JOURNAL OF THE EXPERIMENTAL ANALYSIS OF BEHAVIOR 1980, 34, 219-238 NUMBER 2 (SEPTEMBER)

ECONOMIC CONCEPTS FOR THE ANALYSIS OF BEHAVIOR

STEVEN R. HURSH

WALTER REED INSTITUTE OF RESEARCH

A review of the relationship between schedule of reinforcement, response rate, and choice suggests that certain unifying concepts from economics can contribute to a more complete science of behavior. Four points are made: 1) a behavioral experiment is an economic system and its characteristics—open or closed—can strongly determine the results; 2) reinforcers can be distinguished by a functional property called elasticity; 3) reinforcers may interact as complements as well as substitutes; 4) no simple choice rule, such as strict matching, can account for all choice behavior.

Key words: economics, demand, elasticity, response rate, choice, matching

---

Economists have been attempting to predict and control consumer behavior for centuries. Experimental psychologists have more recently developed a broad base of behavioral principles and have assumed that, as Skinner (1953) has stated, "an adequate science of behavior should supply a satisfactory account of the individual behavior which is responsible for the data of economics in general" (p. 400). A review of economics reveals, however, that economic theory is not, as yet, derivable from current behavior principles; that in fact, a complete behavioral account could profitably adopt and borrow from economics. Several others have independently concluded that economic concepts are relevant to behavior analysis; in particular, Allison, Miller, and Wozny (1979), Lea (1978), Rachlin, Green, Kagel, and Battalio (1976), and Staddon (1979) have generated similar concepts. These economic concepts are not a general theory of behavior, but a contribution to it. This review relies more on intuitive exposition than on mathematical derivation to relate economics to available experimental data. In making these connections, the overriding concern was to make sense of the broadest set of results. Economic theory, being derived in part from intuition and in part from observations of the aggregate behavior of social groups, is not always directly applicable to the analysis of the operant behavior of individual experimental subjects. I have adapted the substance of microeconomics, but absolute loyalty to economic conventions has not always been possible or desirable. My purpose is not to prove or disprove economic theory (see introductions to microeconomics by Samuelson, 1976; Watson & Holman, 1977).

The following four points will be discussed. Each is related to economic theory and is useful for the analysis of otherwise conflicting sets of data.

1. A behavioral experiment is an economic system and its characteristics can strongly determine the results.
2. Reinforcers can be distinguished by a functional property called elasticity of demand that is independent of relative value.
3. Reinforcers may interact as complements, as well as substitutes.
4. Finally, because reinforcers differ in elasticity and because reinforcers can be com-

This material has been reviewed by the Walter Reed Army Institute of Research, and there is no objection to its presentation and/or publication. The opinions or assertions contained herein are the private views of the author and are not to be construed as official or as reflecting the views of the Department of the Army or the Department of Defense. The author acknowledges the following contributions to this works: Timothy Elsmore and George Collier for their generous contributions of data; James Norborg for his insight into economics for behavior analysis; J. A. Nevin and S. E. G. Lea for critical comment; James Morrison, Rodger Heath, and Andy Allen for technical assistance; and Sylvia Danchik for preparation of the manuscript. Reprints may be obtained from Steven R. Hursh, Department of Medical Neurosciences, Division of Neuropsychiatry, Walter Reed Army Institute of Research, Washington, D.C. 20012.

plementary, no simple, unidimensional choice rule such as matching can account for all choice behavior.

These points will be developed separately, illustrated with data and related to some new directions for research.

CLOSED AND OPEN ECONOMIES

Consider an experiment in which animals must emit a certain number of responses to get a bit of food. Once trained the number of responses required for each bit of food is increased every so often. This particular environmental constraint on food supply is called a fixed-ratio schedule (FR). The question is, "how will the animal's rate of responding change as we make these upward shifts in work requirement?" Figure 1 shows the results of two such experiments. Along the x-axis are FR values; along the y-axis is response rate. The filled squares are from a representative subject in a study by Felton and Lyon (1966).

