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LIMITS TO PREFERENCE AND THE SENSITIVITY OF CHOICE TO RATE AND AMOUNT OF FOOD

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Studies of choice holding food-amount ratio constant while varying food-rate ratio within sessions showed that local changes in preference depend on relative amount of food. The present study investigated whether sensitivity of choice to food-rate ratio and sensitivity to food-amount ratio are independent of one another when food-rate ratios are varied across sessions and food-amount ratios are varied within sessions. Food deliveries for rats' presses on the left and right levers were scheduled according to three different food-rate ratios of 1:1, 9:1, and 1:9; each food-rate ratio lasted for 106 sessions and was arranged independently of seven food-amount ratios (7:1, 6:2, 5:3, 4:4, 3:5, 2:6, and 1:7 food pellets) occurring within sessions in random sequence. Each amount ratio lasted for 10 food deliveries and was separated from another by a 60-s blackout. Sensitivity to rate ratio was high (1.0) across food deliveries. Sensitivity to amount ratio was low when food rates were equal across alternatives, but was high when rate ratio and amount ratio opposed one another. When rate ratio and amount ratio went in the same direction, choice ratio reached an elevenfold limit which reduced sensitivity to approximately zero. We conclude that three factors affect sensitivity to amount: (1) the limit to preference, (2) the equal effect on preference of amounts greater than four pellets, and (3) the absence of differential effects of switches in amount in the equal-rates (1:1) condition. Taken together, these findings indicate that rate and amount only sometimes combine independently as additive variables to determine preference when amount ratios vary frequently within sessions.

Key words: food amount, food rate, preference limits, relative effects, dynamic choice, rats

Studies of choice that manipulated the relative amount and rate of food found that the relative rate of responding matches the product of these independent variables (e.g., Neuringer, 1967; Fig. 6). The seminal study of Baum and Rachlin (1969), using response-independent concurrent schedules of reinforcement (Brownstein & Pliskoff, 1968), suggested that the ratio of the times allocated to two alternatives matches the ratio of the values of the activities, where the value (*V*) of a particular activity is the product of the rate, amount, and immediacy of food contingent upon that activity, extending the matching law (Herrnstein, 1961) to include relative independent variables besides food-rate ratio.

$$\frac{T_1}{T_2} = \frac{V_1}{V_2} \quad (1)$$

Research consistent with the time-allocation matching law (Baum & Rachlin, 1969) showed

that the relative rate of key pecking matches the relative amount of food (Catania, 1963) and the relative immediacy of food (Chung & Herrnstein, 1967). Equation 1 predicts preference even in settings where choice is estimated from discrete responses (e.g., Catania, 1966). At an extended time scale, however, preference is described by Baum's (1974) generalized matching law,

$$\log\left(\frac{B_1}{B_2}\right) = s \cdot \log\left(\frac{r_1}{r_2}\right) + \log b, \quad (2)$$

where *B*₁ and *B*₂ are behavior allocations, measured in time or responses, to Alternatives 1 and 2, *r*₁ and *r*₂ may be food rates or food amounts obtained from Alternatives 1 and 2, *b* is a measure of bias toward one alternative or the other arising from factors other than *r*₁ and *r*₂, and *s* is the sensitivity of behavior ratio to food ratio (Aparicio & Baum 2009; Davison & Baum, 2003).

Consistent with a molar view of behavior (Baum, 1995, 2001, 2002), the time-allocation matching law focuses on time spent in activities, considering repeatable responses such as

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a lever press or a key peck (e.g., Blough, 1963; Catania, 1961, 1962; Mechner, 1958a, 1958b) to be portions of the continuous activities of pressing and pecking (Baum, 2004; 2012; 2013). This form of the matching law makes two claims: (a) that the controlling variable of any activity is the relative instead of the absolute value of the variable; and (b) that its effect on preference is independent of the effect of additional controlling variables manipulated in the choice situation (Baum & Rachlin, 1969).

The idea that the effects of two or more relative independent variables on preference are additive (Baum & Rachlin, 1969) was not initially supported in studies of choice based on steady-state concurrent performance. Instead, rate and amount of food seemed to interact to control preference (Davison, 1988; Ito, 1985; Ito & Asaki, 1982; Logue & Chavarro, 1987; Williams & Fantino, 1978), and amount and delay to consequences in studies with human participants also seemed to interact (Green, Myerson, & McFadden, 1997; Kirby, 1997). However, reviews of delay discounting (e.g., Frederick, Loewenstein, & O'Donoghue, 2002) and related research with nonhuman animals (Calvert, Green, Myerson, 2010; Grace, 1999; Green, Myerson, Holt, Slevin, & Estle, 2004; Oliveira, Green, Myerson, 2014; Ong & White, 2004; Richards, Mitchell, de Wit, & Seiden, 1997) rejected the proposal that amount and delay of consequences interact to control choice, supporting additivity (Baum & Rachlin, 1969).

Equation 1 advocates the laws of time allocation as more broadly valid than the laws of response distribution, suggesting that choice is a continuous process even in situations where behavior was defined and measured as comprising discrete responses (Baum, 1973, 1976, 2001, 2002, 2004, 2012). Studies examining this continuity revealed that choice cannot be derived at any time scale from strictly local events; even at the most local time scale, preference proved to depend on early food deliveries from the other alternative, instead of being the result of the just-delivered food from the current alternative (Davison & Baum, 2000). More evidence of control over local preference by extended relative variables such as the food-delay ratio (Davison & Baum, 2007) and the food-amount ratio (Davison & Baum, 2003), was found in

dynamic reinforcing environments, where preference for either alternative depended on food deliveries from both alternatives (Baum & Davison, 2004).

Landon, Davison, and Elliffe (2002) observed that food deliveries affected long-term preference when the food-rate ratio varied within sessions while varying food-amount ratio across conditions (Davison & Baum, 2000, 2002; Landon & Davison, 2001). No evidence, however, indicated strictly local control over preference by variations in the amount of food; instead, the food-rate ratio and the food-amount ratio acted in similar ways to control preference (Landon, Davison, & Elliffe, 2003).

Related research assessing potential interactions between relative amount and relative rate of food in controlling preference arranged three overall rates of food in conditions where seven different food-amount ratios occurred within each session, and the food-rate ratio stayed at 1.0 across components and sessions (Davison & Baum, 2003). Estimates of sensitivity of behavior ratio to food-amount ratio (s in Eq. 2) were lower (0.25) than those (0.75) documented by Landon et al. (2003). However, when Davison and Baum (2003) varied the food-rate ratio within sessions and the food-amount ratio remained invariant across sessions and components (Experiment 2), sensitivity to food-amount ratio was high (1.0).

Aparicio and Baum (2009) replicated Davison and Baum's (2003) study using rats as subjects. They arranged dynamic environments where the overall rate of food was kept constant and the food-amount ratio varied across phases in which seven different food-rate ratios occurred within sessions (Aparicio & Baum, 2009). Their estimates of sensitivity to food-rate ratio were greater (0.8) than those obtained with pigeons (0.6) in comparable experiments (Baum & Davison, 2004; Davison & Baum, 2000, 2002). Nonetheless, Aparicio and Baum's (2009) estimates of sensitivity to food-amount ratio (1.0) replicated those found by Davison and Baum (2003), contrasting with the low estimates of sensitivity to food-amount ratio reported with steady-state concurrent performances (Davison & Hogsden, 1984; Landon et al., 2002; Schneider, 1973; Todorov, 1973).

