DEMAND FOR FOOD ON FIXED-RATIO SCHEDULES AS A FUNCTION OF THE QUALITY OF CONCURRENTLY AVAILABLE REINFORCEMENT[1]

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Six rats lever pressed for food on concurrent fixed-ratio schedules, in a two-compartment chamber. In one compartment, mixed diet pellets were delivered on fixed-ratio schedules of 1, 6, 11, and 16; in the other, either no food was delivered, or sucrose or mixed diet pellets were delivered on fixed-ratio 8. The number of pellets obtained in the first compartment declined as a function of fixed-ratio size in that compartment in all three conditions, but the decline was greatest overall with mixed diet pellets concurrently available in the other compartment, and least with no food concurrently available. The result is discussed in terms of economic demand theory, and is consistent with the prediction that elasticity of demand for a commodity (defined in operant terms as the ratio of the proportionate change in number of reinforcements per session to the proportionate change in fixed-ratio size) is greater the more substitutable for that commodity are any concurrently available commodities.

Key words: demand function, substitution effect, concurrent schedules, quantitatively different reinforcers, fixed ratio, postreinforcement pause, behavioral contrast, lever press, rats

In a fixed-ratio (FR) schedule, reinforcement is delivered when the subject has emitted a fixed number of responses. With food or water reinforcement, subjects typically respond at a high rate, except for pauses after each reinforcement (e.g., Ferster and Skinner, 1957). The duration of the pause is longer, and hence the overall response and reinforcement rates are lower, the larger the fixed ratio (Felton and Lyon, 1966; Powell, 1970). However, in experiments in which the subject is living in the operant situation (Collier, Hirsch, and Hamlin, 1972; Hirsch and Collier, 1974; Logan, 1964), or obtaining most of its daily supply of the reinforcer from it (e.g., Roper, 1975), an increase in fixed ratio may increase overall response rate. The overall reinforcement rate therefore changes by a lesser proportion than the fixed ratio, and in extreme cases it may not change at all (e.g., Hogan, Kleist, and Hutchings, 1970).

This may be put more succinctly by borrowing terms from microeconomic theory, and saying that in the latter cases "demand" for the reinforcer is "inelastic". Elasticity is defined as the ratio of the proportional changes of dependent and independent variables, i.e.:

$$\text{Elasticity} = \frac{(\text{change in } Y)/Y}{(\text{change in } X)/X},$$

where Y is amount of commodity purchased (or number of reinforcements obtained per session), and X is price (or FR size). A function is said to be inelastic when its elasticity is less than unity in absolute value (e.g., Lancaster, 1969). The demand function of a commodity is the quantity purchased as a function of its price, and it seems reasonable to give this the psychological meaning of number of reinforcements obtained per session as a function of FR size.

Elasticity of demand, in this sense, has been shown to depend on a number of factors. Shettleworth (1972) suggested that it varied with the nature of the reinforcer. She cited the results of Hogan et al. (1970), showing that

Siamese fighting fishes' demand for food reinforcement had elasticity of zero, while their demand for display reinforcement had elasticity of unity. Elasticity of demand can also vary within the same reinforcer. Roper (1973, 1975) found that in mice, demand for nest-building material had elasticity of zero or unity, depending on response-reinforcement distance, and demand for food had a range of elasticities between zero and unity, depending on response-reinforcement distance and deprivation level. Carlisle (1969, 1970) found that elasticity of demand for heat reinforcement varied with species and with density of reinforcement. Finally, Herrnstein (1958) found that with concurrent FR schedules, demand for food reinforcement was highly elastic in the region where the two ratios were nearly equal, for virtually all responses were made on whichever ratio was smaller. This suggests that elasticity of demand may be affected by the availability of reinforcement on a concurrent schedule.

An increase in a schedule parameter has two effects. First it means that to obtain the same total amount of the reinforcing commodity, a subject must expend more time, more work, or both. Second, it makes that schedule less attractive relative to any others that may be concurrently available. Again borrowing from demand theory, we may call these the "income" and "substitution" effects, respectively (cf. Hicks, 1939). Observed elasticity of demand is likely to depend on both effects. For example, if nearly all available time is spent working on a schedule, demand will necessarily be elastic because of an income effect. Thus, with FR schedules, increases in the response requirement result in decreases in overall reinforcement rate (see above). But if the animal has continuous access to the apparatus, or has plenty of time in the experimental session to obtain its daily requirement of the reinforcer, demand will tend to be inelastic unless there is a strong substitution effect; the size of the substitution effect will depend on the availability of other schedules. A concurrent source of the same reinforcer would be maximally substitutable, and accordingly we would predict highly elastic demand on the original schedule, as found by Herrnstein (1958). A qualitatively different reinforcer would presumably be less substitutable, so demand would be less elastic, but not as inelastic as

with no other reinforcer available. The exact definition of substitutability is a matter of dispute (Samuelson, 1974, discusses six conflicting definitions), but all theorists would agree with our prediction in this simple case. Note that a qualitatively different reinforcer might or might not be preferred to the reinforcer under study; but relative preference is in principle independent of substitutability, and hence will not be given further consideration in this paper.

