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PIGEONS' DEMAND AND PREFERENCE FOR SPECIFIC AND GENERALIZED CONDITIONED REINFORCERS IN A TOKEN ECONOMY

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Pigeons' demand and preference for specific and generalized tokens was examined in a token economy. Pigeons could produce and exchange different colored tokens for food, for water, or for food *or* water. Token production was measured across three phases, which examined: (1) across-session price increases (typical demand curve method); (2) within-session price increases (progressive-ratio, PR, schedule); and (3) concurrent pairwise choices between the token types. Exponential demand curves were fitted to the response data and accounted for over 90% total variance. Demand curve parameter values, P_{max}, O_{max} and α showed that demand was ordered in the following way: food tokens, generalized tokens, water tokens, both in Phase 1 and in Phase 3. This suggests that the preferences were predictable on the basis of elasticity and response output from the demand analysis. P_{max} and O_{max} values failed to consistently predict breakpoints and peak response rates in the PR schedules in Phase 2, however, suggesting limits on a unitary conception of reinforcer efficacy. The patterns of generalized token production and exchange in Phase 3 suggest that the generalized tokens served as substitutes for the specific food and water tokens. Taken together, the present findings demonstrate the utility of behavioral economic concepts in the analysis of generalized reinforcement.

Key words: generalized conditioned reinforcement, token reinforcement, demand analysis, progressive ratio schedules, concurrent schedules, behavioral economics, pigeons, key peck

Skinner (1953) defined *generalized reinforcers* as reinforcers established and maintained via relations with two or more reinforcers. Generalized reinforcers are ubiquitous in everyday human behavior. Money is the most common example, but Skinner also discussed the importance of generalized reinforcement to social and verbal behavior; signs of attention and approval from others are closely coupled with a wide range of other reinforcers and therefore acquire important generalized reinforcing functions. Add to this the important role of generalized reinforcement in applied settings, in the form of token economies, and it becomes clear that the topic of generalized reinforcement is of enormous conceptual and applied significance.

The expansion from one to multiple reinforcers is functionally significant in that it also expands the number of relevant motivational operations. According to Skinner (1953), and to subsequent interpretations, generalized reinforcers are assumed be more effective than specific-type reinforcers, related to only a single deprivation, because they recruit multiple motivational conditions, any of which may be present at the time of the response. Less dependent on specific deprivation states, generalized reinforcers should be more effective than specific reinforcers across a wider range of circumstances.

The assertion is both plausible and testable. Yet in the 60+ years since Skinner's initial conceptualization, the empirical analysis of generalized reinforcement has scarcely begun. Despite the importance of the topic, little is known about even the most basic functions of generalized reinforcers. A broad aim of the present study was to expand the analysis of generalized reinforcement by comparing generalized reinforcers to specific reinforcers at various costs and in various motivational conditions. Grounding the analysis in concepts and methods from behavioral economics, reinforcer efficacy was defined in terms of demand, response output, and preference.

Pigeons were studied in a token economy, in which different token types could be earned and exchanged for different commodities. The research builds on a recent study by DeFulio, Yankelevitz, Bullock, and Hackenberg (2014), in which pigeons could produce and exchange

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three different token types, singly and in combination: (1) *specific-food tokens* (green tokens exchangeable for food), (2) *specific-water tokens* (red tokens exchangeable for water), and (3) *generalized tokens* (white tokens exchangeable for either food or water). The fixed ratio (FR) token-production price for specific and generalized tokens was manipulated under both food *or* water deprivation, in separate conditions of the study.

Token production and exchange came under control of the deprivation conditions: the pigeons earned mainly food tokens under food deprivation and water tokens under water deprivation. The generalized tokens that were earned were exchanged nearly exclusively for the restricted commodity. As the FR prices of token production were systematically increased across blocks of sessions, token production declined, characteristic of typical demand functions, for both specific and generalized tokens in both deprivation contexts. The rate of decline, however, was somewhat higher for specific than for generalized tokens, especially under food deprivation conditions.

In economic terms, the *own-price elasticity* values were less negative for generalized than for specific token types. Moreover, the slopes of the cross-price functions, indicating the degree to which the constant-price token came to substitute for the increasing-price token, were more positive for generalized than for specific tokens. Pigeons produced roughly similar numbers of food tokens and generalized tokens when the prices were low (FR 1), but came to produce substantially more generalized tokens as the price of the food tokens increased and the price of the generalized tokens remained low. Thus, the generalized tokens came to substitute for the food tokens, one important function of generalized reinforcers. The same general pattern occurred in the context of water deprivation – the generalized tokens substituted for water tokens – though to a somewhat lesser degree.

Due to the restricted range of prices explored by DeFulio et al. (2014), it was not possible to evaluate demand functions using more quantitative criteria. One goal of the present study, therefore, was to compare demand and preference for different token types using more quantitatively precise methods. Using procedures similar to those employed by DeFulio et al., pigeons could produce and exchange red tokens for water, green tokens for food, and white tokens for either food or water. Using methods adapted from Madden, Smethells, Ewan, and Hursh (2007) for comparing qualitatively different reinforcers, the present study examined demand, response output, and preference for the token types under various conditions of food and water deprivation.

In Phase 1, demand for each token type was assessed by increasing price (token production FR) across sessions, and evaluated using Hursh and Silberberg's (2008) exponential model:

$$\log Q = \log Q_0 + k(e^{-\alpha Q0C} - 1),$$

where demand (Q) is consumption (or number of reinforcers obtained) as a function of unit price (P, FR requirement); Q_0 is the consumption at the lowest price. The slope of the function (α) expresses the sensitivity to price changes, or *elasticity*. Other informative parameters include P_{max}, the maximum price before the decline in consumption at which the function turns from inelastic to elastic (slope = −1.0), and O_{max}, the peak response output. The three token types were evaluated in relation to these key parameters from the model.

In Phase 2, demand was assessed by changing token-production price within a session, according to a progressive ratio (PR) schedule that incremented with each reinforcer. This yielded additional measures—last completed FR, or breakpoint, and peak response rates—with which to compare the token types and their demand functions. In Phase 3, the different token types were available concurrently for blocks of sessions in pairwise choices, yielding an additional measure—relative preference between token types—with which to compare to the demand measures. Together, these phases provided a comprehensive analysis of demand and preference for specific and generalized token types.

Bringing this type of analytic focus to the generalized token economy will provide a more complete picture of the functions and relative efficacy of specific and generalized tokens than prior research. If generalized reinforcers are indeed more effective than more specific reinforcers, as is commonly assumed, then the generalized tokens, relative to the specific tokens, should generate higher levels of demand intensity (token production at the lowest price), lower levels of demand elasticity (sensitivity to price changes), elevated response output (P_{max}, O_{max}, peak response rate), and greater preference (choice proportion).

The multiple converging measures of reinforcing efficacy (demand intensity, demand elasticity, breakpoint, peak response rate, preference) are important in light of prior research showing less than perfect agreement among common indices of reinforcer efficacy (e.g. Bickel & Madden, 1999; Bickel, Marsch, & Carroll, 2000; Madden et al., 2007). For example, Madden et al. found, with rats as subjects and food and water reinforcers, that different measures of reinforcer efficacy were not strongly correlated: higher PR breakpoints and demand peak response rates were obtained for food than water, but the rats did not show corresponding preferences when both food and water were available concurrently. Conversely, Johnson and Bickel (2006) found, with human subjects and money and cigarettes as reinforcers, that relative P_{max} and O_{max} values correlated with PR breakpoints and peak response rates, and predicted preference between cigarettes and money (see also Bickel & Madden, 1999).

These different results may be due to reinforcer interactions. In economic terms, food and water are *complementary* reinforcers (consumption of one reinforcer decreases with price increases of the other reinforcer) whereas cigarettes and money are *independent* reinforcers (consumption of one reinforcer is unrelated to price changes of the other reinforcer). Perhaps the close coupling of different measures of reinforcer efficacy seen with human subjects in the studies by Bickel and colleagues is limited to situations with independent reinforcers. Or, perhaps the findings are due to *substitution*, a different type of reinforcer interaction, in which consumption of a constant-priced commodity increases with the price of an alternate commodity (e.g., increased consumption of tea with increases in the price of coffee). Generalized reinforcers such as money are effective in part because they serve as functional substitutes for a wide range of other reinforcers; or more specifically, they enable a system of exchange between substitutable reinforcers. In the present economic conditions, this translates into increased production of generalized reinforcers with price increases for more specific reinforcers.