Aparicio and Baum's (2009) results confirmed Davison and Baum's (2003) suggestion that sensitivity to food-amount ratio is high

and independent of food-rate ratio in settings where the food-amount ratio remains constant across sessions and food-rate ratio changes frequently within sessions. This led them to investigate whether the local effects of food deliveries were additive with the extended effects. They found that each food delivery shifted local preference toward the alternative from which it came, and the largest amount of food (four pellets) shifted local preference more than the smallest amount of food (one pellet). This result differed from that of Landon *et al.*'s (2003) showing similar effects of small and large amounts of food on local preference. To address the question of whether or not shifts in local preference depend on relative or absolute amount of food, Aparicio and Baum (2009) compared preference shifts following large (four pellets) and small amounts (one pellet) of food with those of an earlier study in which one pellet was delivered at both alternatives (Aparicio & Baum, 2006). They found that three or four pellets controlled local preference in the same way as one pellet had in the previous study (Aparicio & Baum, 2006), but also that one or two pellets produced only small effects on local preference, suggesting that accessibility to larger amounts (three or four pellets) reduced the effect of small amounts (one or two pellets) on local preference (Aparicio & Baum, 2009). Local analyses of postfood visits to both alternatives and computations of preference pulses supported the possibility that contrast between different consecutive amounts of food accounted for control over local preference; in particular, discontinuations (*i.e.*, switch in the alternative producing food) affected postfood visits and preference pulses according to relative amount. Aparicio and Baum (2009) concluded that: (1) preference on a more extended time scale depends on relative amount due to contributions of continuations and discontinuations of food deliveries; and (2) control by relative amount in a lean alternative, compared with that in a rich alternative, depends on the amount of food delivered at the lower rate, because the frequency of sampling and length of a sample visit to the lower-rate alternative depend on the amount of food delivered there (Aparicio & Baum, 2009). In the present study, we further explored both extended and local effects of food deliveries differing in

amount. We aimed to test whether additivity of relative rate and amount holds in a procedure with frequently changing food-amount ratios and compare with the results of previous research based on extended presentations of many sessions.

Two recent studies came to opposite conclusions about additivity of rate and amount ratios in extended presentations. Elliffe, Davison, and Landon (2008), in an extensive study varying both ratios, presenting each condition for 50 sessions, found that sensitivity to rate ratio decreased slightly when amounts differed and that sensitivity to amount ratio decreased slightly when rates differed. These decreases seemed to be fairly reliable, occurring in four out of five pigeons.

A meta-analysis of 11 data sets by Cording, McLean, and Grace (2011) drew the conclusion that rate and amount ratios can be considered to affect choice independently and additively. They attributed the contrary results of Elliffe *et al.* (2008) to a single condition in which a 9:1 rate ratio was combined with a 7:1 amount ratio, predicting a 63:1 behavior ratio. They speculated that 50 sessions of exposure might be insufficient for choice to stabilize at such an extreme.

None of the studies analyzed by Cording *et al.* (2011) examined choice in frequently changing environments or at shorter time-scales than sessions. Studies of choice with frequently changing rate and amount ratios have shown that local changes in preference depend on relative amount (Aparicio & Baum, 2009), relative delay (Davison & Baum, 2007), and relative rate of food delivery (Baum & Davison, 2004). Aparicio and Baum (2009) found that the effects of extended relative variables and those of local relative variables are additive, showing control of preference at three different time scales: (a) choice between food deliveries across the components of sessions, (b) visits to each lever between food deliveries, and (c) choice treated response by response following each food delivery. They reported control by relative amount of food at all three time scales—that is, the local effect of each amount on preference depended on the effect of the other amount even when it was not the most recent amount delivered (Aparicio & Baum, 2009).

The present study further examined whether sensitivity to food-rate ratio and

sensitivity to food-amount ratio are independent of one another under conditions where food-rate ratio remains invariant across sessions while food-amount ratio changes frequently within sessions. It follows up the earlier study (Aparicio & Baum, 2009), in which the opposite proposition was assessed, with the amount ratio remaining invariant across sessions while rate ratio changed dynamically within each session.

Method

Subjects

Eight experimentally naïve male Sprague-Dawley rats (Harlan Laboratories, IN) served as subjects. During the study, the rats were placed on a regimen of food restriction; post-session feedings of Purina® Lab Chow of approximately 10 g were provided such that the rats' weights ranged from 280 to 320 g. The rats were approximately 100 days old at the start of the study and were individually housed in plastic cages with free access to water in a temperature-controlled colony room on a 12:12 hr light/dark cycle, light beginning at 0700.

Apparatus

Eight modular chambers, six manufactured by Med Associates® (Model ENV-008, with interior dimensions of 305 mm x 241 mm x 210 mm) and two manufactured by Lehigh Valley Electronics® (Model E10-10SF, with interior dimensions of 290 mm x 250 mm x 290 mm), were enclosed in sound-attenuating boxes that from outside measured 780 mm wide, 540 mm long, and 520 mm high. A square metal grid constituted the floor of the chambers. A 40 by 40 mm opening, centered between the left and right walls 40 mm from the floor, provided access to a food cup into which 45-mg grain pellets (BioServ®) were delivered. Two retractable levers (Med Associates® model #ENV112BM), 45 mm wide and 15 mm long, requiring a downward force of approximately 0.25 N to operate, were mounted on the front wall of each chamber 70 mm above the floor. The centers of the levers were 75 mm to the left or right from the center of the dipper opening; lever extension/retraction required approximately 1 s. Two 28-V DC light bulbs (E11-03) were

installed 70 mm above the levers. A third non-retractable lever (E21-03) 45 mm wide, requiring a force of 0.25 N to operate, was centered on the back wall of each chamber 75 mm above the floor. A 28-V DC house light provided ambient illumination either centered on the back wall 3.0 cm below the ceiling (six chambers) or mounted in the center of the ceiling (two chambers). Continuous white noise was present in the surrounding room to mask extraneous sounds, and each enclosure was equipped with a ventilation fan that provided air circulation within the experimental space. Experimental events were programmed and data were recorded in a separate room by a Windows®-controlled computer using Med Associates® (Georgia, VT) software and interfacing equipment operating at 0.01-s resolution.

Procedure

Initial training. Four 45-mg grain pellets were placed into the food cup and training started with the left lever extended into the chamber. Each press on the extended lever produced a food pellet (fixed-ratio [FR] 1), but there were no attempts to shape manually the response of pressing on it. The FR 1 was operative until the rats pressed on that lever producing 60 pellets or 30 min elapsed, whichever happened first. Once the rats pressed consistently on the left lever producing 60 food pellets in two consecutive sessions, it was retracted from the chamber and the right lever was extended into the chamber; responding on the right lever was trained in a similar fashion. Finally, the right lever was retracted from the chamber and the rear lever was mounted on the back wall of the chamber with the FR 1 associated with it; when the rats pressed on the rear lever producing 60 food pellets in two consecutive sessions, the retractable levers were extended into the chamber and a concurrent FR 1 FR 1 FR1 schedule was used to reinforce presses on the rear and front levers for a final 30-min session.