A similar analogy between demand theory and concurrent FR schedules has been drawn independently by Rachlin, Green, Kagel, and Battalio (1976). Kagel, Battalio, Rachlin, Green, Basmann, and Klemm (1975), using rats as subjects, showed that demand for food with water concurrently available was less elastic than demand for one sweet drink with another of different flavor concurrently available. This supports the analysis outlined above, since water is intuitively less substitutable for food than is one sweet drink for another. However, Kagel et al. did not test either food or sweet drink with more than one alternative, so the differences in elasticity that they observed might be due to differences in the nature of these reinforcers (cf. Shettleworth, 1972). Certainly one would expect demand for an essential good, such as food, to be less elastic than demand for an inessential good, such as a sweet drink. (The latter can safely be said to be inessential because the rats had free access to food and water.)

The present experiment sought to provide further evidence of the usefulness of the analogy between demand theory and operant behavior, by demonstrating that changes in the substitutability of alternatives can affect the elasticity of demand for a single reinforcer. Rats were tested in a two-compartment operant chamber, with food reinforcement concurrently available on FR schedules in the two compartments. In one compartment, presses on the lever delivered mixed diet pellets on a range of FRs from 1 to 16; in the other, either no pellets, identical pellets, or sucrose pellets were available on FR 8. Our prediction was that elasticity of demand for mixed diet pellets would be least with no currently available alternative and greatest with the most substitutable alternative (namely, identical pellets). The conditions were such that inelastic demand would be predicted with a single oper-

ant, *i.e.*, the rats were allowed to earn most of their daily food intake in the operant chamber, and were not fed immediately after testing.

METHOD

Subjects

Six female hooded rats, aged about three months, were selected at random from a group of 10 obtained from Animal Suppliers Ltd., London. They were housed in two cages of three, of equal mean initial weight. Water was always available in the home cages, and food was present for 1 hr per day, approximately 1 hr after the last animal in that cage had been tested. The remaining four rats were kept on freely available food in a separate cage, as weight controls.

Apparatus

The operant chamber has been described by Morgan (1974), and consisted essentially of two single-lever boxes joined back to back, on either side of a central compartment. The latter measured 11 by 20 by 45 cm, and could be entered from either side compartment. Its purpose was to prevent a rat from being in both side compartments simultaneously.

Each side compartment measured 25 by 20 by 45 cm, and contained a single retractable lever and a recessed food tray .The lever operated a sealed-reed switch when depressed with a force adjustable between 0.05 and 0.15 N. Access to the food tray required that a translucent panel be pushed open by the rat, operating a microswitch. Each compartment also contained lights above the lever (barlight), concealed above the foodtray (traylight), and in the center of the ceiling (houselight); movements of the rat from one compartment to another were monitored by photocells.

The whole chamber was placed in a sound-attenuating chest in an air-conditioned room, with white noise continuously present. The apparatus was controlled by a digital computer using a general purpose control system ONLI, and performance was monitored on a cumulative recorder in a neighboring room.

Reinforcement Pellets

These were 45-mg Formula "A" and Formula "F" pellets, supplied by P. J. Noyes Co. They were composed of mixed diet and su-

crose respectively, and had declared calorific values of 4.5 and 4.0 Kcal/g.

Pretraining

During the first stages of pretraining, access to the central compartment was blocked, so that each rat was confined to one of the side chambers during each session. The rats were trained on different sides from day to day according to a double alternation, and received both kinds of pellet in a double alternation out of phase with the first. On Day 1, the food tray was filled with pellets and the panel wedged open, with the house- and traylights on and the lever retracted; on Day 2, the wedge was removed so that the rat had to push open the panel to get to the pellets; on Day 3, a single pellet was delivered each time the panel closed; on Day 4, pellets were delivered on a variable-time 30-sec (VT 30-sec) schedule (Zeiler, 1968). Thereafter, the lever was extended into the compartment throughout the session, with the force criterion set to 0.05 N, and a pellet was delivered for every lever press (FR 1 schedule). On the VT 30-sec and FR 1 schedules, the traylight was normally off and the barlight normally on, but the lights were reversed when a pellet was delivered and remained reversed until the food-tray panel next closed. While the lights were reversed, lever pressing had no scheduled consequences. Four rats learned to press on or before the second day of FR 1, and the remaining two were shaped by means of successive approximations during the following session. When each rat had obtained at least 50 reinforcements on FR 1 in each side compartment, the lever criterion force was increased to 0.15 N, and the fixed ratio was gradually increased to FR 16 over two sessions. Finally, the openings to the central compartment were unblocked, and the rats were given three sessions in which mixed diet pellets were available in one compartment and sucrose in the other, both on FR 8 schedules. All pretraining sessions had a duration of 30 min.

