially given the close temporal proximity between the sample and comparison presentations. Indeed, some studies have shown that subjects engage in differential sample behavior in DMTS tasks with longer intervals (e.g., 5 s) between sample offset and comparison onset than that arranged here, even when such behavior is not required (e.g., Blough, 1959; Chatlosh & Wasserman, 1987; Chudasama & Muir, 1997; Hunter, 1913). Thus, whereas comparison-key choice was controlled by the stimulus that the pigeons attended to in previous divided-attention experiments, comparison-key choice probably did not reflect attention allocation accurately in the present experiment because such choice was strongly controlled by the location of the last-pecked sample key.

Differential sample behavior also helps to explain differences in patterns of preference between compatible and

incompatible test trials in the present experiment. Preference for the stimulus associated with the higher reinforcer rate was less extreme in compatible test trials than in incompatible trials (see Fig. 2). At first glance, this may appear to suggest that relative reinforcer effects had smaller effects in compatible test trials. However, in compatible test trials, both stimuli matched the same comparison, and hence sample-key choice was probably jointly controlled by the location of the correct comparison *and* relative reinforcer rates. That is, strong preference for the sample key on the same side as the correct comparison would have attenuated preference for the stimulus associated with the higher reinforcer rate in compatible test trials. In contrast, in incompatible test trials, there was no “correct” comparison, and, hence, relative reinforcer rates strongly controlled sample-key choice. This line of reasoning suggests that if differential sample behavior were not to develop (e.g., perhaps if the stimuli were presented side-by-side on a screen centered between the comparisons), attention allocation would be apparent from analyses of preference for the comparison matching each stimulus. Whether this is indeed true requires further research.

Thus, in addition to showing that relative reinforcer rates determine divided attention between separately trained stimuli, the present findings also highlight some of the complexities of studying attention allocation in the DMTS procedure. Our results show that comparison-key choice may not always provide a complete picture of attention allocation in DMTS tasks. If differential sample behavior develops during training, such behavior may control comparison-key choice (Urcuioli, 1984, 1985; Urcuioli & Honig, 1980; Weaver et al., 1999), potentially masking control by other variables (e.g., relative reinforcer rates). If this occurs, the effects of such variables may appear to be much smaller than they actually are, and any conclusions about attention allocation based solely on analyses of comparison-key choice may be inaccurate or incomplete. This is consistent with early behavior-analytic research on attention, which suggested that conclusions about attention allocation sometimes differed depending on type of test or measure used (see, e.g., Born et al., 1969; Farthing & Hearst, 1970; Wilkie & Masson, 1976). In such cases, additional analyses, such as our analyses of behavior during sample presentation (see Fig. 2), can help to clarify attention allocation.

Finally, the present findings are also of applied significance, as they suggest that manipulating relative reinforcer rates may be a viable method to shift attention allocation, and hence stimulus control, in behavior-modification procedures. This is consistent with previous work showing that differential reinforcement of observing (eye gaze) can reduce exclusive control by one stimulus and enhance control by other stimuli in individuals with intellectual disabilities (Dube et al., 2010; see also Dube & McIlvane, 1997). Our findings also share some similarities with those that suggest that such stimulus overselectivity may be reduced by

“revaluing” the overselected stimulus separately (e.g., Broomfield, McHugh, & Reed, 2008, 2010; Reed, Broomfield, McHugh, McCausland, & Leader, 2009). In the typical revaluation procedure, control by one element of a two-element compound stimulus is reduced, and control by the other element is enhanced by presenting a choice between the former and a novel element and reinforcing choice of the novel element. That is, changes in the degree of control by each element of a compound stimulus are observed following a change in relative reinforcement associated with one element in separate training trials. Although there is debate over whether stimulus overselectivity is related to deficits in attention (i.e., a failure to attend to all stimuli; Dube et al., 1999) or to deficits in performance (i.e., subjects attend to all stimuli, but this attention is not expressed behaviorally; Reed, 2007), it is clear that training stimulus-reinforcer associations separately may be used to shift control toward some stimuli (those associated with higher reinforcer rates) and away from others (those associated with lower reinforcer rates).

In conclusion, we found that relative reinforcer rates determine divided attention when separately trained stimuli are encountered together. These findings are the first to demonstrate a systematic relation between relative reinforcement and attention allocation between separately trained stimuli, and hence extend previous research demonstrating such a relation in compound-stimulus tasks (Davison, 2018a; Davison & Elliffe, 2010; Podlesnik et al., 2012; Shahan & Podlesnik, 2006, 2007) to a different procedure. In addition, our results suggest that attention allocation in DMTS tasks is sometimes better inferred from analyses of sample-key choice rather than comparison-key choice, particularly when differential sample behavior is likely to develop. The present findings also provide several avenues for future research concerning the conditions (e.g., stimulus configuration) under which relative reinforcer rates do or do not determine attention allocation. Thus, overall, the present experiment brings us one step closer to establishing the generality of the relation between relative reinforcer rates and attention allocation.

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