General procedure. Sessions consisted of seven components with differing food-amount ratios (7:1, 6:2, 5:3, 4:4, 3:5, 2:6, and 1:7 food pellets) occurring within each session in random sequence and without replacement. The sessions were conducted at the same time each day and ended when all components were

completed or 90 min elapsed, whichever occurred first. Each component began with the retractable levers extended into the chamber and the lights above them turned on, signaling the availability of food pellets for pressing the retractable levers. The first response on one of the extended levers, left or right, caused the other extended lever to retract, and further presses on the available-extended lever produced food deliveries according to the schedule assigned to that lever. At any time the rat could leave this lever and switch to the retracted lever by pressing once on the nonretractable or changeover lever (located on the back wall), which caused the extended lever to retract and the retracted lever to extend into the chamber. This fixed-ratio-1 changeover requirement (FR 1 CO) separated the contingencies of reinforcement arranged for each retractable lever (Pliskoff, Cicerone, & Nelson, 1978; Stubbs, Pliskoff, & Reid, 1977) and simulated travel when switching from one extended lever to the other retracted lever (Aparicio & Baum, 1997, 2006, 2009; Baum & Aparicio, 1999). Each component lasted until 10 food deliveries had been obtained, and components were separated from one another by a 60-s blackout during which all lights were extinguished and the levers retracted from the chamber.

Rate of food delivery. For each retractable lever, the computer queried a probability gate every 9 s to determine whether or not to set up a food delivery. Three pairs of probabilities (.14:.14, .27:.03, and .03:.27) defined three food-rate ratios (1:1, 9:1, and 1:9). These probabilities programmed an average rate of food delivery for lever presses of about two per min or one delivery every 32.14 s. Each food-rate ratio lasted for 106 sessions and was arranged independently of the seven food-amount ratios. In Phase 1 the food-rate ratio was 1:1—the computer used the same probability (.14) to set up food deliveries in the left and right retractable levers. Phase 2 arranged a 9:1 food-rate ratio: The probability to set up a food delivery in the left lever was higher (.25) than that of setting up a food delivery in the right lever (.03). Phase 3 reversed these probabilities defining a 1:9 food-rate ratio: The probability to set up a food delivery in the left lever was lower (.03) than that of setting up a food delivery in the right lever (.25). The study concluded with a redetermination of Phase 1 (1:1,

$p = .14 : .14$) that lasted 26 sessions, and was cut short due to circumstances beyond our control.

Within components, food deliveries were arranged dependently; that is, food deliveries were probabilistically assigned to one of the two retractable levers, and no further food deliveries were assigned until that one had been produced. Whenever a component arranged a food delivery for a lever that was retracted, obtaining the food required the rat to make a changeover response so as to extend this lever into the chamber. A single press on the extended lever produced the assigned food delivery, after which scheduling of food deliveries resumed.

Amount of food delivery. For each session of each phase, the experimental program arranged seven different food-amount ratios or components (7:1, 6:2, 5:3, 4:4, 3:5, 2:6, and 1:7 food pellets) occurring in random sequence and without replacement.

Thus, to assess a possible interaction between food-amount ratio and food-rate ratio in governing preference, the present study kept overall food rate invariant (i.e., about two deliveries per min) on two levers and manipulated food-rate ratio across phases in which the food-amount ratio varied across seven components within each session.

Data Analysis

For all conditions (except the last) a minimum of 100 sessions were conducted to ensure a sufficient sample of behavior. The ratios of responses (left / right), computed from the daily records of total responses on the left and right levers across components, were transformed into base-2 logarithms. Similarly, the numbers of responses per visit to the left and right levers were calculated across components. The logs of response ratios and responses per visit on the left and right levers, computed for each rat, were plotted for each session and used to judge stability visually. The data of individual rats showing no systematic trends (up or down) in logs of response ratios and responses per visit on the left and right levers were judged stable, allowing the selection of the last 68–74 consecutive sessions for data analysis. For the redetermination of Phase 1, all sessions that could reasonably be regarded as stable (about 18 consecutive sessions) were included for data analysis.

The data from all selected sessions were pooled across sessions by food delivery within the sequence of 10 food deliveries. The number of responses on the left and right levers prior to each of the 10 food deliveries in each component were summed and then used to compute response ratios (L/R), which were sorted by component or by prior left-right sequence of food deliveries. The same was done with food deliveries left and right to calculate food-rate ratios (L/R). The series of consecutive responses following either a food delivery or a changeover, up to the next changeover, defined the length of each visit to a lever (i.e., presses per visit).

Results

The first analysis examined sensitivity to food-rate ratio. For each amount-ratio component and each food delivery within a component, the left graph in Figure 1 shows estimates of sensitivity (s in Eq. 2) to food-rate ratio across the four conditions. Prior to the first food delivery (zero on the x-axis), sensitivity to rate was similar across components ($s = 0.9$). With consecutive food deliveries in the 4:4, 5:3, and 3:5 components, sensitivity to rate ratio increased from 0.9 to slightly more than 1.0. Sensitivity increased a little (s close to 1.0) with successive food deliveries in the 2:6 and 6:2 components. Sensitivity to rate ratio remained level (s about 0.9) across food

deliveries in the 7:1 and 1:7 components. The right graph summarizes these results by plotting sensitivity to food-rate ratio as a function of $\log_2$ of food-amount ratio. Equal but opposite food-amount ratios were combined (1:7 and 7:1, 2:6 and 6:2, and 3:5 and 5:3) and sensitivities averaged across food deliveries 6 through 9. The thinner lines without symbols show the sensitivities for the eight individual rats. The solid heavy line with diamonds shows rate sensitivity for the grouped data. Group rate sensitivity was approximately 1.0 for food deliveries in the 4:4, 5:3 and 3:5, and 6:2 and 2:6 components and about 0.9 for food deliveries of the 7:1 and 1:7 components. Thus, amount ratio appears to have had a small but reliable effect on rate-ratio sensitivity, similar to that reported by Elliffe et al. (2008) in their study of long-term choice. Their results, averaged across pigeons and opposite amount ratios (e.g., 7:1 and 1:7, both plotted as $\log_2 7$) are shown in Figure 1 as the broken line with squares.