Procedure

The experiment consisted of three main test series interspersed with recovery sessions. For each rat, one side compartment was designated "experimental" and the other "alternative", the left compartment being experimental for Rats 1, 4, and 5.

In each test series, mixed diet pellets were available in the experimental compartment for three days on each of the following fixed-ratio schedules: FR 1, FR 6, FR 11, FR 16, and FR 1. The reinforcer available in the alternative compartment varied between series. In the first series (FR $n_{\text{mixed diet}}$ versus empty compartment), the lever in the alternative compartment was retracted and the barlight switched off. In the second series (conc FR $n_{\text{mixed diet}}$ FR 8_{sucrose}), sucrose pellets were available on FR 8 in the alternative compartment. In the third series (conc FR $n_{\text{mixed diet}}$ FR $8_{\text{mixed diet}}$), mixed diet pellets were available on FR 8 in the alternative compartment.

With one exception, all rats experienced the three test series in the same order and on the same days. The exception was Rat 3, whose response rate dropped markedly on FR 6 and FR 11 in the second series. Observation showed that instead of lever pressing for food, Rat 3 was "fishing" for pellets that had dropped beneath the floor grid. This behavior ceased, and the response rate returned to normal, when the droppings tray was emptied after every session; Rat 3 was retested on the two atypical schedules at the end of the experiment. Two sessions of conc FR $8_{\text{mixed diet}}$ FR 8_{sucrose} were interposed between pretraining and the first series, between the first and second series, and after the third series. Two sessions of conc FR $8_{\text{mixed diet}}$ FR $8_{\text{mixed diet}}$ were interposed between the second and third series to accustom the animals to the delivery of mixed diet pellets in both compartments.

In addition, three sessions at FR 1 and FR 16, in each of the three main experimental conditions, were conducted at the end of the experiment in a fully counterbalanced manner. Two rats were tested with the empty compartment as alternative, two with sucrose, and two with mixed diet. For one rat of each pair, the left compartment was experimental, and for the other the right; for one of each pair, the three days of FR 1 preceded FR 16, and for the other the reverse.

All sessions in the main test series and in the counterbalanced series lasted 60 min, but the conc FR 8 FR 8 sessions were reduced to 30 min for reasons of convenience. Preliminary observation suggested that even at FR 16, rats did not spend a whole hour working for food, so a ceiling effect with changes in FR size was unlikely.

The following data were recorded: number of responses and reinforcements per session, and total time spent in each compartment; number of first-order transitions between lever press, feeder operation, panel closure, and photocell operation; duration of all postreinforcement pauses; number of reinforcements obtained in each compartment between visits to the other; and inter lever-press times in each compartment, excluding those that included a feeder operation or a visit to the other compartment.

RESULTS

Figure 1 shows the median number of pellets obtained per session at each ratio in the experimental and alternative compartments and in toto, for each of the three main test series and the recovery sessions that bordered on them. For this and all subsequent figures, we have taken the median over all three sessions at each ratio, since there was no consistent trend within the grouped data at any ratio, and examination of the individual data showed that the distribution of orders of the three sessions was almost exactly that which would be expected by chance (see Table 1).