The present study was designed to explore in greater depth these types of reinforcer interactions in a generalized token economy. First, unlike the DeFulio et al. (2014) study, some conditions in the present study were conducted in a fully closed economy in which daily intake of food and water occurred within the experimental sessions, designed to enhance the generalized functions of the tokens. Second, using known complementary reinforcers (food and water) but including a generalized type with the potential to function as a substitute for these more specific reinforcers, we directly assessed the substitutability function of the generalized tokens. And finally, the multiple converging measures enabled a multifaceted assessment of the functions of specific and generalized tokens, and the degree to which the different indices of reinforcer efficacy converge. Together, the methods provide quantitatively precise ways to assess some basic functions of generalized conditioned reinforcers in a motivationally complex but analytically tractable environment.

Method

Subjects

Six male White Carneau pigeons served as subjects. The pigeons were obtained from *Double T Farms* (Glenwood, IA), and were approximately 2 years of age and experimentally naïve at the start of the experiment. They were housed individually in stainless steel home cages in a colony room with a 12-hr light/dark cycle. Most conditions were conducted in a closed economy, in which daily intake of food and/or water occurred within daily sessions, occasionally supplemented with postsession access, as described below.

Apparatus

Pigeons were trained and tested in custom-made operant chambers measuring 50.8 cm by 57.15 cm by 45.72 cm. An *Elo*® touchscreen, measuring 22.86 cm by 30.48 cm, with a pixel resolution of 1024 by 768, was located at the front of the chamber, situated 11.43 cm above the wire mesh floor. Illumination was provided by a houselight located at the top of the chamber. Access to *Purina Nutriblend*® food pellets was provided via a mechanical hopper and opening located underneath the touchscreen, 24.13 cm from each side of the chamber. Food delivery was signaled by the onset of the hopper light. Water was delivered using a *MED-PC*® pump, via a plastic tube, which fed into a 4 cm × 3 cm × 2.3 cm plastic reservoir located underneath the right side of the touchscreen, the center of which was 15.24 cm from the right hand side of the chamber. Water delivery was signaled by the onset of a single LED light located above the container. Programs were created in *Visual Studio 2008*©, and run using *Dell*® computers and *Windows 7 OS*©. White noise was played on an external speaker located behind each touchscreen during all sessions to mask external noise. An external exhaust fan provided ventilation for all the chambers.

Pretraining

The pigeons were trained to produce and exchange green tokens (exchangeable for food), red tokens (exchangeable for water), and white tokens (exchangeable for either food or water). Figure 1 shows the locations of token production keys and tokens for each of the three commodities on the touchscreen. The houselight was illuminated for the duration of the session and was only turned off during the delivery of the food or water reinforcers. All training sessions ended after 60 min or 50 reinforcers had been delivered, whichever came first. Each training condition continued until reliable responding had been acquired.

The order in which training occurred for the food and water tokens was counterbalanced across groups of pigeons: three pigeons (126, 1851, 764) were trained first with the green (food) tokens, and second with the red (water) tokens, while the other three pigeons (1770, 1750, 136) were trained first with red (water) tokens, and second with green (food) tokens. Pigeons in both groups received training with the white (generalized) tokens last; complete counterbalancing was not feasible, as the generalized condition necessarily followed the earlier conditions in which the specific

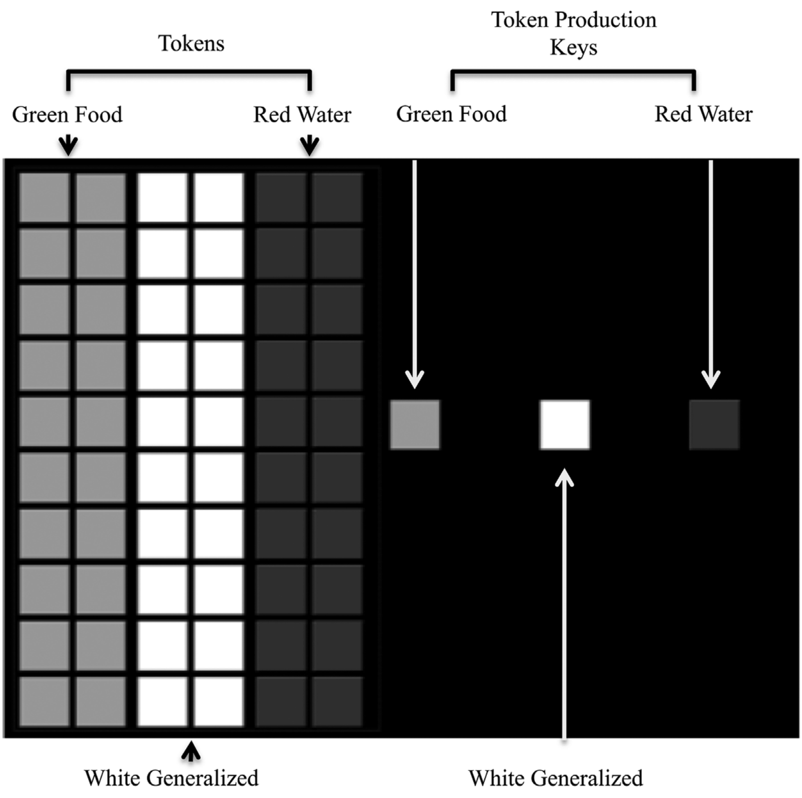

Fig. 1. Location of all stimuli on the touchscreen for experimental conditions. (Note: all of these were never visible simultaneously).

functions of the green and red tokens were established. These conditions will be described separately.

Food token training. Food was unavailable outside of the training sessions except, as needed, to maintain body weights to at least 85% free feeding weights. (Once the experimental conditions began, no supplemental feeding was necessary.) Water was unavailable during the sessions, but continuously available outside the session in home cages. Pigeons were first trained to eat from the food hopper and to peck a green square presented in the middle of the touchscreen; each peck produced 4.5-s access to food. When pigeons were reliably pecking the green key, responding was placed under a FR 1 schedule, in which each peck produced food. Pigeons were then trained to peck a token, a flashing green square (sized 1.47 cm^2 that flashed on/off). The location of the token varied randomly within an array of 10×4 squares, presented on the left hand side of the screen) for food reinforcement. When this token-exchange response had been established, *token-production* responding was established by presenting the flashing green token as a consequence of a peck on a solid green square located in the center of the screen. When this token-production response had been established, the FR token production requirements increased (as described below, *Phase 1: FR Demand*).

Water token training. Water was unavailable except during the training sessions; food was continuously available in home cages outside the sessions. Pigeons were trained to peck a red square presented on the left hand side of the screen for 2.8 s of water reinforcement (equivalent to 0.51 mls, an amount tested and confirmed to be sufficient for pigeons to consume with the water reservoir we used). For some pigeons, the water reinforcement contingencies evoked beak dragging, rather than individual key pecks, and this resulted in errors in recording responses. Consequently, the size of the red square was systematically reduced until responses became more discrete. The size of the red square was then gradually increased back to the original size, while the pecking topography remained discrete. The beak dragging topography did not reemerge for the remainder of the study. Training then followed the same procedure described above for food, except using water reinforcers and red tokens instead of food reinforcers and green tokens.

Generalized token training. Food and water were unavailable outside of the sessions; all daily intake therefore occurred within the sessions. Given the prior training with the green food tokens and the red water tokens, no explicit training was needed to establish responding for white (generalized) tokens. A single peck on a white flashing token turned it off and produced a green and red token on the immediate left and right side of the white token, respectively. A peck on the red token turned off both tokens and produced a water reinforcer; a peck on the green key turned off both tokens and produced a food reinforcer. The pigeon could thus choose which reinforcer (water or food) for which to exchange a white token.

Experimental Procedure

The experiment consisted of three phases, with the reinforcing efficacy of the three token types assessed within each phase, either separately or in combination. In the first phase, demand functions were produced for each of the three token types separately, by increasing FR response requirements across successive sessions. In the second phase, PR breakpoints and peak response outputs were obtained for each token type separately by increasing FR requirements within a session. In the third and final phase, preference was assessed using pairwise combinations of the token types. These phases will be described separately.

Phase 1: FR Demand. Demand functions were obtained for the two specific token types (food and water) with the order counterbalanced across pigeons. As in the training conditions, when the demand functions were being generated for one commodity, the pigeons had free access to the other commodity outside the session. Three-hour experimental sessions were conducted daily. The FR schedules increased through the progression 1, 5, 15, 30, 50, 90, 150, 300, 500, 900, 1500, with each FR value presented for 5 successive days. The progression was discontinued if a pigeon failed to earn more than five reinforcers for three consecutive sessions; this was followed by an immediate return to unlimited access to food and water. On the rare occasion in which these conditions occurred, it was brought about by weak responding under *Water* conditions. The three-session rule we adopted was based on prior research with water restriction in pigeons (Jenkins & Moore, 1973; Lumeij, 1987; Martin & Kollias, 1989), and therefore was considered a reasonable limit.