The next analysis examined how interfood behavior ratios changed within components. Figure 2 shows $\log_2$ behavior ratio (left/right) as a function of food deliveries within each component. The upper graphs show the results for the 1:1 rate ratio and its replication, and the lower graphs those for the 9:1 and 1:9 rate ratios. Although the vertical axes differ in range, they all span 2.5 log units, allowing comparisons of changes. Log behavior ratios

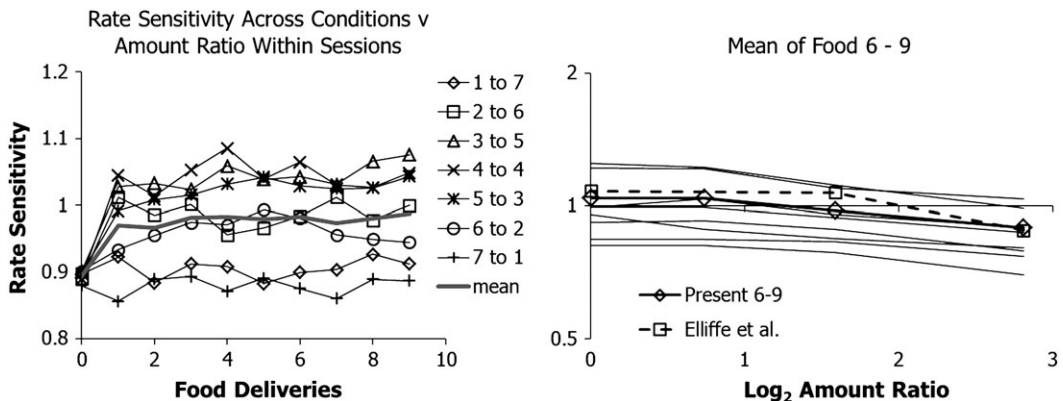


Fig. 1. The left graph shows sensitivity to food-rate ratio as a function of food deliveries (the data were pooled over the eight rats) and the right graph sensitivity to food-rate ratio as a function of $\log_2$ of food-amount ratio (equal but opposite food-amount ratios were combined and sensitivities averaged across food deliveries 6 through 9). The thinner lines show rate sensitivity for the individuals, and the solid heavy line with diamonds that for the pooled data. The broken line with squares shows similar rate-ratio sensitivity found by Elliffe et al. (2008).

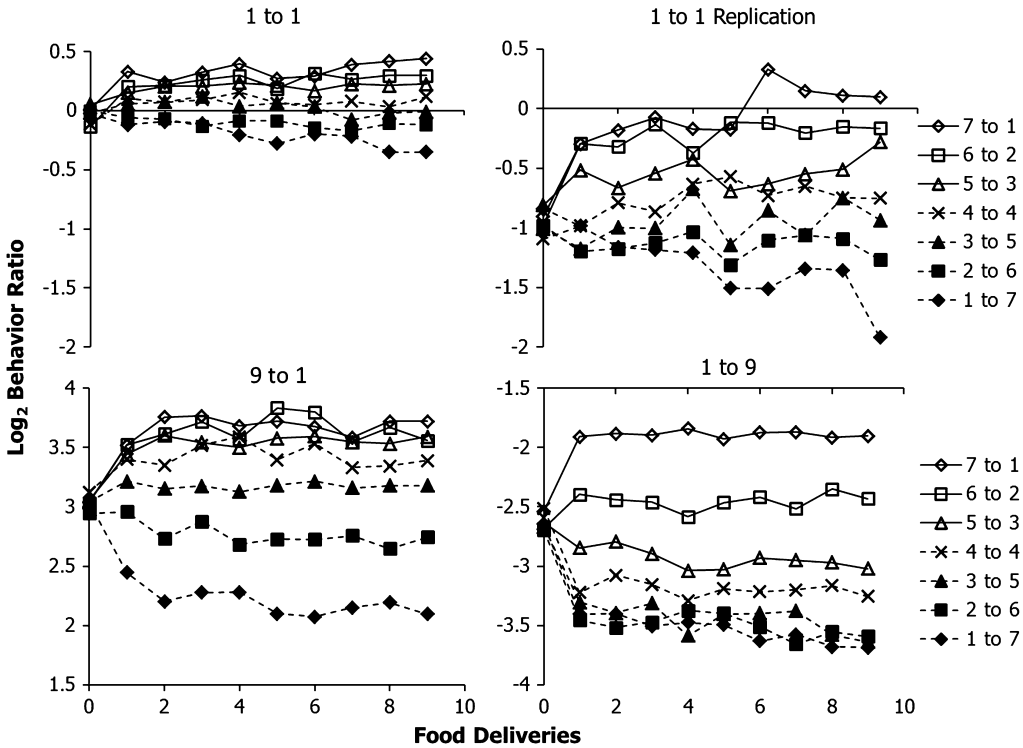


Fig. 2. Development of preference within components. For each condition, interfood choice ($\log_2$ behavior ratio) is plotted against food deliveries in each component. The upper graphs show the results for the 1:1 food-rate ratio and its replication, and the lower graphs those for the 9:1 and 1:9 rate ratios.

within components spread out less when rates were equal than when rates were unequal, indicating lower sensitivity to amount ratio. Sensitivity to amount ratio was higher in the 1:1 replication than in the initial 1:1 condition. Little separation occurred between amount ratios of 7:1, 6:2, and 5:3 when the rate ratio was 9:1 and between amount ratios 1:7, 2:6, and 3:5 when the rate ratio was 1:9. This result indicates a lack of sensitivity to amount ratio when it favored the same alternative as the rate ratio favored. All leveled out at about 3.5 or -3.5 (equivalent to a ratio of 11.3 to 1 or 1 to 11.3), suggesting a possible limit to preference under these conditions.

Differences in sensitivity to food-amount ratio when rate and amount opposed one another and when they agreed with one another were analyzed for the last two inter-food intervals (IFI) of the food-rate ratios 1:1 and its replication, 9:1, and 1:9. Figure 3 plots $\log_2$ of behavior ratio as a function of the $\log_2$ of amount ratio. The equation of each

regression line appears alongside of the line. Rate sensitivity can be inferred from the intercepts of the lines for the components in which rate and amount opposed one another. For the 9:1 and 1:9 rate ratios, the intercepts of 3.42 and -3.25 translate into behavior ratios of 10.7:1 and 1:9.5, slightly overmatching. Sensitivity to amount ratio was much higher when rate and amount opposed one another than when rates were equal (s about 0.5 versus s about 0.14 or 0.31). When rate and amount ratios went in the same direction, sensitivity to food-amount ratio was about zero. This indicates a possible limit to preference; it would not go above approximately 3.5 or below approximately -3.5 (equivalent to ratios of 11.3 to 1 and 1 to 11.3).

We estimated sensitivity to amount food-by-food when rate and amount opposed one another and when they went in the same direction. These sensitivities were plotted in Figure 4 against number of food deliveries. For comparison, data for the 1-to-1 and 1-to-1

replication conditions also are presented in each panel. Figure 4 shows that when rate and amount opposed one another (left graph) sensitivity to amount quickly rose to around 0.4 - 0.5, replicating results of Figure 3. For the 1:1 condition (diamonds), sensitivity was consistently lower (s about 0.1). When amount and rate ratios went in the same direction (right graph), sensitivity to amount ratio was extremely low (s about 0.05) across food deliveries. The 1:1 rate replication (circles) shows a higher sensitivity to amount (s about 0.3) than that observed in the first 1:1 rate condition (s about 0.10), but was based on a smaller number (about 18) of sessions. Whether or not it would have returned to the low level of the first 1:1 condition with a more extended number of sessions, the rate sensitivity in the replication clearly falls below sensitivity in the 9:1 and 1:9 conditions.