Figure 1 shows that the number of reinforcements obtained in the experimental compartment declined as a function of FR size in all three main series, while number of pellets obtained in the alternative compartment increased in series 2 and 3. Total number of pellets clearly declined in series 3, but showed a less systematic change in series 2. The following results suggest that these were not merely sequential effects. First, Figure 1 shows that numbers of reinforcements obtained when the rats were returned to FR 1 at the end of each main series were similar to the corresponding scores for FR 1 at the beginning of the same series. Second, the rats were tested on conc FR $8_{\text{mixed diet}}$ FR 8_{sucrose} for two 30-min sessions before main series 1 and 2, and after main series 3, and the numbers of reinforcements obtained in these sessions were in all cases very similar (conditions R1, R2, and R3 in Figure 1). Third, two rats were tested at FR 1 and FR 16 in each of the three main conditions at the end of the experiment. The data from these sessions are represented in Figure 1 by the disconnected points at these ratios, and the majority of the points lie very close to those ob-
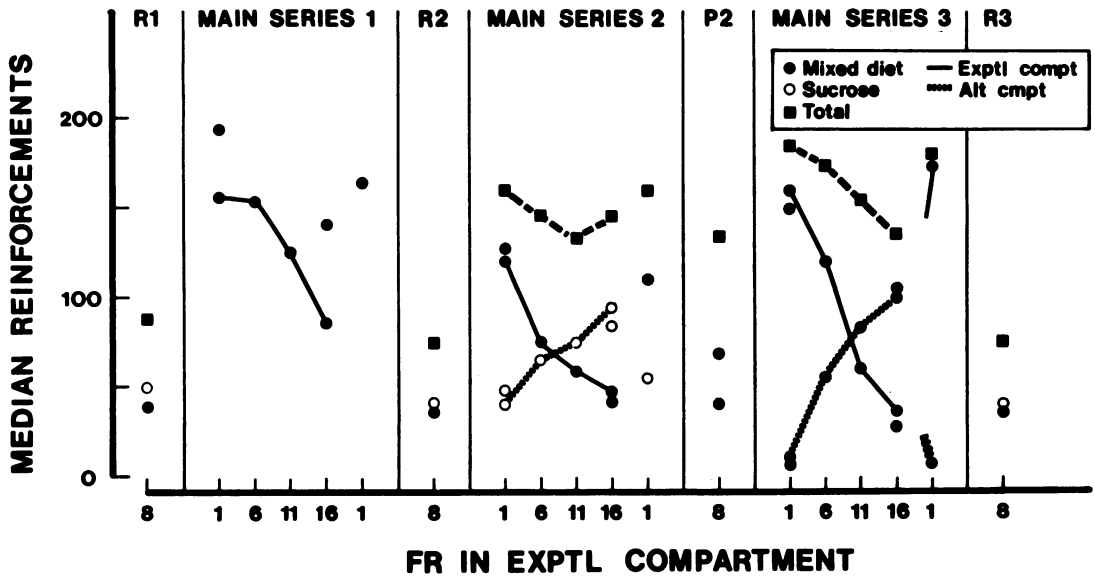
Fig. 1. Median number of reinforcements obtained at each ratio in each condition of the experiment. Main series 1, FR $n_{mixeddiet}$ *versus* empty compartment; main series 2, *conc* FR $n_{mixeddiet}$ FR $8_{sucrose}$; main series 3, *conc* FR $n_{mixeddiet}$ FR $8_{mixeddiet}$; R1, R2, and R3, *conc* FR $8_{mixeddiet}$ FR $8_{sucrose}$; P2, *conc* FR $8_{mixeddiet}$ FR $8_{mixeddiet}$. Data points from the main series are connected, except for the FR 1 recovery sessions at the end of each series. Unconnected points at FR 1 and FR 16 are from recovery sessions at the end of the experiment.

tained during the main series. In the case of series 1, the scores at both ratios were higher than in the original series, but the slope of the line joining the two points was very similar, and the scores closely resembled the scores produced by the same two rats in the original series.

Figure 2 shows the median number of responses emitted and reinforcements obtained per session in the experimental compartment, as a function of FR size in that compartment, for each of the three main series. With the empty compartment (EC) concurrently available, number of responses increased almost enough to maintain a constant number of reinforcements from FR 1 to FR 6, but then decelerated toward an asymptote, resulting in a steeper decline in number of reinforcements. With sucrose (S) concurrently available, number of responses increased at a slower rate overall, so that number of reinforcements fell more steeply. With mixed diet (MD) concurrently available, number of responses rose initially at an intermediate rate but reached an asymptote between FR 6 and FR 11, and declined from FR 11 to FR 16, with the result that number of reinforcements declined more steeply overall than in either of the other series.

Figure 3 again shows median number of reinforcements as a function of FR size, but in this case the data are plotted on log-log scales. On these scales the slope of the demand curve equals its elasticity, and a horizontal line corresponds to an elasticity of zero (*e.g.*, Lancaster, 1969, p. 300 ff.). If only the points for FR 1 and FR 16 are considered, the graph shows that elasticity of demand for mixed diet pellets was greatest with mixed diet concurrently available and least with the empty compartment. However, the intervening points at FR 6 and FR 11 show that elasticity increased as a function of FR size, at a rate that varied between schedules and conditions. As a result, the predicted order of elasticities did not obtain between all pairs of FR values.