The demand functions for specific food and water tokens were then repeated, but with FR changes occurring each session rather than after five sessions. All other aspects of the procedure were identical to those described above for the 5-day method. Once the progression had been completed once, reinforcers were switched (from food to water, or vice versa) and the progression repeated with the alternate reinforcer. Because there was no significant difference in data between the 1-day and 5-day demand tests (see Results), the remaining conditions with the white (generalized) tokens used the 1-day method only. These generalized token conditions were conducted in a closed economy, in which daily intake of both food and water occurred within the 3-hr daily experimental sessions

Phase 2: Progressive Ratio. Pigeons were tested under a PR schedule, in which the response requirement increased following each reinforcer according to the following equation (adapted from Madden et al. 2007):

$$\text{PR} = (10^{*}(e^{0.08x}))-3,$$

where x was the trial number (number of obtained reinforcers + 1). Three blocks of five 3-hr sessions were run for each token type, interspersed by 2 days of free food and water to regain baseline levels of intake, and one day of deprivation. Pigeons experienced the same order of all three token types as in the demand phase for better comparability between these two phases. The procedure was otherwise identical to the previous condition, except for the following procedural modifications to increase water intake in some conditions with generalized tokens. Due to low levels of water-token exchange and water intake in the first several sessions with generalized tokens, measures were taken to increase daily water intake, while still carrying through with the PR manipulation. First, the duration of the water dispenser was increased from 2.8 s to 4.8 s (increasing water volume to 0.87 ml per reinforcer). Second, 10 ml of water was provided immediately following any sessions in which water was not consumed.

Phase 3: Preference. To test for preference, the different token types were arranged concurrently within a session, as pairwise choices, in the following order: *Food (green) versus Water (red), Food (green) versus Generalized (white),* and *Water (red) versus Generalized (white).* All food and water was earned during the experimental sessions, similar to the generalized token conditions, described above. Within each comparison, the FR price of each token was increased systematically (and together) across blocks of three sessions, using the same progression as in the FR Demand assessment in Phase 1. Completing the FR requirements on one key turned off both token production keys and presented a single flashing token within the respective array: green for food, red for water, and white for either food or water (as described above). This condition ended when the end of the FR progression had been reached, or if fewer than six water reinforcers were obtained per session over three consecutive sessions (the latter criterion was met just twice, once each for Pigeons 126 and 1770 in the *Food vs. Water* condition). The pigeons were then returned to free access to food and water prior to the next block of sessions. This free-access phase lasted for 11 days between Conditions 1 and 2, and 9 days between Conditions 2 and 3.

Results

Phase 1. FR Demand Assessment

Figure 2 shows normalized demand curves for food (left) and water (right) under both the 5-day and 1-day methods, averaged across all six pigeons. Quantitative fits were performed using Hursh and Silberberg's (2008) exponential demand curve, with Q_0, α free to vary, and k set as a constant, calculated for each individual, and across all three commodities, as (maximum log consumption – minimum log consumption) + 0.5. Sessions where consumption was 0 were excluded from analyses. Dependent sample t-tests with individual data were used to compare the 5-day and 1-day methods with respect to the following fitted parameters of the model: R^2, Q_0, α, Q P_{max} and O_{max}. For FR values that were replicated over multiple days, mean consumption was used for model fits. No significant differences were found between the 1-day and 5-day conditions on any of these measures. Given the lack of consistent difference, the final condition with generalized

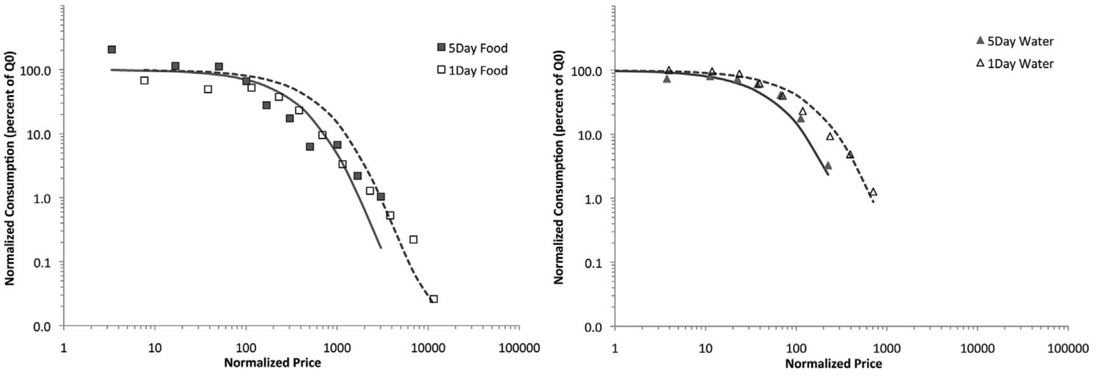

Fig. 2. Fully normalized demand curves using group average data from the 5-day and 1-day food and water conditions. Normalized consumption is plotted as a function of normalized price for food and water in the left and right panels, respectively.

tokens was conducted under the 1-day method only. To maintain comparability across the token types, all results were analyzed using the 1-day data only.

Figure 3 shows normalized demand functions for all six pigeons and token types. Parameter values from demand curve model fits for Equation 1 can be seen in Table 1 (absolute frequencies of responses and reinforcers are shown in Appendix A in the online supplemental materials). Normalized reinforcer magnitude units (q) were calculated using the equation $q = 100/B$, where B is consumption at the lowest price (FR 1). Consumption at each FR value was multiplied by q to obtain normalized consumption; normalized price was calculated as FR/q. The functions are well described by the exponential model, accounting for an average of 94% of total variance overall, and between 93-96% total variance across the three commodities.

Despite the good overall fits, the functions for different token types differ in consistent ways. To begin with, the functions differ in elasticity (α). Figure 4 (top left panel) shows individual and group mean α values. The mean values were consistently highest (suggesting greater elasticity) for water ($M = 1.83$E-05, $SD = 8.31$E-0.6), followed by generalized ($M = 8.62$E-06, $SD = 4.03$E-06), and lastly, food ($M = 5.22$E-06, $SD = 1.67$E-06). (Elasticity values differed significantly, $F(2,10) = 16.28$, $p < .001$). A Tukey HSD test found that food tokens, but not generalized tokens, were significantly more inelastic than water tokens (mean difference between water and food = 1.31E-05, $p < .001$, and mean difference between water and generalized = 9.67E-06, $p < .01$). There was no significant difference in elasticity for food and generalized tokens.

The bottom left panel of Figure 4 shows Q_0, consumption at the lowest price. Unlike elasticity, Q_0 was highest for generalized tokens ($M = 1008.64$, $SD = 483.96$), followed by food ($M = 721.4$, $SD = 448.4$) and then water ($M = 91.02$, $SD = 12.47$). These values differed significantly, $F(2,10) = 14.48$, $p < .005$. A Tukey HSD test found consumption of water tokens was significantly lower than both food tokens (mean difference = 630.4, $p < .01$) and generalized tokens (mean difference = 917.98, $p < .01$).

The functions also differed in P_{max} values, reflecting different degrees of price tolerance. The top right panel of Figure 4 shows individual and group mean P_{max} values. These values were consistently greatest for food tokens ($M = 330.70$, $SD = 97.83$), followed by generalized ($M = 214.50$, $SD = 81.59$), followed by water tokens ($M = 99.37$, $SD = 33.21$). A repeated measures ANOVA found a significant difference in P_{max} values ($F(2,10) = 29.43$, $p < .001$) and a Tukey HSD test confirmed significant differences between all pairwise combinations of commodities ($p < .01$).

The functions also differed in peak response output (O_{max}) values (bottom right panel of Fig. 4). In general, the O_{max} values showed the same pattern as P_{max} values at both the individual and group level; a repeated measures ANOVA found a significant effect of commodity, $F(2,10) = 29.39$, $p < .01$. O_{max} values for food tokens were consistently highest, followed by generalized, followed by water; Tukey HSD tests