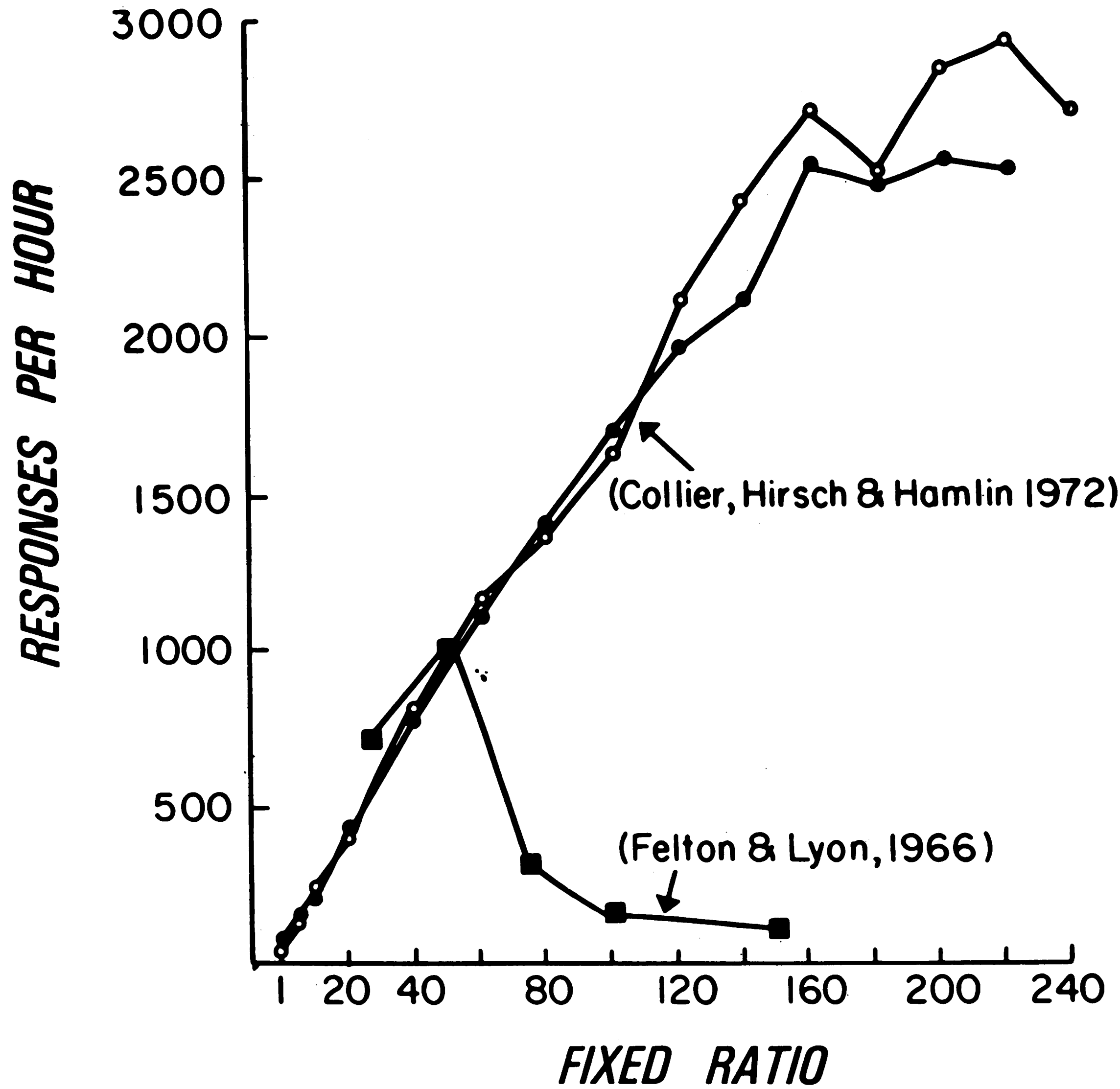

Fig. 1. Data from two experiments showing overall responses per hour as a function of FR size. Circles (Collier, Hirsch, & Hamlin, 1972) are two rats working 24 hrs per day. Squares (Felton & Lyon, 1966) are from a representative pigeon studied in short sessions; data were derived by computations from postreinforcement pause and running-rate measures provided in the original report (details on request).

Food deprived pigeons worked for small grain reinforcers in short sessions. Response rate increased up to a ratio of 50 responses per reinforcer (FR 50), but then dropped precipitously to much lower levels at FR 80, 100, and 150. Performance under these last two requirements gave evidence of serious behavioral disintegration called "strain." Similar inverted U-shaped response functions have been observed with food deprived rats (Barofsky & Hurwitz, 1968; Collier & Jennings, 1969) and monkeys (Hamilton & Brobeck, 1964).

By contrast, Collier, Hirsch, and Hamlin (1972) studied two rats who lived in chambers 24 hours a day and pressed levers for their food without artificial deprivation. Both rats showed strongly increasing response rates at the same ratios that produced behavioral "strain" in the Felton and Lyon (1966) example, not reaching a peak in rate until they were paying about 160 responses for every piece of food they ate. This high rate was sustained even at FR 240.

How can a disintegrated performance in one case be reconciled with an exceptionally well-maintained performance in the other case? Perhaps animals cannot sustain FR performance when food deprived. Or perhaps the difference in outcomes results from a difference between short sessions and continuous access. Another example helps clarify the issues and suggests an economic interpretation.

In two other studies, subjects earned food by responding under variable-interval schedules. The schedules set the minimum average time between available reinforcers, but did not directly require any specific number of responses per reinforcer. Across conditions this minimum average time between reinforcers was increased. The question was "will response rate go up or go down"? Figure 2 shows two outcomes. The open circles show the data of a representative subject from the study by Catania and Reynolds (1968). They studied food-deprived pigeons given small grain reinforcers in sessions terminated after a fixed number of reinforcers. They found a systematic decrease in response rate with increasing time between reinforcers. The filled circles are from a study by Hursh (1978) showing the result from one of two monkeys. These subjects worked for their total daily food ration in a session lasting about 100 minutes. They were food deprived, earning only about 80% of their normal ration. These subjects showed a strongly increasing response rate over the same range of schedules that Catania and Reynolds found decreased response rate. These results are analogous to those in the FR studies; an increase in constraint on reinforcement altered response rate in conflicting ways. Based on this evidence, schedule type, session length, and food deprivation per se can be eliminated as critical factors. Species differences are not important since both monkeys (Hursh, 1978) and rats (Hursh & Natelson, in press, see Figure 10 below; see also Figure 5 in Graft, Lea, & Whitworth, 1977) show an increasing function with VI schedules.

I propose that in these and all other behavioral studies *the economic system controlling consumption can strongly determine the results.* In the studies by Felton and Lyon (1966) and Catania and Reynolds (1968), the subjects were held at a fixed body weight (80% of ad lib feeding weight) and given supplemental feeding to keep food intake about constant. The total daily consumption of food was not the result of the subjects' interaction with the environment during the sessions, but was arbitrarily controlled by the experimenter. This is what I call an *open economy*. In the

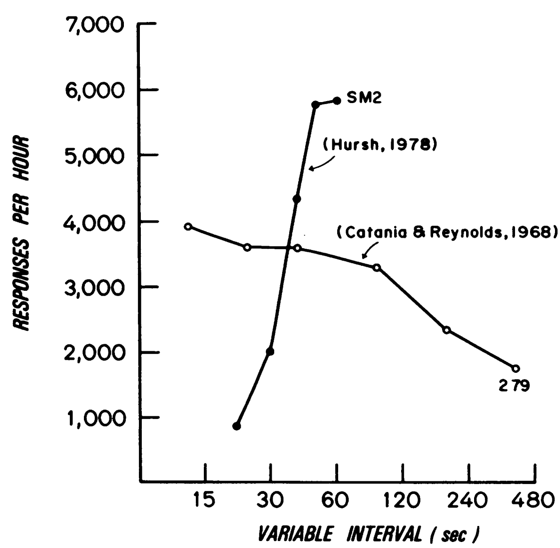

Fig. 2. Data from two experiments showing overall responses per hour as a function of VI values (sec). Filled circles are from a representative rhesus monkey working for food concurrently with water. The procedure was essentially that described in Hursh (1978) except all food was obtained from a single VI schedule (see discussion of Experiment I). Open circles are from a representative pigeon described by Catania & Reynolds (1968).