Figure 4 shows the same functions for the individual rats. Again considering only the points at FR 1 and FR 16, the predicted order of elasticities held perfectly for all but Rats 2 and 4. Rat 2 took more pellets at FR 16 with sucrose alternative than with no alternative, but the point for sucrose alternative is almost certainly anomalous, since it is higher than the corresponding point at FR 11. Rat 4 took fewer pellets at FR 16 with sucrose alternative than with mixed diet alternative, but here the mixed diet datum appears anomalously high

Table 1

Number of reinforcements obtained per day by each rat, in each compartment, for each of the three main series. Numbers separated by commas are the scores on the three successive days at each schedule.

Series	Cmpt	Rat	FR in Experimental Compartment				
			1	*6*	*11*	*16*	*1*
1	Exptl	1	135,175,165	103,124, 94	94,111,110	85, 75, 56	167, 87, 98
		2	142,161,164	161,146,178	108, 69, 68	44, 42, 59	195,197,165
		3	162,167,135	142,149,153	146,159,163	144,147,134	125,129,129
		4	136,158,145	146,130,140	121,100,105	102, 96, 88	187,158,191
		5	136,123,136	148,142,128	135,136,140	84, 83, 91	146,155,143
		6	208,194,207	198,210,220	167,170,182	123,128,128	237,240,242
2	Exptl	1	103, 97, 95	77, 67, 68	55, 56, 58	41, 37, 47	110,106,103
		2	128,146,156	77, 82, 77	64, 68, 72	62, 73, 77	117,113,118
		3	77, 64, 61	72, 67, 80	42, 34, 40	35, 45, 45	101,110,101
		4	153,154,143	53, 49, 43	33, 33, 45	55, 49, 48	94, 99,111
		5	106,129,106	98,103, 90	63, 54, 57	33, 32, 31	141,105,104
		6	185,185,190	170,172,165	119,107,111	81, 87, 88	179,197,195
	Alt	1	19, 18, 14	47, 45, 41	57, 54, 58	79, 78, 79	42, 27, 36
		2	33, 46, 34	60, 55, 81	62, 56, 60	94,114,103	73, 72, 74
		3	36, 34, 27	72, 69, 61	51, 48, 51	89, 85, 98	42, 40, 34
		4	65, 58, 60	94,106,105	76, 94, 91	105,113,112	61, 68, 63
		5	48, 52, 58	80, 91, 72	78, 91, 72	86, 78, 89	47, 33, 23
		6	64, 44, 55	71, 78, 79	101,110,108	131,122,132	61, 65, 57
3	Exptl	1	102,113,106	120,119,137	57, 53, 43	34, 33, 24	168,136,171
		2	188,198,147	114,146,128	79, 67, 64	28, 39, 31	186,185,189
		3	125,138,152	51, 49, 32	17, 23, 16	17, 20, 36	157,148,163
		4	154,160,146	89, 77, 95	34, 30, 46	51, 58, 54	152,188,196
		5	183,189,186	119,137,147	79, 88, 61	28, 24, 33	151,164,207
		6	197,257,251	203,202,200	117,110,114	74, 73, 38	233,250,259
	Alt	1	9, 8, 5	20, 19, 24	66, 75, 99	77,105, 98	5, 6, 2
		2	9, 3, 9	60, 47, 45	88, 96,138	211,175,179	12, 4, 0
		3	30, 5, 9	100, 67,141	148,103,123	107, 86, 96	6, 0, 7
		4	16, 27, 12	67, 72, 92	113, 83,102	108, 92,110	57, 0, 0
		5	12, 4, 2	32, 23, 37	41, 61, 63	61, 53, 88	3, 4, 1
		6	43, 8, 8	41, 73, 64	85, 81,107	156,169,165	5, 14, 3

in comparison with FR 11. As in the median data, the order of elasticities between adjacent FR values was quite variable.

Figure 5 shows the duration of postreinforcement pauses (PRPs) as a function of FR size. The upper three graphs refer to the experimental compartment, and the lower two to the alternative compartment (in which the schedule was always FR 8). In each case three scores are shown: the mean pause duration, including pauses that contained a visit to the other compartment; the mean duration, excluding pauses that contained a visit to the other compartment; and the median duration, including pauses that contained a visit. Mean PRPs in the experimental compartment including visits (upper graphs, filled circles) increased as a function of FR size in all three conditions, but the increase was more marked in series 2 and

3 than in series 1. When scores were derived by excluding pauses that contained a visit to the alternative compartment, or by taking medians rather than means, the increase was largely or completely abolished. Mean PRPs including visits to the alternative compartment (lower graphs, filled circles) declined in duration as FR in the experimental compartment increased; again, this trend was greatly reduced by excluding pauses that contained a visit to the other compartment, or by taking medians rather than means.