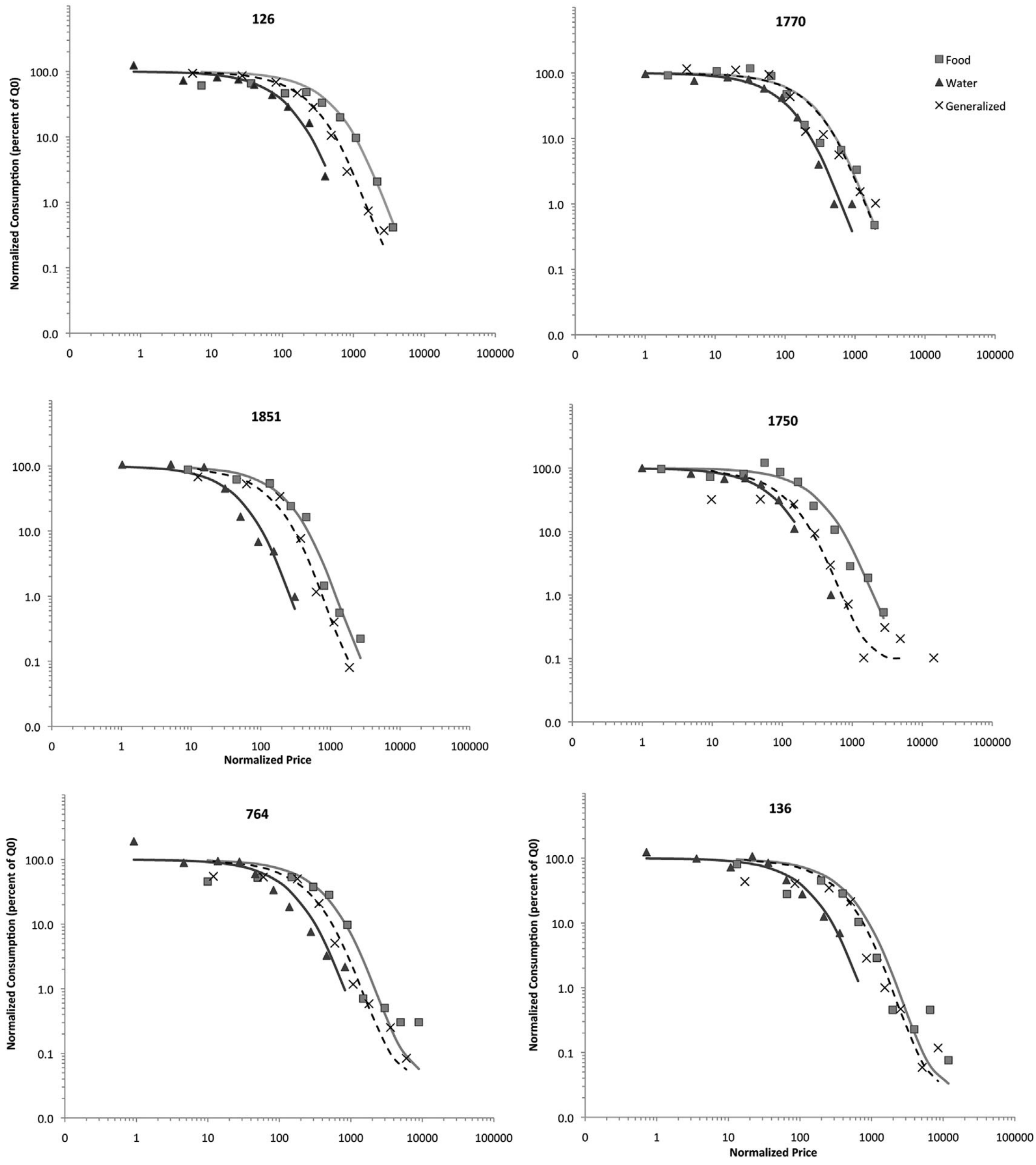

Fig. 3. Rapid (1-day) demand curves. Normalized consumption plotted as a function of normalized price for food (squares), water (circles) and generalized (triangles), for each individual.

confirmed that all these differences were significantly different ($p < .01$).

Phase 2. Progressive Ratio

Figure 5 shows the PR breakpoints, averaged across all three blocks, for each token type for each pigeon, across the 15 sessions per condition (14 sessions in the *Generalized PR* phase). Absolute response and reinforcer data for each pigeon are shown in Appendix B in the online supplemental materials. Averaged across pigeons, the highest breakpoints were obtained for food tokens ($M = 279.63$, $SD = 118.75$), followed by water tokens ($M = 214.26$, $SD = 75.67$), then generalized tokens ($M = 206.60$,

Table 1

Parameter values for 1-day exponential demand curves fitted to average group and individual data.

	k	R^2				Normalized P_{max}			O_{max}			Q0			α		
		Global	Food	Water	Gen	Food	Water	Gen	Food	Water	Gen	Food	Water	Gen	Food	Water	Gen
Group	3.97	92.4	91.8	97.3	90.9	572.4	116.2	249.7	18239.6	3620.1	15945.8	755.23	84.17	539.76	2.33E-06	1.15E-05	5.34E-06
126	3.2	97.6	97.2	96.1	98.4	457.3	108.6	241.1	15187.8	3606.6	8008	722.78	79.89	540.91	3.54E-06	1.49E-05	6.71E-06
1851	3.43	97.3	96.7	95.4	98.8	207.6	45.6	132.9	6844.1	1502.7	4381.7	899.73	102.47	1249.22	7.30E-06	3.33E-05	1.14E-05
764	3.32	91.4	86.7	90.6	96.1	367.1	137.6	237.8	12153.8	4557.1	7873.3	992.42	92.07	1195.36	4.26E-06	1.14E-05	6.58E-06
1770	3.16	93.2	93	95.8	89.8	233.4	102.4	226.8	7760.3	3405.2	7540.6	210.69	100.36	391.63	7.03E-06	1.60E-05	7.24E-06
1750	3	95.5	96.5	99.2	93.6	313.5	78.0	112.3	10444.3	2599.5	3740.1	186.84	99.37	974.90	5.53E-06	2.22E-05	1.54E-05
136	3.53	90.7	85.9	98	93.1	405.4	123.9	336.0	13308.2	4068.5	11030.5	1316	71.94	1699.81	3.64E-06	1.19E-05	4.39E-06
Mean	3.27	94.3	92.7	95.9	95.0	330.7	99.4	214.5	10949.7	3289.9	7095.7	721.41	91.02	1008.64	5.22E-06	1.83E-05	8.63E-06
SEM	0.08	1.21	2.11	1.21	1.41	39.9	13.6	33.3	1319.82	447.08	1091.53	183.06	5.09	197.57	6.82E-07	3.39E-06	1.65E-06

SD = 37.24). However, a one-way repeated measures ANOVA found no significant effect of commodity ($F = 1.71$, *n.s.*). This is most likely due to the inconsistency in the group and individual breakpoint functions. Breakpoints for food tokens were markedly greater than water and generalized tokens for four of the six pigeons (1851, 1770, 1750, 136) but were approximately similar to generalized tokens for the remaining subjects (126, 764). Breakpoints for water tokens were noticeably greater than food and generalized tokens for Pigeons 764 and 1770.

Peak response output patterns in Phase 2 resembled those seen in the PR breakpoints. Mean peak response outputs were greatest for food ($M = 3244.37$, $SD = 1476.41$), followed by water ($M = 2408.54$, $SD = 904.95$), and then generalized tokens ($M = 2321.31$, $SD = 1113.55$). There was no significant difference found between these ($F = 1.86$, *n.s.*).

Phase 3. Preference Assessment

Figure 6 shows the proportion of the different token types produced for each condition, averaged across all prices. Absolute frequencies of responding and reinforcement for each pigeon are shown in Appendix C in the online supplemental materials. A strong preference for food tokens can be observed in the *Food versus Water (F-W)* and *Food versus Generalized (F-G)* comparisons, and a strong preference for generalized tokens in the *Water versus Generalized (W-G)* comparisons. A repeated measures ANOVA found a significant difference between proportion of tokens produced between all three commodities, averaged across pairings $F(2,17) = 144.9$, $p < .001$. Bonferroni post-hoc tests showed all commodities differed significantly from each other ($p < .05$). Additional Bonferroni tests were conducted to examine effects within and across pairings. Preference for the available token types were significantly different within each pairing ($p < .05$). No significant differences were found for the food and water tokens across conditions, suggesting preference for these commodities remained constant regardless of whether it was available concurrently with the other primary reinforcer or the generalized reinforcer. Conversely, preference for generalized tokens was dependent on the concurrently available token type; preference for generalized tokens was