Collier et al. (1972) study and the Hursh (1978) study, total daily food consumption was determined solely by the subjects' interaction with the schedules of reinforcement, either across a 24 hr day in the Collier et al. study or during a timed session in the Hursh study. No extra food was provided. This is what I call a *closed economy*.

These strikingly different results demonstrate that it is important to extend our studies of behavior to situations that are closed economies, i.e., situations in which the subjects' adjustments to the experimental constraints control daily consumption, and deprivation is not artificially held constant. The closed economy can be defined in more technical terms. For economists the behavior of the individual consumer considered in the ideal case reflects an equilibrium between the supply of a commodity and the consumer's demand—how much gasoline will be produced at current prices, on the one hand, and how much consumers will buy at those prices, on the other. This equilibrium process is diagrammed in Figure 3. Price is on the x-axis, which in most animal studies translates as responses-emitted-per-reinforcer because there is no medium of exchange such as money. Along the y-axis is the quantity consumed or presented, which in animal studies represents the obtained rate of reinforcement, such as food pellets per hour or cocaine infusions per day. Note that in many economics text books, price is on the vertical axis, although it is still thought of as the independent variable. Here I adopt the convention of other sciences, as do many mathematical economists.

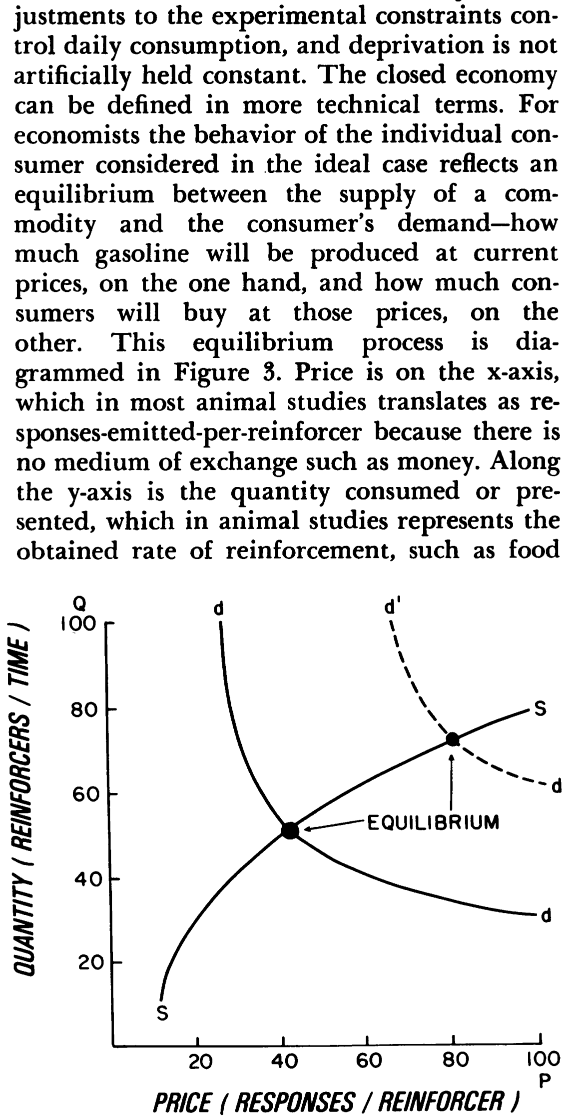

Fig. 3. The theoretical basis for behavioral equilibrium based on the intersection of the subject's demand (d) and the environment's supply (s). An increase in demand is shown as d' with the consequent change in equilibrium point.

The first determiner of equilibrium is the *supply curve* (*s* in Figure 3) or schedule, which translates as the environmental constraints on obtaining the commodity, expressed as quantity per unit time provided at a given price. As the price paid per unit goes up, the rate of production increases. Supply schedules can be simple schedules of reinforcement or complicated contingencies arranged by a school teacher or parent. For example, the higher one is willing to reach for each apple, the greater the yield from the apple tree.

The supply curve is mathematically related to what has been previously described as the "feedback function," i.e., the rate of reinforcement provided by a schedule of reinforcement as a function of response rate (Baum, 1973; Rachlin & Burkhard, 1978; Staddon & Motheral, 1978; Heyman & Luce, 1979). The supply curve treats responses per reinforcer (price) as the independent variable and the "feedback function" treats responses per unit time as the independent variable. The supply curve is also a feedback function and can be derived from the feedback function, defined in terms of response rate, by simply dividing the responses per time at any point by the reinforcers per time at that point giving the price or responses per reinforcer. For consistency with economic theory, the supply curve is used here as the feedback function, but any conclusion based on the supply curve could just as easily be derived from a feedback function defined in terms of response rate.

The second determiner of equilibrium is the *demand curve* (*d* in Figure 3) or schedule, which describes the amount that the subject will consume at a given price or the price that will be paid for a given rate of consumption. As price increases, consumption generally decreases. For example, one will settle for fewer apples when most of them are toward the top of the tree.