DISCUSSION

On the basis of an analogy between operant behavior and consumer demand theory, we predicted that the elasticity of demand for a reinforcer would depend on the substitutabil-
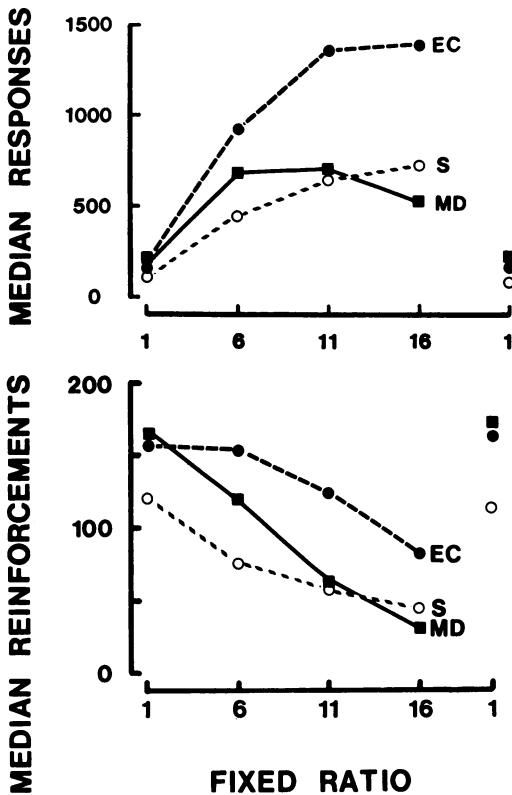
Fig. 2. Median number of responses made (upper panel) and reinforcements obtained (lower panel) in the experimental compartment, as a function of FR size in that compartment, for each test series. EC: empty compartment concurrently available; S: sucrose concurrently available; MD: mixed diet concurrently available.
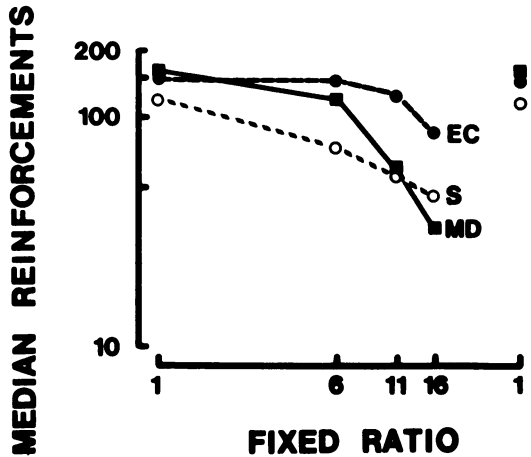

Fig. 3. Median demand curves (number of reinforcements obtained as a function of FR size) in the experimental compartment, for each test series. Data are plotted on log-log scales, so that the slope of the demand curve equals its elasticity. EC: empty compartment concurrently available; S: sucrose concurrently available; MD: mixed diet concurrently available. Each point represents the median over three sessions.

ity of other reinforcers that might be concurrently available. Specifically, we predicted that the elasticity of demand for mixed diet pellets would be greater with identical pellets concurrently available, less with sucrose pellets concurrently available, and least with no food concurrently available. Considering only the extremes of the range of schedules (*i.e.*, FR 1 and FR 16), this prediction was confirmed. Our results therefore support those of Kagel *et al.* (1975), and extend those of Roper (1973, 1975) and Hogan *et al.* (1970) by showing that elasticity of demand for a reinforcer depends not only on the nature of the reinforcer (as suggested by Shettleworth, 1972), but also on the context in which it is available.

Detailed examination of the results shows, however, that the predicted order of elasticities did not obtain between FR 1 and FR 6 (where demand was more elastic with sucrose than with mixed diet as alternative), or between FR 11 and FR 16 (where demand was more elastic with no alternative than with sucrose). In the latter case, excessive elasticity with no alternative was probably caused by an income effect. Contrary to expectations based on pretraining results, the rats sometimes spent the whole session working for mixed diet on FR 16, when there was no alternative food reinforcer. Hence, the number of reinforcements given no alternative was occasionally curtailed by session length. The suggestion of an income effect is further supported by the fact that in the present experiment, total response output declined from FR 11 to FR 16, whereas in an experiment by Collier *et al.* (1972), in which sessions were 24 hr long, it continued to increase up to FR 160. Note that our rats always stopped lever pressing before the end of the session when mixed diet or sucrose were concurrently available.