Figures 3 and 4 show that sensitivity to amount ratio increased considerably when food rates were unequal, in the 9:1 and 1:9 rate-ratio conditions. But to draw this conclusion, we excluded the components in which rate and amount went in the same direction (i.e., 7:1, 6:2, and 5:3 amount ratios in the 9:1 food-rate ratio, and 1:7, 2:6, and 4:5 amount ratios in the 1:9 food-rate ratio), because of the apparent limit to preference (3.5 or -3.5). For conditions where food-rate ratio opposed food-amount ratio, sensitivity to amount was estimated across food deliveries 6 to 9 and plotted in Figure 5 as a function of the

absolute value of $\log_2$ of food-rate ratio. For each rat and the group, there is one point from 9:1 and one point from 1:9. Each line was fitted to the averages of two points at 0 and two points at 3, a total of four points. For every rat, the amount sensitivity was higher in the replication, for some only a little. The regression lines all have positive slope, confirming that amount sensitivity was higher in the uneven-rate conditions for every rat. For the 1:1 rate condition and its replication, sensitivity to amount ratio was lower (0.1 and 0.3) than for the 9:1 and 1:9 rates (both about 0.5), confirming results of Figures 3 and 4.

Figure 6 summarizes the effects of continued food deliveries from the same alternative (i.e., continuations) on preference. $\log_2$ of behavior ratio (small/large or left/right) is plotted as a function of food deliveries: The different symbols indicate the various amounts. The unequal-rates conditions (9:1 and 1:9; middle and bottom panels) show the same limit to preference as in Figures 2 and 3 (about 3.5 or -3.5) for the larger amounts. In the equal-rates condition (upper panel), another result stands out: Continuations of five, six, and seven pellets (the filled symbols) all produced the same preferences, and the effect of four pellets on the left (4L) only differed a little from the effect of five, six, or seven pellets after the fourth continuation. The effects of the different amounts followed a counting pattern of "1, 2, 3, 4, many" or possibly "1, 2, 3, many," where "many" indicates

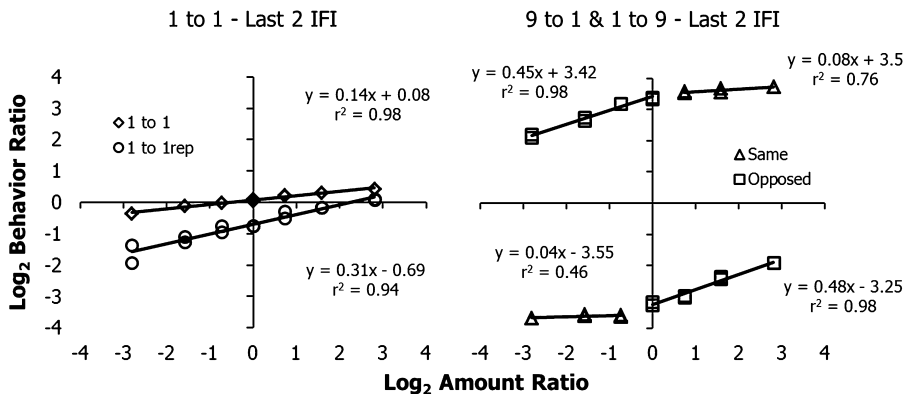


Fig. 3. For the last two interfood intervals (IFI) of the food-rate ratios 1:1 and its replication (left graph), and 9:1 and 1:9 (right graph), $\log_2$ of behavior ratio is plotted against $\log_2$ of amount ratio. The equation of each regression line appears beside the line.

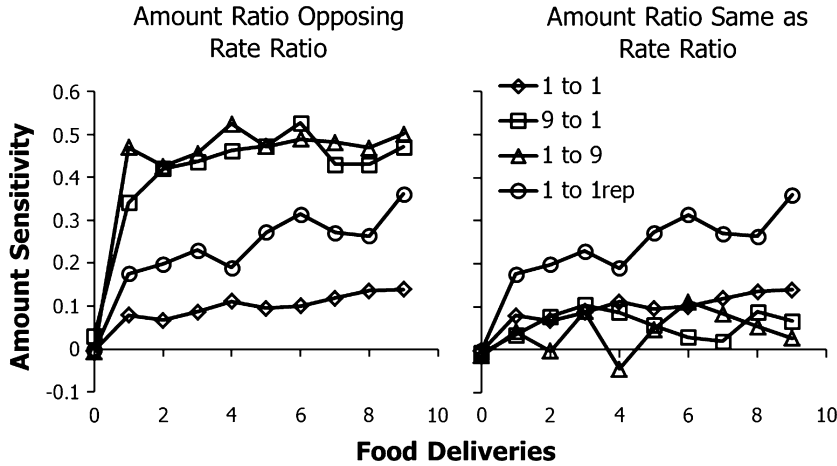


Fig. 4. Sensitivity to amount food-by-food when rate and amount opposed one another (left graph) and when they went in the same direction to food-amount ratio (right graph) as a function of food deliveries. Sensitivities in the two 1:1 conditions are included for comparison.

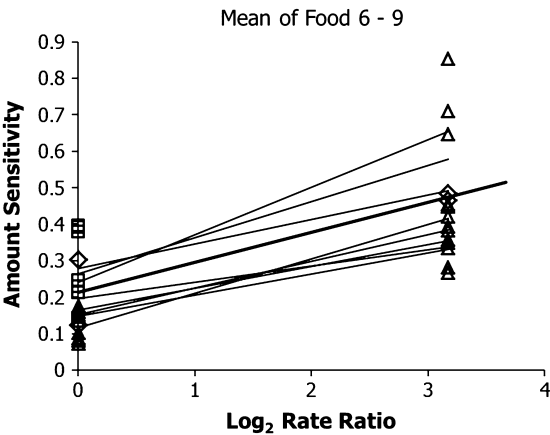


Fig. 5. For conditions where food-rate ratio opposed food-amount ratio, estimates of sensitivity to amount across food deliveries 6 to 9 are plotted against $\log_2$ of food-rate ratio. The thinner lines, triangles, and squares show results for individuals; the squares demarcate the replication of the 1:1 rate condition. The diamonds and heavy line show amount sensitivity for the grouped data.

equivalence of the larger amounts. Either pattern would have reduced sensitivity of preference to amount ratio for the equal rates.

Because continuation preferences in the 1:1 condition changed in a linear fashion with respect to food number, we fitted regression lines to the preferences, as a function of food deliveries, in Figure 6 to confirm that amounts greater than three or four pellets had comparable effects on sensitivity to amount. The top

graph in Figure 7 shows the slopes of these regression lines plotted against amount. The slopes for one and two pellets were both close to zero, and for more than two pellets, the slope increases as expected but then flattens out for five, six, and seven pellets. Thus, one and two pellets had small and roughly equal effects on preference, and five, six, and seven pellets had large and roughly equal effects on preference. In the lower graph, the solid line shows the effect on preference of continuations in the unequal-rate conditions (collapsing 9:1 and 1:9); calculated as the shift in preference from that prior to food to preference following food (averaging across food deliveries 1–9 because of the flatness of the curves). Consistent with the limit to preference, the line flattens for food amounts of five, six, and seven pellets. Continuations on the right lever in the 1:9 condition (squares) affected preference slightly more than continuations on the left lever in the 9:1 condition (triangles), indicating the small overall bias toward the left lever noted above.