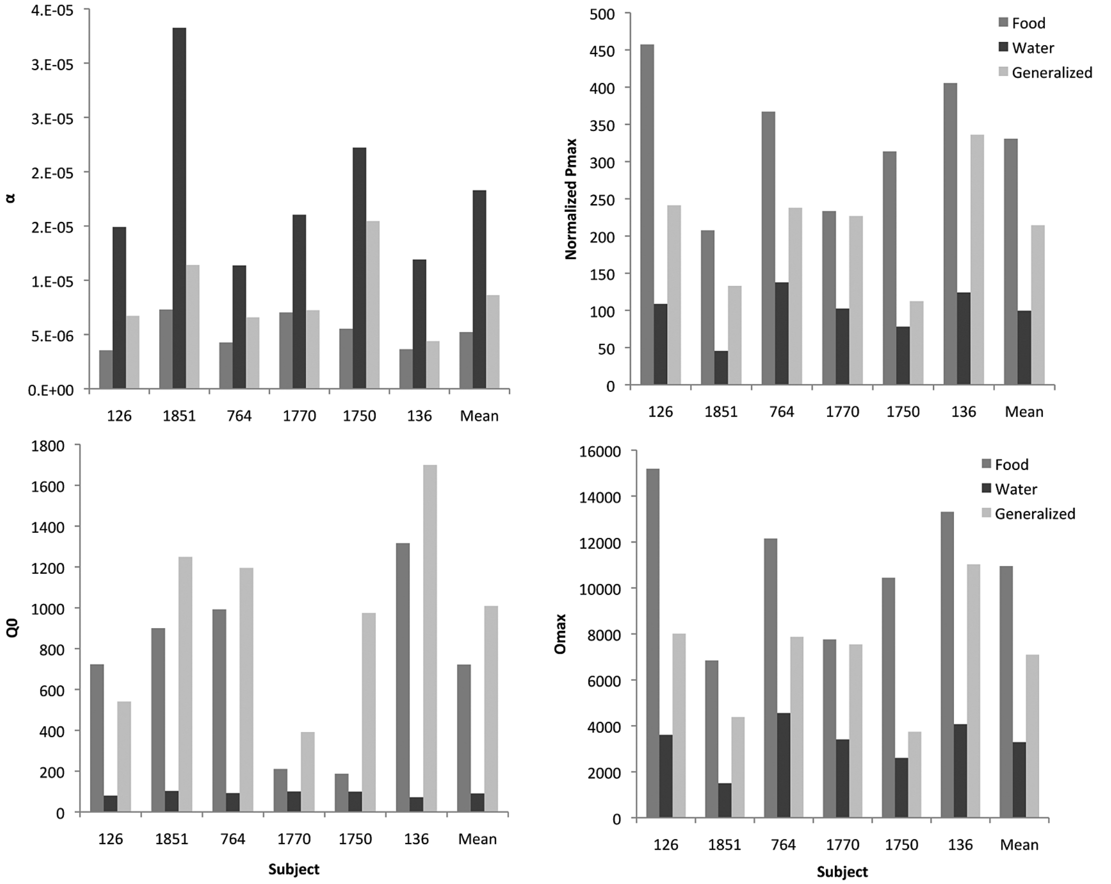

Fig. 4. Individual and group mean α, Q_0, normalized P_{max} and O_{max} values for 1-day demand curves.

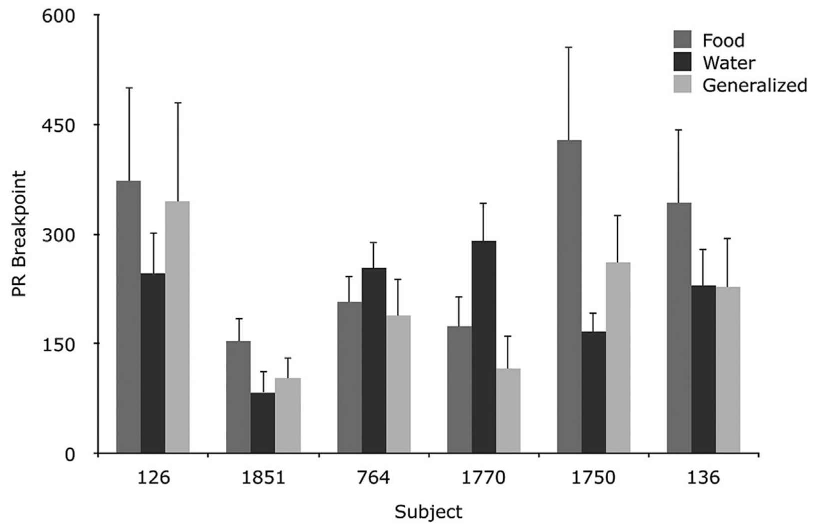

Fig. 5. Mean progressive ratio breakpoints for each pigeon for food (dark gray series), water (black series) and generalized (light gray) commodities. Error bars show ± 1 SD.

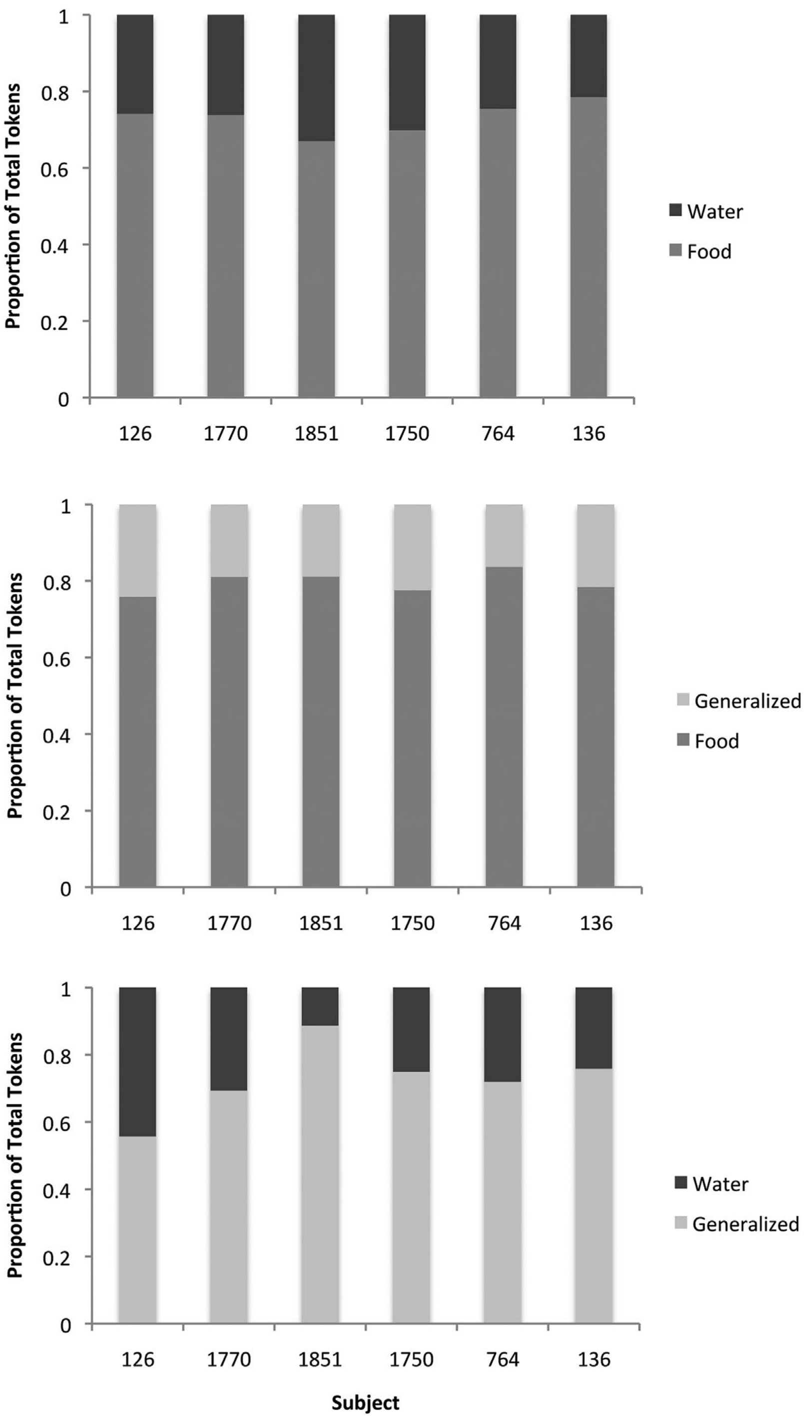

Fig. 6. Average total proportion of tokens produced in the *Food-Water*, *Food Generalized* and *Water-Generalized* conditions in the preference demand assessment.