Equilibrium is the stable outcome of these two curves, shown in Figure 3. Where they intersect is the only point of agreement between the subject's demand and the environment's constraint on supply. Economic theory includes an account of the processes leading to stability (or instability), but these will not be discussed here (for an example, see Watson & Holman, 1977, pp. 238-252, 280-282). Given a stable pair of demand and supply curves, a single behavioral outcome is observed—a certain price is paid and a certain quantity is consumed. If there is no other source of the commodity, daily consumption will depend on this equilibrium point. If demand increases, the demand curve moves to the right, shown as d′ in Figure 3. The new equilibrium moves upward and to the right, implying a higher price and a greater rate of consumption, all else being constant. The technical definition of a *closed economy* is this ideal state when daily consumption is the result of the equilibrium of supply and demand. The Collier et al. (1972) and Hursh (1978) studies fit this definition because no external source of food was provided, and daily consumption was a result of the subject's interaction with the supply schedules or reinforcement schedules. By contrast, the *open economy* is any of a variety of experimental arrangements that provides at least a measure of independence between daily consumption and the equilibrium condition. Examples would be holding a subject at 80% of weight with supplemental food, providing two hours of access to free food after the session, or insuring a constant daily consumption of food by turning off the session when a fixed food ration was earned.

The concept of open economies probably defines a continuum. Specific arrangements of between-session feeding and control of session length would include conditions that are very nearly closed in providing only a small degree of independence between daily consumption and the equilibrium conditions, while others may be strictly open in the sense that daily consumption is totally independent of behavior under the test conditions. Several earlier articles (e.g., Logan, 1964, on the "free behavior situation"; Moran, 1975) have included discussion of this continuum. In this paper, the continuum is defined in economic terms. Most of the examples considered here characterize points very near the extremes of entirely closed and strictly open.

This analysis led to a replication of the study using monkeys on VI schedules for food with an open economy instead of a closed economy (Hursh, 1978, Experiment II). Identical VI schedules were arranged, but instead of terminating each session after a fixed time period, the length of the session was modulated so that a fixed number of food pellets (180) was earned. This eliminated any connection between daily food consumption and equilibrium, much like any other sort of open economy. Figure 4 shows the large shift in results. As you recall, the closed economy generated a sharply increasing response rate with increasing VI shown here as filled circles. When the sessions were terminated by amount of food (open circles) response rate tended to decrease, as Catania and Reynolds (1968) found with pigeons within this range of schedules. It is the economic system which produced the different results.

The difference in outcomes between open and closed economies (Figures 1, 2, and 4) has considerable significance for recent models of operant behavior. Allison, Miller, and Wozny (1979) propose a "conservation" model which most adequately accounts for behavior in closed economies. Staddon (1979) describes limitations of the conservation model that result from its application to cases of open economies in which substitutable amounts of the contingent commodity are available be-

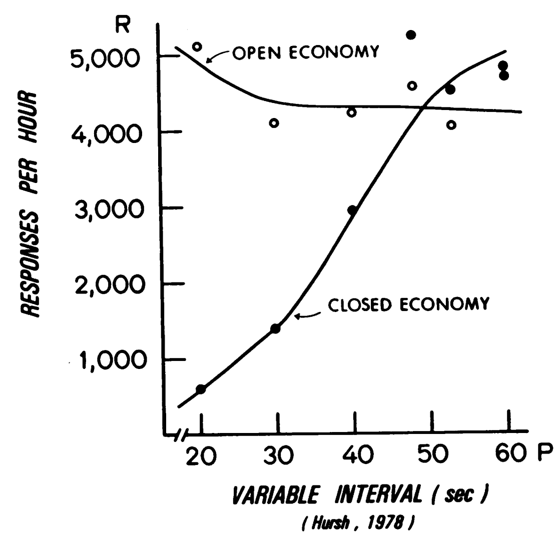

Fig. 4. Representative data from Hursh (1978), Experiment I (filled circles) and Experiment II (open circles), showing response rate as a function of variable-interval schedules. Data were computed from the sum of responses on two concurrent VI schedules for food as a function of the average variable-interval between food pellets from both schedules.

tween sessions (presumably to hold "motivation" constant). It is difficult to formulate a general account of equilibrium in operant behavior without consideration of the total economic system. For example, Mazur (1979) and Herrnstein (1979) attempt to dismiss the closed economy by reference to hypothetical changes in motivation. One could just as easily dismiss consideration of open economies by reference to the changes in between-session feeding. Although I suspect that most natural economies are best described as closed systems, the standard use of open economies serves to isolate important variables. Either way, the economic system plays a central role in determining our results and must be considered in any general account of behavior that can be extended to the natural environment.

It may seem curious that subjects in a closed economy increase response rate when food is scarcer or costs more. To understand this, the concept of demand must be examined more closely. Demand is the amount that will be consumed at a given price or the amount that will be paid for a given rate of consumption. To map a demand curve you must observe its intersection with a set of supply curves; demand is the outcome of an experiment. The top panel of Figure 5 shows how this could be done with a range of FR schedules, each a supply schedule with constant price for any quantity consumed. Each intersection is an equilibrium point under stable conditions. Connecting the equilibrium points yields a demand curve. The bottom panel shows how this is accomplished with a set of VI schedules. These schedules do not set the price, but rather limit the maximum rate of consumption. The supply curve set by VI schedules is the independent variable while price and consumption are dependent variables resulting from equilibrium. For this study, the exact shape of the supply curve is unimportant and approximations have been drawn based upon empirical observation (see Figure 19). Again, connecting the equilibrium points under stable conditions yields a demand curve. In both cases, the demand curve shows relatively little change in consumption with changes in price—what economists call inelastic demand (Samuelson, 1976; Lea, 1978). Note, however, that the two demand curves, one from a hypothetical FR experiment and the other from a VI experiment, are not identical. The demand curve, as I define it, is not entirely determined by the organism or the reinforcer, but is an outcome of an experiment. Its shape may depend on the method of measurement just as the shape of a generalization gradient depends on the schedules of reinforcement (e.g., Hearst, Koresko, & Poppen, 1964).[1]