The discrepancy between FR 1 and FR 6 is more interesting. Herrnstein (1958) found that in concurrent FR schedules, all responding usually occurred on the smaller ratio. One might therefore argue that in *conc* FR $n_{mixed\ diet}$ FR $8_{mixed\ diet}$, there was no effective alternative to FR n for as long as n was less than 8, and hence no reason why demand should be more elastic in this condition than when there was no scheduled alternative. With
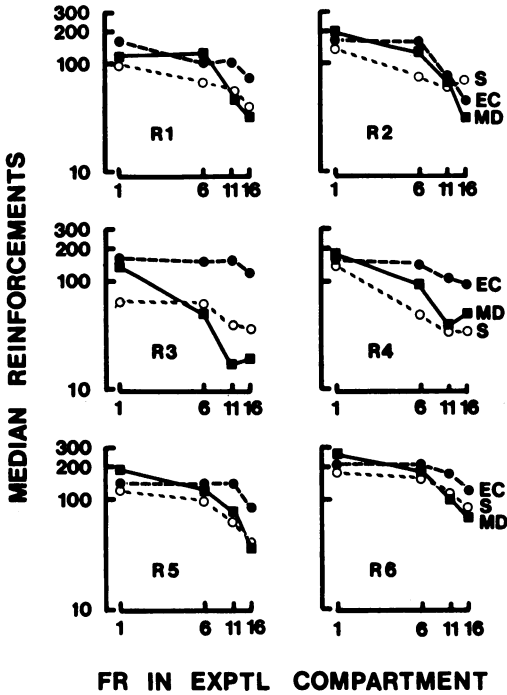
Fig. 4. Individual demand curves (number of reinforcements obtained as a function of FR size) in the experimental compartment, for each test series. Each point represents the median over three sessions. Conventions as in Figure 3.
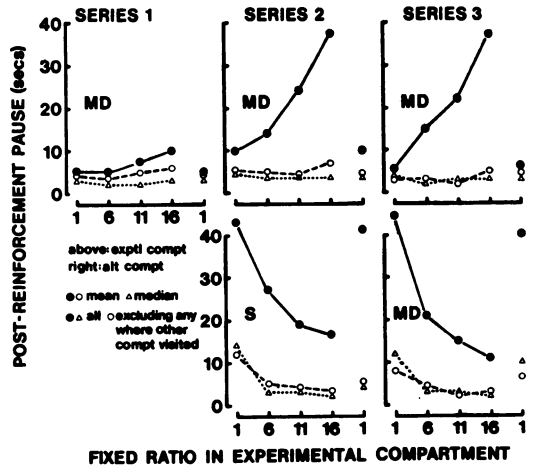

Fig. 5. Postreinforcement pause as a function of FR size in the experimental compartment, for the experimental compartment (upper panels) and the alternative compartment (lower panels), in each of the test series. MD: mixed diet as reinforcer; S: sucrose as a reinforcer. Each point is the median over rats of the median over three sessions, but the average within each session was taken in three different ways: as mean and median of all pauses, and as mean excluding those pauses during which the rat visited the other compartment. All three averages were taken over the first n reinforcements in the session, where n was the minimum obtained by that rat in that test series.

sucrose alternative, on the other hand, there is no objectively "best" solution, and it is reasonable to suppose that the extent to which the rat will work for "cheap" mixed diet rather than "expensive" sucrose will depend on the price differential. In the language of demand theory, the distinction between these two situations is that between "efficiency" and "private" substitution effects (Lancaster, 1966). The former occurs when buying one commodity is simply a more efficient way of fulfilling a particular need than buying another, and it is associated with step-like substitution. The latter occurs when two commodities fulfil different needs, and it is associated with smoother substitution. In fact, we did not observe complete absorption on the better schedule in conc FR $n_{mixed\ diet}$ FR $8_{mixed\ diet}$, and hence we did not obtain a completely step-like demand function. The difference between this result and that of Herrnstein (1958) probably reflects the substantially longer periods of training in each condition used by Herrnstein.

In all three conditions, demand became more elastic as fixed ratio in the experimental compartment increased. This is of interest because constant elasticity is commonly assumed when demand curves are estimated from econometric data (e.g., Allan, 1972). Direct measurement of elasticity of demand has rarely been attempted in a real economic situation (see Dalrymple and Thompson, 1969, chapter 11), and it is possible that operant techniques could be usefully applied for this purpose.