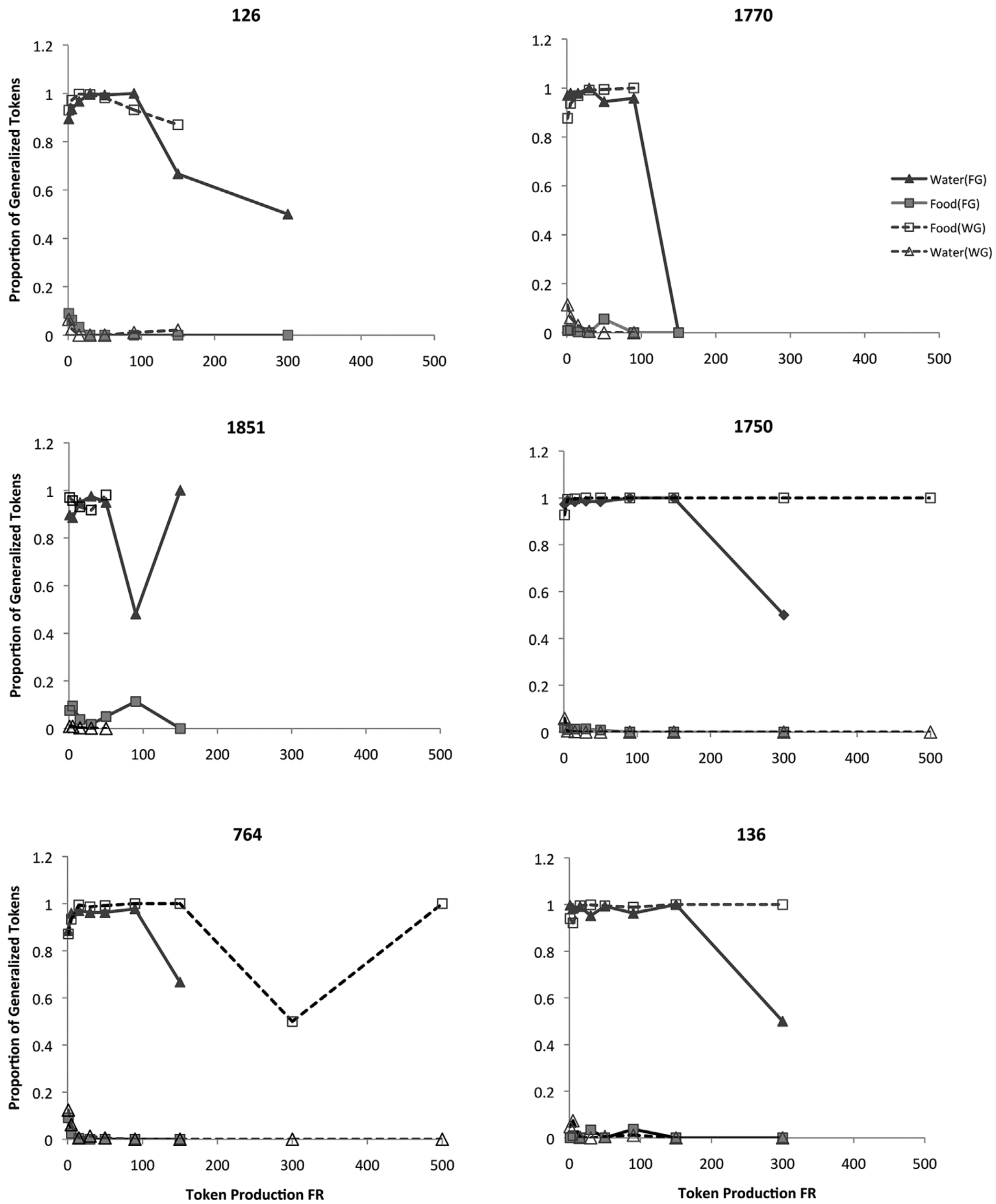

Fig. 7. Average total proportion of generalized tokens exchanged for water or food in the *Food-Generalized* (solid lines) and *Water-Generalized* (dotted lines) conditions of the preference assessment.

significantly greater when presented with water than with food.

Figure 7 shows the proportion of generalized tokens exchanged for food and water for the *F-G* and *W-G* conditions, averaged across FR replications. (Note that the proportions do not add to 1 for certain FR values, as pigeons occasionally stopped responding and did not exchange all available tokens before the session ended.) In the *F-G* condition, the majority of generalized tokens were exchanged for water, whereas in the *W-G* condition they were mostly exchanged for food; the generalized tokens thus served as a substitute for the commodity not available. Generalized tokens were occasionally exchanged for the commodity that was concurrently available; however this occurred only at the low FR values. As price increased, the proportion of generalized tokens exchanged tended to decrease.

Convergence Among Measures

Phases 1 and 2. To assess the convergence of different measures of reinforcer efficacy from Phases 1 and 2, Spearman rank-order correlations were calculated for each commodity: normalized P_{max}, PR breakpoints, O_{max}, and peak response output. For food, the correlations between normalized P_{max} and PR breakpoints and O_{max} values and peak response outputs were equal and moderate but not significant (Spearman's $\sigma = 0.66$). Correlations for water were identical for both pairs of measures but were also not significant (Spearman's $\sigma = 0.6$). An even weaker relationship was found for generalized tokens; the correlation between normalized P_{max} and PR breakpoint was 0.31, and 0.38 for O_{max} and peak response output.

Averaged across pigeons, both normalized P_{max} and average PR breakpoint were greatest for food tokens, but there was little consistency between these two measures for water and generalized tokens; the normalized P_{max} value for generalized tokens was much greater than for water, but the average breakpoint was lower, though not significantly different, from the average breakpoint obtained for water.

Normalized O_{max}, calculated by multiplying normalized P_{max} by consumption at P_{max}, failed to successfully predict the rank order of peak response output for any of the token types. Both values were greatest for food tokens ($O_{max} = 138196.6$ and peak response output $= 3248.34$), but mean peak response output was slightly higher for water ($M = 2381.40$, $SD = 895.82$) than generalized tokens ($M = 2321.31$, $SD = 1113.55$)—opposite to the pattern seen in the O_{max} values (water normalized $O_{max} = 3125.52$ and generalized normalized $O_{max} = 43089.60$).

The success with which normalized P_{max} predicted PR breakpoints for individual data varied depending on the token type. Normalized P_{max} successfully predicted greater PR breakpoints for food than for generalized tokens for all six pigeons, for food than for water for four of the six pigeons (excluding 764 and 1770), and for generalized than for water for three of the six pigeons (excluding 764, 1770 and 1750). However, a Fisher's exact test showed that normalized P_{max} did not predict PR breakpoints for all commodities significantly better than chance ($p = 0.26$, *n.s.*). Normalized O_{max} predicted peak response output correctly for four out of six pigeons when comparing food and water (excluding 764 and 1770), for three of six pigeons when comparing water and generalized (excluding 764, 1770 and 136) and for all six pigeons when comparing food and generalized. A Fisher's exact test showed normalized O_{max} failed to predict peak response output significantly better than chance ($p = 1$, *n.s.)*. On the whole, then, the main performance measures in Phase 2 (breakpoints, peak response rates) were not well predicted by the demand curve parameters from Phase 1.

Phases 1 and 3. To compare the demand function data from Phase 1, conducted in a single-schedule context, with that from Phase 3, conducted in a concurrent-schedule context, we computed the following Phase-3 parameters from Equation 1: P_{max}, Q_0 and α. These are shown in Figure 8 for each token type in the context of each of the other two. Demand curve parameters for Phase 3 data can be seen in Table 2. Hursh and Silberberg's (2008) model provided a good account of the data, accounting on average for at least 90% of the variance in responding.

Characteristics of the fits were largely consistent with the ordinal data from Phase 1. First, demand was most inelastic (lower α values) for food tokens, followed by generalized tokens and water tokens (compare the right panels of Fig. 8 and the upper left panel of Fig. 4). A repeated measures ANOVA found no significant effect of condition ($F(2,10) = 3.62$, *ns*) or commodity ($F(1,5) = 1.93$, *ns*), but did find a significant interaction ($F(2,10) = 19.6$, $p < .001$); demand for food tokens was more inelastic than the other commodities, $t(5) = 10.32$, $p < .001$ with water, and $t(5) = 8.83$, $p < .001$, with generalized. Demand for generalized tokens was significantly more inelastic than water tokens in the *W-G* condition ($t(5) = 3.29$, $p < .05$) but when pitted against water tokens, was significantly more elastic than that of food tokens ($t(5) = 8.69$, $p < .002$), and also significantly more elastic than water tokens