Figure 8 shows the change in $\log_2$ behavior ratio produced by a discontinuation (i.e., a food delivery from the opposite alternative following one or more food deliveries from the initially productive alternative—e.g., LLR or RRRL) as a function of number of food deliveries up to and including the discontinuation. The upper panel shows change in preference (small/large) following discontinuations in

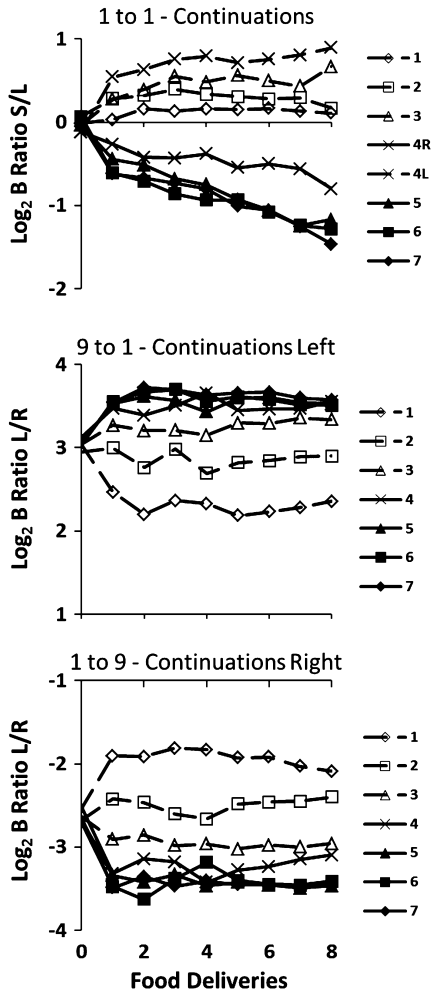


Fig. 6. For the 1:1, 9:1, and 1:9 rate conditions $\log_2$ of behavior ratio (small/large or left/right, respectively) is plotted as a function of repeated food deliveries of the same amount from the same alternative (continuations).

the 1:1 condition (so changes following large amounts appear as negative). The middle and lower panels show change in preference following discontinuations (Left/Right) with the 9:1 and 1:9 rate ratios. The general flatness of the lines suggests that the number of prior continuations mattered little.

The preference changes shown in Figure 8 were summarized in Figure 9 by averaging across sequences to show the effects of different amounts of food on preference. The upper panel shows that with equal rates (1:1), all discontinuation amounts had about the same effect on preference, whether on the left

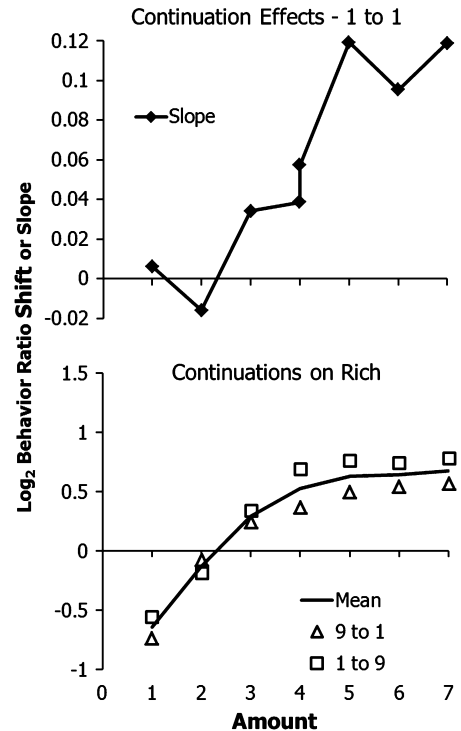


Fig. 7. Continuation effects for the 1:1 rate condition (upper graph). The slope of the regression line, fitted to $\log_2$ of behavior ratio, is plotted against amount. The squares stand for continuations on the right—rich lever in the 1:9 condition and the triangles for those corresponding to the left—rich lever in the 9:1 condition; the solid line shows the effect on preference of continuations (collapsing 9:1 and 1:9).

or on the right. For conditions with unequal rates (9:1 and 1:9), the line connecting the triangles shows that discontinuations on the low-rate or lean alternative had effects that increased with amount up to five pellets, but leveled off for five, six, and seven pellets, in keeping with the effects of continuations (Fig. 7). Delivery of only one pellet had some tendency to a negative effect, increasing preference for the other alternative, and two pellets had no effect at all. The line connecting the squares shows the effect of first food in a component delivered by the low-rate or lean alternative. The pattern is different from that for discontinuations: Delivery of 1, 2, or 3 pellets had about the same small effects, whereas the effects of larger amounts increased with amount. The line connecting the diamonds shows the effects of a food delivery from the high-rate alternative following the first food

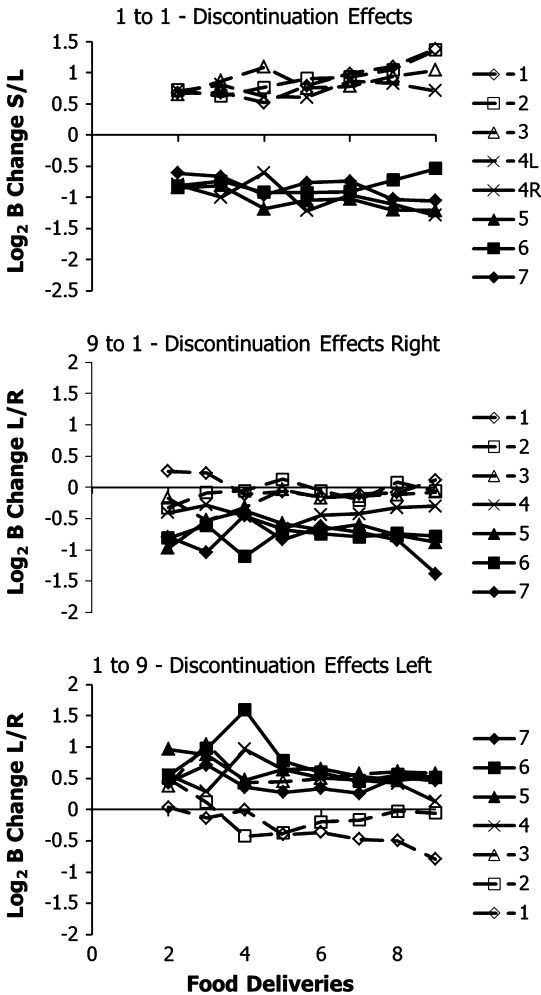


Fig. 8. Change in preference following discontinuations in the 1:1 condition (small/large), or that following discontinuations in the 9:1 and 1:9 rate conditions (left/right), as a function of number of food deliveries up to and including the discontinuation.

from the low-rate alternative. The expected shift in preference upward with amount appears, but it may not be reliable, because the sample sizes for these events tended to be small.