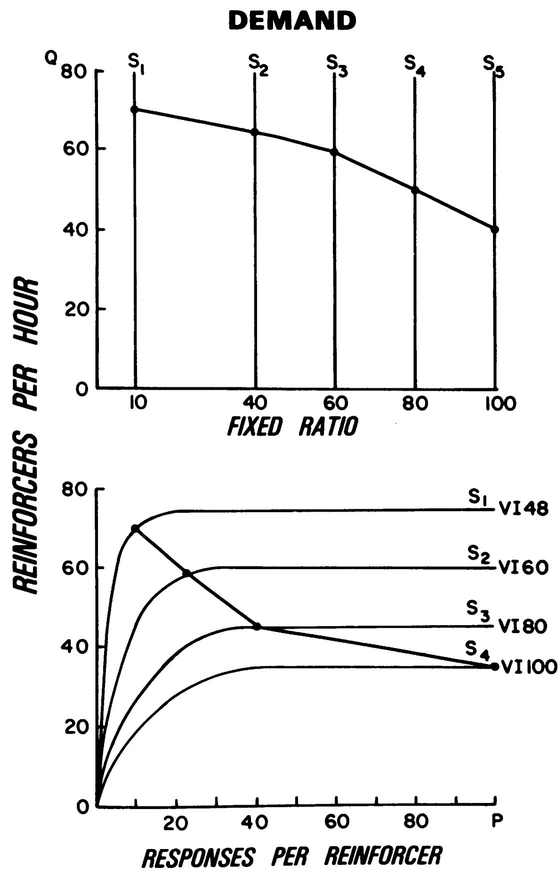

Fig. 5. Two examples of demand curves determined using either FR schedules (top panel) or VI schedules (bottom panel) to control supply (S_1, S_2, S_3, etc.); i.e., rate of reinforcers obtainable as a function of changes in responses "paid" per reinforcer.

The demand curve determines mathematically the overall rate of responding. For economists, total expenditure is the unit price times the quantity consumed. For our purposes, total expenditure is response rate. For example, if the price of gasoline is $1.00 per

[1]Note that with interval schedules of reinforcement the minimum price is one response per reinforcer and that when the supply curves pass through the origin (e.g., Figure 5), they go through the point (1,0). I am grateful to S. E. G. Lea for this observation.

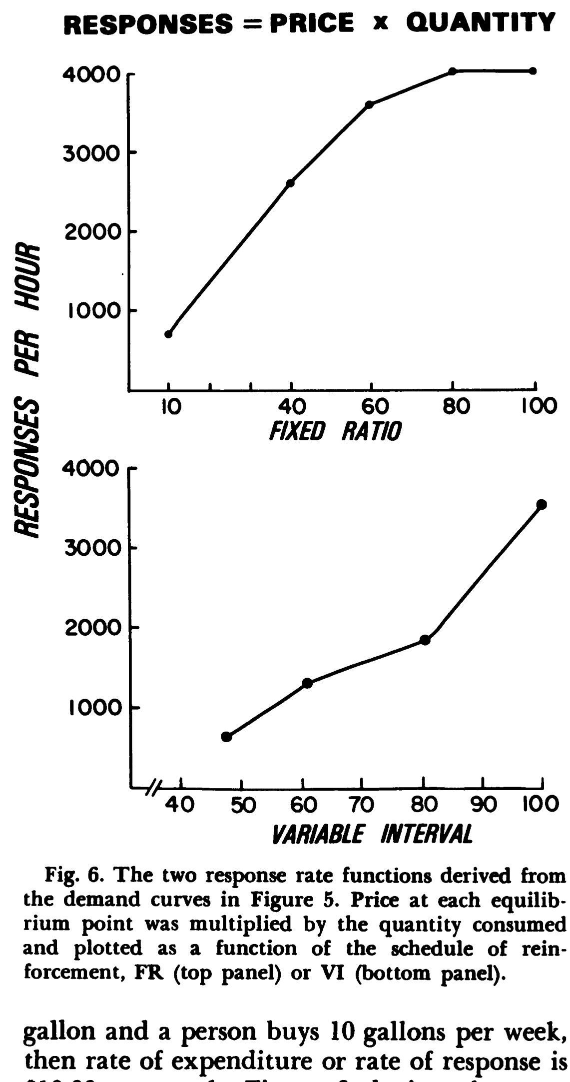

Fig. 6. The two response rate functions derived from the demand curves in Figure 5. Price at each equilibrium point was multiplied by the quantity consumed and plotted as a function of the schedule of reinforcement, FR (top panel) or VI (bottom panel).

gallon and a person buys 10 gallons per week, then rate of expenditure or rate of response is $10.00 per week. Figure 6 depicts the rates of response associated with the equilibrium points of the gently sloping demand curves in Figure 5. Response rate must increase with price or FR value in the top panel to minimize the changes in consumption shown in Figure 5. Likewise, in the bottom panel, response rates will increase with increasing VI schedules if the demand curve minimizes changes in consumption across VI's or increasing prices. These hypothetical examples are substantiated in Figure 7 by the demand curve from the Collier et al. (1972) study. Demand for food evidenced minimal change in consumption with increasing price and this was accomplished by increasing response rate (see Figure 1). Likewise, the demand curve asso-

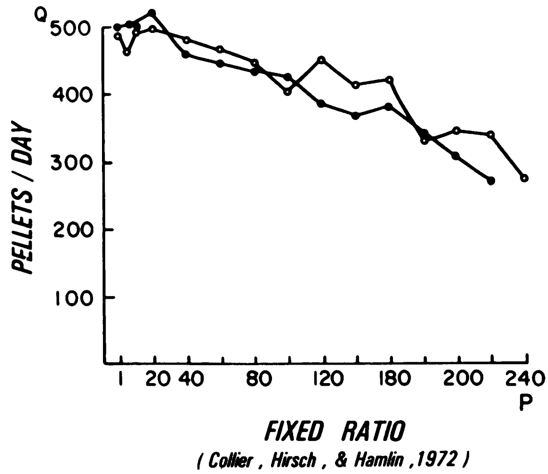

Fig. 7. The demand curve for food pellets by two rats working 24 hrs per day reported by Collier, Hirsch, and Hamlin (1972).