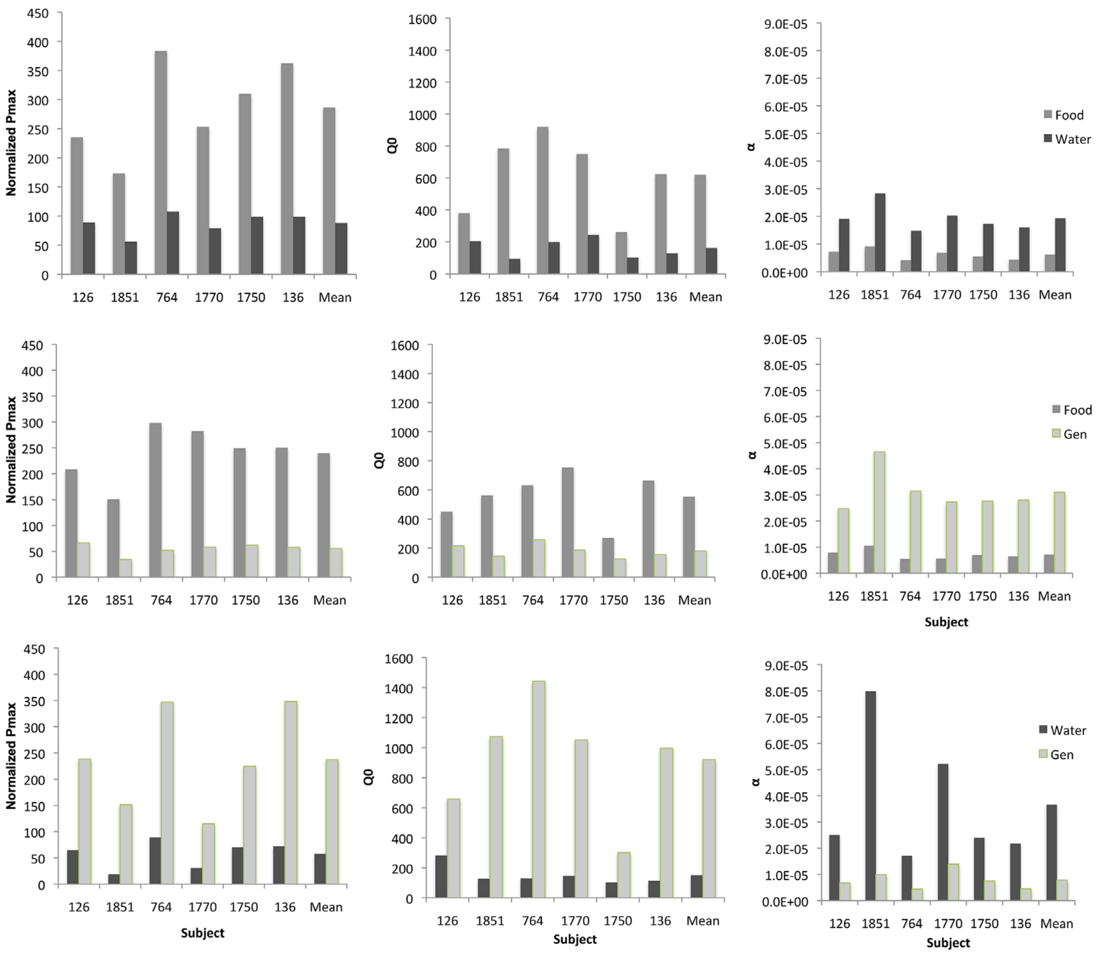

Fig. 8. Normalized P_{max} (left column), Q_0 (middle column) and α (right column) values obtained from demand curve fits in the preference assessments for *Food-Water* (top row), *Food-Generalized* (middle row) and *Water-Generalized* (bottom row) conditions.

when both were pitted against food ($t(5) = 7.09$, $p < .001$).

Second, also consistent with the Phase 1 data, P_{max} values were largest and approximately similar for tokens that were exchanged primarily for food in all three conditions (compare left panels of Fig. 8 with upper right panel of Fig. 4). P_{max} values were greatest for food tokens in the *F-W* condition ($M = 286.23$, $SD = 39.90$), for food in the *F-G* condition, and generalized tokens in the *W-G* condition were second highest and similar ($M = 239.77$, $SD = 35.60$ and $M = 237.27$, $SD = 62.22$, respectively). A repeated measures ANOVA, with commodity pair and individual commodity as factors, found no significant effect of pairing on P_{max} values ($F(2,10) = 3.90$, $p = 0.05$), but did find a significant effect of commodity ($F(1,5) = 34.0$, $p < .01$), and a significant interaction ($F(2,10) = 58.1$, $p < .001$). This suggests P_{max} values for food, water and generalized tokens differed significantly and the effect of commodity was also dependent on the alternative commodity available.

Unlike Phase 1, demand intensity, Q_0, was ordered in the following way: food, generalized, water (compare the middle panels of Fig. 8 with the lower left panel of Fig. 4). Q_0 of food tokens at FR 1 was significantly greater than water, $t(5) = 4.60$, $p < .01$, and generalized tokens, $t(5) = 5.68$, $p < .01$. Q_0 values for generalized tokens were significantly greater than water $t(5) = 4.61$, $p < .01$ in the *W-G* condition. Q_0

Table 2

Demand curve parameter values for preference assessment (Phase 3).

Bird	k	R^2		Normalized Pmax		Q0		α	
		Food	Water	Food	Water	Food	Water	Food	Water
126	3.07	0.99	0.96	235.3	88.8	378.65	204.08	7.18E-06	1.90E-05
1851	3.28	0.96	0.76	173.18	55.91	784.43	94.01	9.14E-06	2.83E-05
764	3.24	0.97	0.9	383.64	107.68	918.9	197.37	4.17E-06	1.48E-05
1770	3.23	0.89	0.95	253.13	78.91	749.53	243.53	6.82E-06	2.03E-05
1750	3.05	0.89	0.94	309.85	98.57	260.54	102.54	5.49E-06	1.73E-05
136	3.28	0.98	0.89	362.29	98.56	623.3	126.58	4.36E-06	1.60E-05
Mean	3.19	0.95	0.9	286.23	88.07	619.23	161.35	6.19E-06	1.93E-05
SE	0.04	0.02	0.03	32.81	7.58	103.38	25.22	7.75E-07	1.98E-06
		Food	Gen	Food	Gen	Food	Gen	Food	Gen
126	3.15	0.99	0.99	208.34	66.42	450.71	216.81	7.92E-06	2.48E-05
1851	3.27	0.98	0.98	150.7	34.16	562.07	143.75	1.05E-05	4.65E-05
764	3.18	0.97	0.96	297.97	51.81	630.99	257.98	5.47E-06	3.15E-05
1770	3.26	0.92	0.98	282.33	58.35	752.7	185.93	5.63E-06	2.73E-05
1750	3.01	0.97	0.99	249.08	62.17	268.89	125	6.92E-06	2.77E-05
136	3.2	0.99	0.99	250.21	57.87	663.74	155.57	6.47E-06	2.80E-05
Mean	3.18	0.97	0.98	239.77	55.13	554.85	180.84	7.16E-06	3.10E-05
SE	0.04	0.01	0	21.84	4.64	70.58	20.33	7.67E-07	3.22E-06
		Water	Gen	Water	Gen	Water	Gen	Water	Gen
126	3.22	0.96	0.98	64.46	238.22	281.4	657.48	2.50E-05	6.75E-06
1851	3.46	1	0.97	18.83	151.17	126.79	1073.84	7.98E-05	9.94E-06
764	3.41	0.83	0.72	89.08	346.9	129.42	1442.59	1.71E-05	4.39E-06
1770	3.24	0.83	0.89	30.68	115.03	146.86	1052.26	5.21E-05	1.39E-05
1750	3.08	0.97	0.96	70.26	224.41	101.76	300.65	2.40E-05	7.50E-06
136	3.3	0.97	0.94	71.86	347.91	112.51	997.48	2.18E-05	4.51E-06
Mean	3.29	0.93	0.91	57.53	237.27	149.79	920.72	3.66E-05	7.83E-06
SE	0.06	0.03	0.04	11	39.49	27.06	160.5	1.00E-05	1.48E-06

values for generalized tokens in the *W-G* condition were significantly greater than Q_0 values for food tokens in the *F-W* condition ($t(5) = 4.70$, $p < .01$) and *F-G* conditions ($t(5) = 3.33$, $p < .05$), but did not differ significantly from Q_0 values for water in the *W-G* condition ($t(5) = 1.23$, *n.s.*). A repeated measure ANOVA found Q_0 differed significantly between the paired commodities ($F(2,10) = 13.0$, $p < .001$); this was due to a significant interaction between condition and commodity ($F(2,1) = 23.0$, $p < .001$), and not commodity alone ($F(1,5) = 1.05, ns$).

Pairwise comparisons were conducted to evaluate differences in P_{max} as a function of commodity within each condition. P_{max} values were significantly higher for food tokens when pitted against both water tokens ($t(5) = 7.62$, $p < .001$) and generalized tokens ($t(5) = 9.29$, $p < .001$). P_{max} values for water tokens were significantly lower than generalized tokens when they occurred together ($t(5) = 5.95$, $p < .005$). The P_{max} values obtained for generalized tokens and water tokens when they both occurred with food, were significantly different ($t(5) = 5.74$, $p < .01$).

The ordinal rankings of the P_{max} and α parameters of the model were thus consistent across Phases 1 and 3, but Q_0 differed across the two phases. Only the former could therefore be used to predict ordinal preferences in Phase 3: food tokens > generalized tokens > water tokens. Preference for generalized tokens depended on the concurrently available alternative, substituting for food when occurring in the context of the water token alternative and for water when occurring in the context of the food alternative.

Discussion

A broad aim of the present study was to develop a method for analyzing basic mechanisms of generalized reinforcement, a topic long overdue for an experimental analysis. Using concepts and models from behavioral economics, we sought to put a sharper quantitative point on Skinner's (1953) assertion that generalized reinforcers are more effective than more specific conditioned reinforcers, in part, by more rigorously defining reinforcer efficacy —in relation to demand, response output, and preference and as a function of price and economic context.