Discussion

We assessed whether sensitivity to food-rate ratio and sensitivity to food-amount ratio are independent of one another when food-amount ratios vary within sessions. Sensitivity to rate ratio was high (*s* about 1.0) across food

deliveries and varied little across amount-ratios (Fig. 1), indicating that sensitivity to rate ratio is largely independent of amount ratio, consistent with earlier research showing independence of sensitivity to rate ratio from amount ratio (Aparicio & Baum, 2009; Davison & Baum, 2003). The picture for sensitivity to amount ratio was more complex. Sensitivity to amount ratio was relatively high when rate ratio and amount ratio opposed one another (Fig. 4), indicating that these two variables combine additively (Baum & Rachlin, 1969). The estimates of sensitivity to amount ratio were higher (around 0.5) than those estimated in studies where amount ratio was varied with choice in steady-state (range 0.2 to 0.4; Davison & Hogsden, 1984; Landon *et al.*, 2002; Schneider, 1973; Todorov, 1973). When rate ratio and amount ratio favored the same alternative, however, sensitivity to amount ratio was close to zero (Figs. 3 and 4).

A 9:1 or 1:9 rate ratio moved log₂ behavior ratio up or down approximately by about 3.0—an eightfold change—relative to the initial 1:1 condition, indicating a long-term effect of rate ratio on choice (Fig. 2). Figure 2 shows that preference was compressed across amount ratios that favored the same alternative as the rate ratio, but clearly separated when amount ratio opposed the rate ratio, with more responses occurring on the lever associated with the larger amount over the lever associated with the smaller amount of food. This result is reflected in the large differences in sensitivity shown in Figs. 3 and 4. The relatively high sensitivities when amount and rate ratios opposed one another agree with those documented in studies where the food-rate ratio was manipulated within sessions and food-amount ratio was either kept constant between sessions (Aparicio, 2008; Aparicio & Barajas, 2002; Aparicio & Baum, 2006; Aparicio & Otero, 2004; Baum & Davison, 2004; Davison & Baum, 2000, 2002, 2003, 2007), or was varied across phases (Aparicio & Baum, 2009).

If we focus on the components in which amount ratio opposed rate ratio, we have a tentative answer to the question of whether unequal rates affect sensitivity to amount. The left-hand graph in Figure 4 shows that unequal rates resulted in much higher sensitivity to amount ratio than equal rates. Thus, in these conditions our results indicate that sensitivity

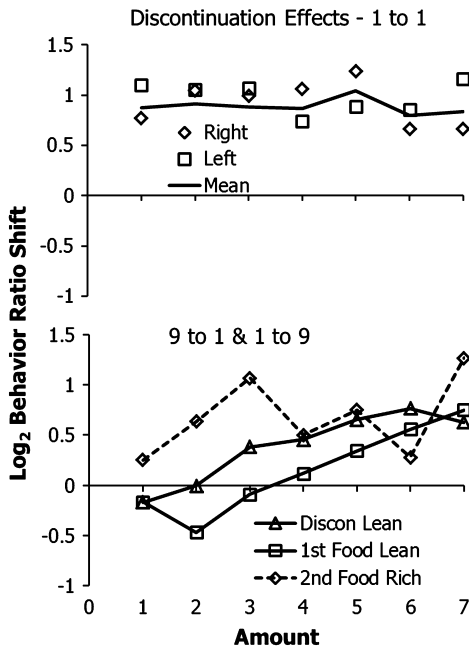


Fig. 9. Preference shift as a function of amount of food. For the 1:1 condition (upper graph), the squares stand for discontinuations on the left and the diamonds for those on the right lever. For the 9:1 and 1:9 conditions (lower panel), the line connecting triangles stands for discontinuations on the lean lever, the line connecting the squares for the effect of first food in a component delivered by the lean lever, and the broken line connecting the diamonds for the effects of a food delivery from the rich (high-rate) lever following the first food from the lean lever.

to amount ratio is not independent of rate ratio, but is enhanced by unequal rates at the two alternatives.

The lower sensitivity to amount ratio in the 1:1 condition is reflected in the smaller spread of the lines in the upper graphs of Figure 2 compared with the lower graphs. In those lower graphs, little separation occurred between preferences for amount ratios of 7:1, 6:2 and 5:3 when they went in the same direction as the rate ratio, indicating lack of sensitivity to amount ratio. In Figure 2 and Figure 3, $\log_2$ behavior ratio leveled out at about 3.5 or -3.5 , indicating a limit to preference at a ratio of about 11.3 to 1 or 1 to 11.3. Amount ratio failed to push preference beyond this level, with the result that ratios of 7:1, 6:2, and 5:3 pellets all had similar effects on preference. Baum and Davison (2014) reported a similar limit to preference, but

when rate ratio changed frequently within sessions. Their results, together with the present results, suggest that when concurrent pairs of schedules change often, preference may reach a limit by the end of a component—a limit not usually seen in experiments where a concurrent pair of VI schedules continues for many sessions. For example, Baum, Schwendiman, and Bell (1999) found preferences greater than 100:1 for comparable rate ratios (i.e., matching).

Food-by-food estimates of sensitivity across components revealed that when rate and amount ratio opposed one another, sensitivity to amount ratio quickly increased within components in the uneven rates conditions (Fig. 4), reaching a level (s about 0.5) close to the average level of sensitivity to rate ratio (0.6) formerly reported with pigeons (Baum & Davison, 2004; Davison & Baum, 2000, 2002). In the equal-rates conditions, however, estimates were constantly low (s about 0.2). Similarly, when rate and amount ratio favored the same alternative, food-by-food estimates were extremely low (s about 0.05) across food deliveries of the 9:1 and 1:9 conditions. Estimates for the 1:1 condition replication were slightly higher than for the first 1:1 condition (s 0.3 vs. 0.10); but we do not know whether it would have declined further had we been able to conduct the replication for more sessions. The mean across food deliveries 6–9 of the uneven-rates conditions revealed that sensitivity to amount was considerably higher (s about 0.45) than that estimated for the even-rates conditions (s about 0.20), confirming that sensitivity to amount increased substantially in the uneven-rates conditions (Fig. 5). Together, these findings indicate that sensitivity to rapid changes in the amount ratio was considerably higher when the rates were unequal; but to draw this conclusion, we have to exclude the components in which rate ratio and amount ratio favored the same alternative, because of the limit in preference.

The limit to preference may explain the small effect on rate sensitivity shown in Figure 1. If one examines the right graph in Figure 3, comparing the separation of points arranged exactly above one another, the two squares at zero on the x-axis (equal amounts) show the largest separation, and the vertically paired circles and diamonds (left graph) show lesser degrees of separation, indicating lower

sensitivity due to the flatness of the lines of diamonds (i.e., the preference limit). Had the diamonds paralleled the circles, no such decrease in sensitivity would have been observed. Could some limit to preference in the study by Elliffe *et al.* (2008) explain their similar results shown in Figure 1, as Cording *et al.* (2011) speculated? Figure 10 shows choice plotted against log amount ratio averaged across the five pigeons in the Elliffe *et al.* study. The upper filled symbols show choice in the conditions with 9:1 rate ratio, and the lower unfilled symbols show choice in the conditions with 1:9 rate ratio. The lines were fitted to the three points (squares) from conditions in which the rate and amount ratios were not favoring the same alternative—were either opposed or the amount ratio equaled 1.0. Choice in the conditions in which amount and rate ratio favored the same alternative (circles) all fall away from the line in the direction of indifference, with the result that the two points directly above one another are closer together than they would have been had the circles been in keeping with the squares. The decrease in spread would manifest as a lower sensitivity to rate ratio. Four of the five pigeons showed the pattern depicted in Figure 10. The exception was Pigeon 136, which also showed no change in rate