ciated with the Hursh (1978) study of VI schedules was gently sloping downward, shown in Figure 8, yielding an increasing response rate function (see Figure 2). Remember, however, that since the exact shape of the demand curve depends in part on the method of measurement, it is possible that between classes of reinforcement schedules equivalent levels of

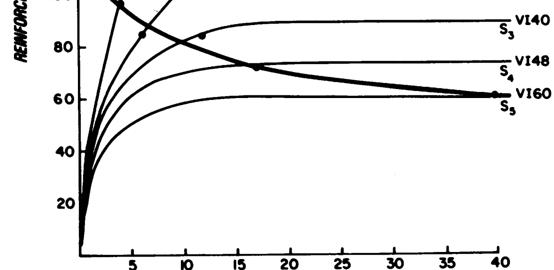

Fig. 8. The demand curve for food pellets by a monkey working in a short session reported by Hursh (1978). The curve was computed by plotting the observed rate of food reinforcement under each schedule condition as a function of the price paid, i.e., the number of responses for food divided by the number of obtained reinforcers.

consumption will be observed at different prices and maintain different response rates. This presents no particular problem as long as all substantive comparisons are made within single classes of reinforcement schedules.

To summarize to this point, the behavior of subjects can depend critically upon whether the experimental situation is an open or closed economy. If the situation is a closed economy and the subject minimizes changes in consumption (demand slopes downward slowly) for an essential commodity such as food, then the result of raising price or increasing VI will be an increasing expenditure of behavior or an increasing response rate function. This contrasts sharply with results obtained in the more traditional open economy. In those studies, subjects did not minimize changes in consumption by increasing response rate. This suggests that principles of behavior based on observations of changes in response rate in open economies might not apply in closed economies. This is important for a general theory of behavior because most animals, including humans, live in habitats that approximate closed economies.

DEMAND ELASTICITY

So far, I have stipulated that demand for food in a closed economy slopes downward gently with increasing price. This observation cannot be extended to all reinforcers or situations. Consider the following results from a closed economy (Hursh & Natelson, in press). Three rats lived in individual operant chambers 24 hrs per day. They had two levers. One provided half-second trains of reinforcing electrical brain stimulation (EBS); the other lever provided 45 mg food pellets. The schedules of reinforcement for each were always equal VI schedules with a change-over-delay of 2 sec (Herrnstein, 1961). The VI's were increased from 3 sec to 60 sec with intermediate steps at 7.5, 15, and 30 seconds and a replication at VI 3 sec. Figure 9 shows the changes in daily response rate as a function of increasing VI value averaged across subjects (note the log-log coordinates). As with the monkeys in the previous study, response rate for food in this closed economy was an increasing function of VI schedule. By contrast, the response rate for EBS was a decreasing function resembling one for food in an open economy (cf. Figure 2).

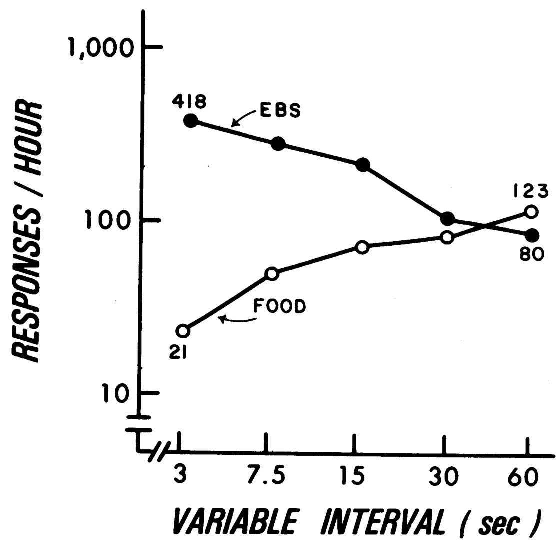

Fig. 9. Mean response rate by three rats working 24 hrs per day for electrical brain stimulation (EBS) or food on equal VI schedules. Data reported by Hursh and Natelson (in press).

Again, this is a case of conflicting results under similar schedules of reinforcement, this time with different reinforcers. These results lead to my second economic point—*reinforcers can be distinguished by their demand elasticity apart from differences in value,* where value is inferred from response rate in a standard defining situation (e.g., Premack, 1965). Allison, et al. (1979), Hogan and Roper (1978), Lea (1978), and Rachlin, et al. (1976) have noted the relevance of elasticity to the analysis of operant behavior. In this section I will underscore that observation with some selected data and will later integrate the concept of elasticity with the concept of substitution in open economies.

Economists have long stipulated that all commodities are not equally important to the consumer. Some are more essential than others. This difference can be expressed in terms of the shape of the demand curve, summarized in Figure 10. Consider the first three demand curves on the left. A demand curve that decays slowly with increasing price means that a big change in price (P) has a relatively small effect on consumption (Q). A demand curve that decays steeply with increasing price means that a small change in price has a big effect on quantity consumed or demanded. A gradually decaying demand curve is called *inelastic* demand; a steeply decaying curve is called *elastic* demand. For example, consumption of

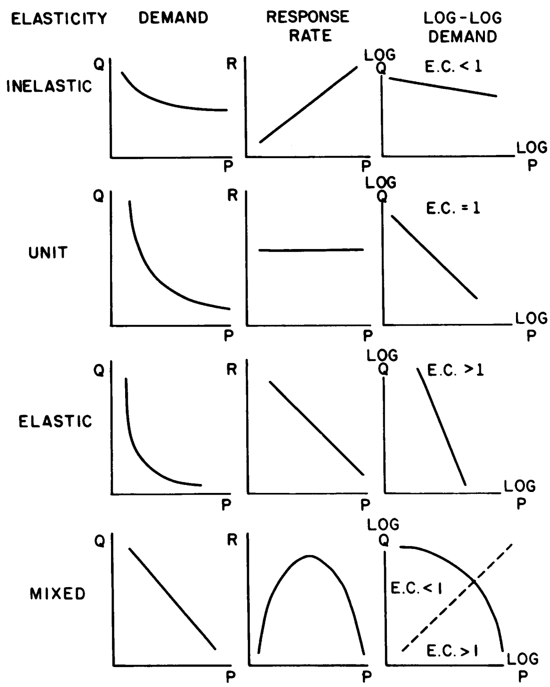

Fig. 10. Definitions of inelastic, unit elastic, elastic and mixed demand in terms of the demand curves, the response rate curves and the elasticity coefficients of the log-log demand curves (see text for explanation).

gasoline per capita has changed very little over the last ten years as the price of gasoline has quadrupled. In contrast, attendance at movies is greatly influenced by price. The boundary condition between these two categories is *unit* demand in which each change in price produces an equi-proportional change in quantity demanded (Watson & Holman, 1977, Chapter 3).