The comparisons of the different token types were quantified in relation to Equation 1, Hursh and Silberberg's (2008) essential value model. Taken as a whole, the functions were remarkably consistent with the model, accounting for more than 90% of the total variance. These results support a growing body of data consistent with Equation 1 (e.g., Barrett & Bevins, 2012; Bentzley, Fender, & Aston-Jones, 2013; Cassidy & Dallery, 2012; Christensen, Silberberg, Hursh, Huntsberry, & Riley, 2008). A chief benefit of the model is that it summarizes reinforcer efficacy with a single metric (α), expressing price and consumption in standardized units. This conceptualization is especially useful in comparisons of different reinforcer types, including different token types, because it allows direct and quantitatively meaningful comparisons.

The token types differed, based on the various indices of efficacy. With respect to demand elasticity, α values were consistently lowest (most inelastic) for food tokens, followed by generalized tokens, then by water tokens. Food tokens also had higher P_{max} and O_{max} values, and higher breakpoints in the PR phase, than the other token types. In contrast, the generalized tokens were consistently higher than either of the specific tokens with respect to Q_0 values only, reflecting greater consumption at the lowest price. This pattern of differential production of generalized tokens was not seen, however, when the tokens were available concurrently with food tokens in Phase 3. In fact, the opposite pattern occurred: Higher levels of food than generalized tokens were produced at the lowest prices. Q_0 values in Phase 1 did not predict either Q_0 values or preferences in Phase 3.

In a majority of conditions, then, food tokens appeared to be of greater efficacy than either generalized or water tokens. In comparing the token types, however, it is important to consider some differences in the methods used to generate the specific and generalized demand functions. First, in the generalized token economy, a second response was required to deliver either a food or water reinforcer after the generalized token had been earned, slightly increasing the number of responses (and delays) to reinforcement. These delays between the presentation of the generalized token and the exchange for food or water were typically quite short, and therefore made a negligible contribution to the overall reinforcer delays. The degree to which this extra response (or delay) was a factor probably varied across procedures. In the individual demand function runs of Phase 1, the marginal costs of an additional response were relatively negligible at the higher FR prices, whereas in the concurrent demand-function runs of Phase 3, with equal price changes on the specific and generalized token types, earning and exchanging specific tokens was always a less expensive and more efficient method of obtaining that reinforcer than earning and exchanging generalized tokens. This is perhaps to be expected, given that concurrent FR schedules tend to generate strong preferences for the lower priced alternative (Herrnstein & Loveland, 1975).

It is also possible that the extra response required under generalized token conditions increased the likelihood of choice "errors" (i.e., the water key was pecked by accident when food was actually the intended target, or vice versa). Such outcomes may reduce the efficacy of the generalized tokens, resulting in higher demand for food tokens. We saw little evidence of this, however. By the time of the generalized token phase the pigeons all had extensive histories with the specific tokens in specific contexts (green/food and red/water), and food and water exchanges were under good stimulus control. Moreover, the orderly patterns of exchange in Phase 3 showed that behavior was sensitive to the motivational conditions: Generalized tokens were consistently exchanged for food when food was restricted and for water when water was restricted (see Fig. 7). This suggests that even if exchange errors occurred occasionally, they did not play a major role in the results.

A second important difference concerns the motivational conditions. In the demand functions for the specific tokens in Phases 1 and 2, daily intake of the target commodity (food or water, depending on the condition) occurred within the session, and therefore approximated a closed economy. The alternate commodity, on the other hand, was freely available outside the session, and therefore approximated an open economy. In the generalized token economy, daily intake of both food and water occurred within the session, and was thus a more fully closed economy than the specific token economy. Thus, unlike the conditions when demand for food and water tokens was assessed, in which demand was centered on a single commodity and a single deprivation, demand for generalized tokens occurred in a context of two commodities and two deprivations.

The double deprivation conditions used when testing generalized tokens were arranged to maximize the potential generalized functions of the tokens, making them less dependent on a single deprivation; by necessity, however, it created a more dynamic economy with many potential interactions between reinforcers. In the semi-open economies in which the alternate commodity is freely available outside the session, most or all behavior is allocated to the target commodity. In the more closed generalized token economies, on the other hand, the tokens are produced and exchanged for the both food and water.

The preference conditions (Phase 3) were conducted under the more fully closed economies surrounding the generalized token conditions in Phases 1 and 2. These permit more balanced comparisons of the different token types across economic conditions, while adding an additional measure (relative preference) to the analysis. These conditions produced consistent preferences for food over both water and generalized tokens, and for generalized over water tokens. This preference hierarchy is understandable in terms of the substitutability function of the generalized tokens. When generalized tokens were presented concurrently with water tokens, demand for the former was greater and more inelastic than when they were presented concurrently with food tokens; P_{max} values and Q_0 values were much higher, and α values much lower for generalized token demand functions when choosing between generalized tokens and water, than with food. This would be predicted if the generalized tokens were functioning as substitutes for food tokens in the *Water vs. Generalized* conditions, and as substitutes for water tokens in the *Food vs. Generalized* conditions. In other words, the generalized tokens served as water tokens when they were pitted against food, and as food tokens when they were pitted against water.

This type of functional substitution effect can also be seen in Figure 8. In the pairwise choices between water tokens and generalized tokens, the majority of generalized tokens were exchanged for food, whereas in choices between food tokens and generalized tokens, most generalized tokens were exchanged for water. The generalized token demand function is really a composite of two functions: generalized tokens exchanged for food and generalized tokens exchanged for water. Viewed in this way, the ordering of the demand functions, with the generalized token function in between the food and water functions, makes functional sense.

The consistent preference for the food tokens over the other token types in the pairwise choices in Phase 3 of the present study was predictable on the basis of the P_{max} and α parameters from Phases 1 and 3. When presented concurrently in Phase 3, food tokens were preferred over generalized tokens and water tokens, and generalized tokens were preferred over water tokens. The consistency between preference and demand obtained with each commodity separately is in line with previous research showing that preference could be predicted by consumption in demand analysis in isolation (Bickel & Madden, 1999; Jacobs and Bickel, 1999; Johnson & Bickel, 2006). To date, however, this type of predictability of preferences based on demand indices is limited to humans and independent reinforcers, such as money versus drugs. The present findings expand the analysis to a different species (pigeons) and a different economic context (fully closed economy).

While this type of consistency across measures is at least broadly consistent with a unitary construct of relative reinforcing efficacy, other aspects of the present results run against this view. Rank-order P_{max} values from Phase 1 did not predict rank-order breakpoints in Phase 2; neither did O_{max} values from Phase 1 predict peak response rates in Phase 2. These aspects of the results, along with others reported in the literature (Madden et al., 2007), suggest less than perfect agreement among various measures of the sort required by unitary conceptions of relative reinforcer efficacy. As more refined methods are developed for analyzing the multiple functions of reinforcers, we may find even less convergence among measures. Ultimately it may be more productive to view reinforcer efficacy not as a unitary construct reflected in the different indices, but rather, as a description of the measures that comprise it (e.g., demand, preference, peak response rates). The relationship between the measures is therefore a question to be worked out empirically, rather than assumed. One of the benefits of a behavioral economic approach is that it provides a theoretically coherent framework for describing the interrelationships among these various measures of reinforcer efficacy.

The topic of generalized reinforcement falls squarely in the middle of conceptual issues in the study of conditioned reinforcement, such as whether stimuli correlated with reinforcement are properly considered conditioned reinforcers (Williams, 1994) or as discriminative stimuli, or *signposts* (Shahan, 2010). The present study was not designed to distinguish between these two accounts, though past research on token reinforcement has shown both consequent/reinforcing *and* antecedent/signaling functions of tokens (Hackenberg, 2009). So too, it is likely that tokens in the present study served both functions. However, because token presentations and exchange periods were so closely coupled in the present procedures, the signaling functions cannot be clearly separated from the reinforcing functions. In prior research designed to disentangle stimulus functions of tokens, however, Bullock and Hackenberg (2015) showed the separate influences of reinforcing, discriminative, and eliciting functions of tokens. When contingent on behavior, tokens served reinforcing functions; when arranged as signals for an operant contingency, they served discriminative functions; and when arranged as signals temporally correlated with exchange periods but without an operant contingency, they served eliciting functions. The particular function (or functions) of the tokens was shown to depend on the contingencies in which they were embedded. Expanding these methods to the study of generalized reinforcement will enable an even sharper specification of the mechanisms of generalized reinforcement.

In conclusion, the present study advances the analysis of generalized reinforcement in several key ways. We developed a more rigorous and quantitatively precise way to assess specific and generalized reinforcers. We enhanced the generalized functions of the tokens by embedding them in a closed token economy, where their interactions with other reinforcers and motivational conditions could be systematically explored, and the underlying mechanisms better understood. Expanding the number and type of reinforcers and motivational conditions will *generalize* the token economy even further, as the generalized tokens become more akin to human monetary currencies. Developing these types of generalized token economies will bring within reach a wide range of economic variables never before studied in the laboratory, and with it, exciting new possibilities for an experimental analysis of economic behavior.

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