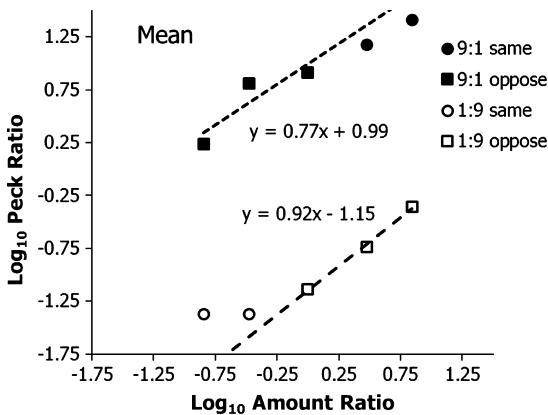


Fig. 10. Choice plotted against log amount ratio averaged across the five pigeons in the Elliffe *et al.*'s (2008) study. The upper filled symbols display choice in conditions with the 9:1 rate ratio and the lower unfilled symbols choice in conditions with 1:9 rate ratio. Regression lines were fitted to ratios in which rate and amount were not pulling in the same direction (squares), excluding ratios in which amount and rate ratio pulled in the same direction (circles).

sensitivity with amount ratio (Elliffe *et al.*, 2008; Fig. 5). Thus, the speculation that the extreme conditions in that study may have been anomalous may be correct (Cording *et al.*, 2011). A 9:1 rate ratio combined with a 7:1 amount ratio would predict a 63:1 behavior ratio, and such an extreme preference would almost certainly require more than 50 sessions to develop, as Baum *et al.* (1999) found.

If 50 sessions of long-term exposure are insufficient, one might suppose that the brevity of the components in the present experiment could explain the variation in rate sensitivity with amount ratio shown in Figure 1. Figure 2 contradicts that speculation, however, because choice leveled off in all components in this experiment just as in all the earlier experiments with frequently changing choice components. Rather, the limit to preference with extreme amount ratios, which produced the small change in rate sensitivity (Fig. 1), needs to be explained in some other way.

The analyses at the smaller time scale of interfood choice may offer an explanation of the preference limit, because the local effects of different amounts of food shed light on the more extended effects. Our analyses of the different sequences of food deliveries revealed substantial effects of individual food deliveries on choice, replicating previous findings with rats (Aparicio & Baum, 2006, 2009) and pigeons (Baum & Davison, 2004; Davison & Baum, 2000, 2002; Landon & Davison, 2001; Landon *et al.*, 2002, 2003). An almost symmetrical spread of preferences with food deliveries (a “tree” diagram; figure not shown), similar to that reported in our earlier studies (Aparicio & Baum, 2006, 2009), was observed in the equal-rates condition with the levers providing equal amounts (four pellets each), although it was imperfect due to a bias for the left lever. Continuations of food deliveries produced clear effects on preference, but these effects followed amount imperfectly, because one and two pellets affected choice little and five, six, and seven pellets all affected choice about equally (Fig. 7, top graph). The equivalence of five, six, and seven pellets cannot be attributed to the ± 3.5 preference limit, because the preferences in this 1:1 condition all fall below that limit.

When rates were unequal, continuations affected preference differently from the equal-

rates condition. When rate and amount ratios went in the same direction, $\log_2$ behavior ratio rapidly reached the ± 3.5 limit, confirming that our procedure imposed a limit on preference. Continuations of four, five, six, and seven pellets all pushed preference to the ± 3.5 limit. When rate and amount opposed one another, continuations of one, two, or three pellets produced stable preferences too, but smaller than the limit. Figure 7 shows that continuation of amounts greater than four pellets all produced approximately the same preferences in all conditions. The effects of the different amounts followed a counting pattern of "1, 2, 3, 4, many pellets" or "1, 2, 3, many pellets." Either pattern would have reduced sensitivity to amount both for the equal rates and the unequal rates when amount and rate ratios went together (Figs. 3 and 4).

Discontinuations occurred only on the lower-rate lever, and had effects on choice that depended little on amount (Figs. 8 and 9). When food rates were equal, discontinuations moved preference toward the just-productive lever, but to an extent that was independent of the amount of the discontinuation. The lack of dependence on amount likely contributed to the low amount of sensitivity in the 1:1 condition (Figs. 3, 4, and 5). When food rates were unequal, discontinuations of seven, six, five, and four pellets all moved preference towards the lever producing them, but all to about the same extent, whereas discontinuations of small amounts of one, two, and three pellets affected preference less or even slightly favored the not-just-productive (higher-rate) lever (Figs. 8 and 9). The lack of differentiation among the large amounts may have lowered the amount sensitivity in the components where rate and amount ratios opposed one another. Figure 9 shows also the effects of the occasions on which first food in a component came from the lower-rate lever (squares). When the amount was small, preference shifted slightly toward the higher-rate lever, and nondifferentially, likely decreasing amount sensitivity in the components where rate and amount ratio went together. Larger amounts shifted preference toward the just-productive lower-rate lever, likely enhancing amount sensitivity in the components where amount and rate ratios opposed one another.

We discovered three factors affecting sensitivity to amount: (1) the limit to preference

seen in Figures 2 and 3; (2) the approximately equal effects of amounts greater than four pellets seen in Figure 7; and (3) the almost complete absence of effect of differences in amount when the source of food switched (i.e., discontinuations) seen in Figures 8 and 9. To the extent that choice varied with amount, the present results support previous research indicating that sampling of the lower-rate lever depended on the amount delivered by that lever (Aparicio & Baum, 2009). Comparison between the equal and unequal rates indicates that the nearly equivalent effects of amounts greater than four pellets occurred for different reasons in the equal- and unequal-rates conditions. In the unequal-rates conditions, equivalent effects of amounts greater than four pellets may have been due to the preference limit, or, alternatively, lack of discrimination may have produced the preference limit. One piece of evidence goes against lack of discrimination, however. When the first food in a component was produced by the lower-rate lever, Figure 9 shows clear discrimination among all the larger amounts. Thus, the preference limit was probably not due to reduced discrimination among the large amounts.

The third factor, the absence of differential effects of amount in discontinuations, contributed to the low sensitivity to amount in the equal-rates condition. Figures 8 and 9 show that equal rates diminished the effects of amount, particularly large amounts, compared with unequal rates. The reason for this difference remains to be discovered.

Conclusion

The present study aimed to examine the independence or additivity of rate and amount ratios, but produced results complicated by a limit on preference at about 11.3:1 and 1:11.3. Due to this limit, our results only partially support the additivity of rate and amount (Baum & Rachlin, 1969)—each affecting choice independently of the other (Davison & Baum, 2003). Only when rate and amount ratios opposed one another was additivity upheld. The limit to preference, which may be peculiar to procedures in which rate or amount ratios change frequently, calls for further research. It resulted in amount sensitivity

close to zero when amount and rate ratios favored the same alternative. Finally, our analyses at the shorter timescale of interfood times indicated equivalent effects of amounts greater than four pellets, which may have been forced by the preference limit when rates were unequal, but apparently occurred for other reasons when rates were equal. This ineffectiveness of varying amount remains to be explained.

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