Response rate is mathematically determined by demand. It is the quantity consumed times the unit price. The relationship between demand and response rate is summarized in the center panels of Figure 10. If quantity demanded decays gradually with increases in price (P) then gross expenditure or response rate (R) will be an increasing function of price. For example, since demand for gasoline is *inelastic,* per capita expenditure for gasoline has increased with the increasing prices. If demand is a steeply decaying function, then, by contrast, response rate will be a decreasing function. For example, in some families the demand for fish is *elastic.* As price for fish has increased, they have nearly stopped eating it and their annual expenditures for fish have decreased over the years. A unit demand curve is that demand curve that generates a precisely flat level of expenditure or response rate with increasing price. Each increase in price is precisely balanced by a decrease in consumption.

The curvature of a demand curve can be defined precisely in terms of its slope scaled in double logarithmic units depicted on the right of Figure 10. Since nearly all demand curves slope downward, the slope is always negative. The absolute value of that slope is the *elasticity coefficient* (E. C.) and is less than 1 for inelastic demand, greater than 1 for elastic demand, and equal to 1 for unit demand.

The first three demand curves depicted in Figure 10 have the convenient property that elasticity is the same at all points along their extent, hence linear in logarithmic coordinates. Practical demand curves must curve in these coordinates as unit price approaches total income. Then one must speak of the elasticity at a point on the curve rather than of the slope of the entire function, hence the term point elasticity. The mixed elasticity case is shown in the bottom three panels of Figure 10. If the slope of a demand curve (disregarding sign) increases in log-log coordinates from an absolute value less than 1 to an absolute value greater than 1, then the response rate function will be bitonic. For example, a linear demand curve in *arithmetic* coordinates with a slope of -1, shown in the bottom left panel of Figure 10, changes from inelastic to elastic and yields a symmetrical bitonic response rate function. Other linear demand curves in arithmetic coordinates also change in elasticity from point to point and yield bitonic response rate functions with the point of maximum rate at different prices. The bitonic response rate functions predicted by Staddon (1979) are consistent with these kinds of demand curves. Inelastic, elastic, unit and mixed demand are all illustrated in the review of different reinforcers by Hogan and Roper (1978). A mathematical account of the relationship between demand and response rate is included in Appendix A.

Returning to the experiment with EBS and food on VI schedules, Figure 11 shows that the demand curve for EBS was elastic with a slope greater than 1 and that the demand curve for food was inelastic with a slope less than 1. As a result, response rate decreased for EBS and increased for food (see Figure 9). These

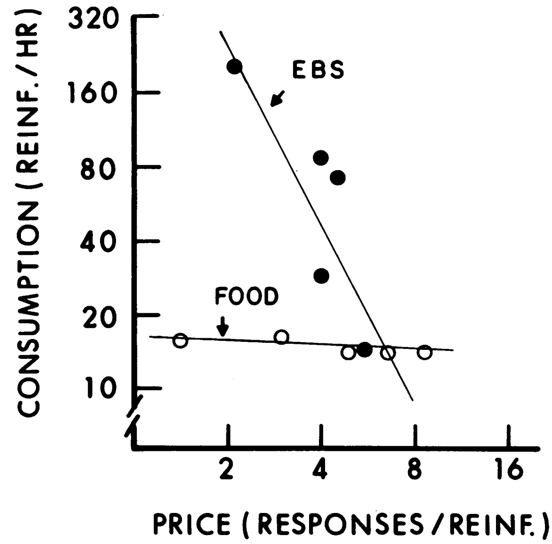

Fig. 11. Mean demand curves from three rats for electrical brain stimulation (EBS) and food reported by Hursh and Natelson (in press).

results with concurrent food and EBS can be contrasted with the results of a similar study by Hollard and Davison (1971). They also used concurrent VI schedules but found that behavior for food was essentially similar to behavior for brain stimulation. Their results do not represent a conflict with the data presented in Figures 9 and 11. Elasticity of demand is not an intrinsic property of the reinforcer, but a result of the economic context as well, a point I will return to again. Since Hollard and Davison (1971) studied behavior reinforced by food in an open economy, i.e., the subjects were maintained at 80% of ad lib weight by between-session feedings, demand for food was just as elastic as demand for brain stimulation.

The finding that EBS demand was elastic contrasts sharply with the finding that when EBS was freely available or nearly so on a VI 3-sec schedule it was highly valued compared to food; it maintained 20 times the response rate at VI 3-sec. So, the concept of elasticity is independent of the value of a reinforcer when freely available. For example, when the price of labor was low, many people had maids as well as doctors. When wages went up, most people gave up maids, an expendable service, but continued to see their doctor, a more essential and less elastic service. The elasticity of a commodity cannot be inferred from the gross expenditure, or response rate, for it