The present results were consistent with the well-established finding that postreinforcement pause (PRP) duration increased as a function of FR size (Felton and Lyon, 1966; Powell, 1970). In addition, we obtained a marked simultaneous behavioral contrast effect (cf. Rachlin, 1973), in that PRP duration in the alternative compartment (in which the schedule was always FR 8) decreased as FR in the experimental compartment increased. Both effects were largely abolished by taking medians rather than means, or by excluding pauses that did not contain a visit to the other compartment. Changes in pause duration were therefore mainly attributable to a relatively small number of pauses in which the animal left the compartment in which it was working.

Wood, Martinez, and Willis (1975), using concurrent fixed-ratio fixed-interval schedules, also obtained contrast if the reinforcers in the two schedules were both mixed diet, but not if the reinforcer in the FR component was water. However, the latter result does not conflict with ours, since they observed contrast in response rate during fixed-interval components, and their rats did not switch between levers except immediately after reinforcement. Their data are therefore most closely analogous to the open circles of Figure 5, which were calculated by excluding pauses during which the alternative compartment was visited; these points show little behavioral contrast.

Hollard and Davison (1971) obtained simultaneous behavioral contrast using concurrent food and brain stimulation as reinforcers on variable-interval schedules. They were able to make their results consistent with Baum and Rachlin's (1969) modification of Herrnstein's (1961, 1970) matching law, by multiplying the rate of one of the reinforcers by a constant q_1/q_2. Willis, Van Hartesveldt, Loken, and Hall (1974) suggested that the constant might vary according to relative deprivation. The essence of this proposal, as applied to the present experiment, is that a sucrose pellet differs from a mixed diet pellet only in being a factor of q_1/q_2 better. If this were so, the demand curve for mixed diet with FR 8_{sucrose} as alternative would be the same as the demand curve for mixed diet with FR $q_1/q_2 \times 8_{\text{mixed diet}}$ as alternative; the latter would be the same as that observed with FR $8_{\text{mixed diet}}$ as alternative, but would be shifted along the horizontal axis. But in fact, the demand curves with sucrose and mixed diet as alternative cross, and so cannot be made the same by any shift along either axis. In Lancaster's (1966) terms, Hollard and Davison allow only for efficiency substitution, whereas we also observed private substitution. Lancaster argues that if n commodities are bought by a single consumer, there must be at least n different ways in which they are valuable. Thus, if responses are distributed between schedules of two different reinforcers more evenly than they would be between schedules of a single reinforcer, there must be at least two different noncommensurable ways in which they are reinforcing. The argument here is like that used by Herrnstein (1964) and Morgan (1974) to show "added attraction" for, respectively, variable- rather than fixed-inter-

val schedules, and variable-time rather than variable-interval schedules.

An alternative approach that might be relevant to our results is the theory of time allocation between reinforcing activities, originated by Premack (1959, 1965) and subsequently developed by Timberlake and Allison (1974), Allison (1976), and Mazur (1975). None of these authors explicitly considered concurrent schedules of different reinforcers, but Allison's "conservation" model (1976, Equation 1) predicts that elasticity of demand for a single reinforcer should be zero for low ratios and approach unity as the ratio increases. This is a reasonable summary of our results as presented in Figures 3 and 4. To predict the effects of adding the alternative reinforcer would require consideration of the extent to which deprivation of the response of eating mixed diet pellets is reduced by eating sucrose pellets. The issue here is precisely that of predicting substitutability, as Lancaster (1966) set out to do in an economic context.

A third source of models for choice between two different reinforcers is the literature on brand preference in consumer science. Sowter, Gabor, and Granger (1971) suggested that, given two similar (but not identical) brands of a product, the probability that the cheaper will be bought should be a cumulative normal distribution function of the log ratio of prices. Applying their model to the data from our second test series (*conc* FR $n_{\text{mixed diet}}$ FR 8_{sucrose}), and substituting fixed-ratio sizes for prices and number of reinforcements for quantity purchased, we obtained a linear correlation of 0.98 from the median data (Figure 3). This is substantially higher than the correlations obtained by Sowter *et al.* from consumer purchase data. However, the graphs for all six rats showed consistent curvature, which necessitates rejection of Sowter *et al.*'s model.

We have tried in this paper to point out an analogy between the study of consumer demand and the study of reinforcement schedules. In doing so, we do not wish to imply that the behavior of individual animals should be predicted from the behavior of whole societies. However, since choice is a central concern of both psychology and economics, it is possible that effects that have been neglected in one discipline are well known in the other. The effect of substitutability on demand is, we would argue, one such case.

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