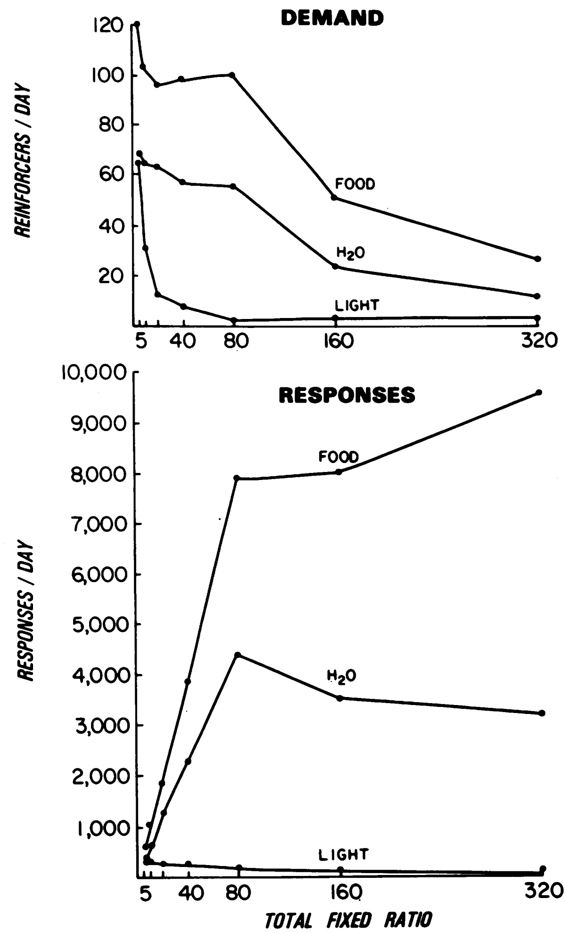

Fig. 12. Demand curves and response output functions for food, water, and light by one monkey working 24 hrs per day reported by Findley (1959).

under just one set of conditions (cf. Premack, 1965; Allison et al., 1979; Mazur, 1979).

This observation can be illustrated in a few other examples from the literature. The top panel of Figure 12 shows demand curves found by Findley (1959) for food, water, and general illumination by a monkey working in a continuous environment and closed economy. Demand for food and water decayed gradually as the number of responses per reinforcer was increased. As a result, response rate for these two commodities also increased, shown in the bottom panel. Demand for light decayed more steeply (top panel) so that, although it was of nearly equal value to water at FR 5, response rate decreased with increasing price (bottom panel). Its "value" became very low at high prices.

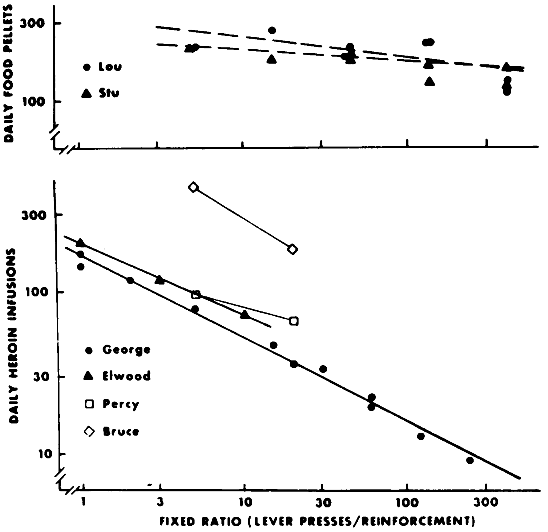

Fig. 13. Demand curves for food and heroin infusions from a group of monkeys working 24 hrs per day reported by Elsmore (Note 1).

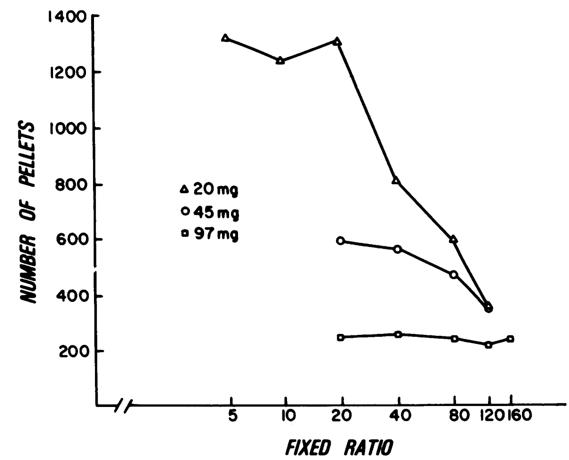

Fig. 14. Pellets consumed of various sizes as a function of fixed ratio by rats working 24 hrs per day reported by Hill (Note 2).

Another example is provided by Elsmore (Note 1, see Figure 13). Six monkeys worked in continuous environments and closed economies for either food pellets shown in the top panel or infusions of heroin shown in the bottom panel. Although both demand curves were inelastic, demand for food (top panel) decayed more gradually than demand for heroin (bottom panel) as price (FR size) was increased. These differences in elasticity led to differences in the growth of response rate with price. Food responding increased more steeply than heroin responding at the same prices. Unfortunately, these data are not conclusive with regard to the greater elasticity of heroin reinforcement since the subjects working for heroin had food freely available while those working for food reinforcement had no heroin available. Another part of Elsmore's study (Note 1) reported below, directly compared heroin reinforcement with food reinforcement and supports the notion that demand for heroin is more elastic than demand for food.

Highly valued commodities such as brain stimulation and heroin can be more elastic than a commodity such as food. This dimension of reinforcement can help explain how behavior for different commodities will often show divergent changes when opposed by similar environmental constraints expressed as price. In this sense, the concept of demand elasticity is similar to Nevin's (1974) concept of response strength. Yet it would be misleading to call them identical. The concepts of demand and demand elasticity can be viewed as part of a more general economic framework and have precise definitions within that framework. Demand interacts with the supply schedule to generate the stable equilibrium performance. Differences in elasticity of demand for different reinforcers produce divergent changes in response rate. Some additional applications of the concept of demand and elasticity can help explain other existing data, including the difference between open and closed economies.

When comparing the elasticities of different demand curves, it is essential that the units of price and consumption be commensurate. The results of a study by Hill (Note 2) illustrate this problem. Rats worked in a continuous environment or closed economy for food pellets provided on FR schedules. For different subjects, the food pellets were either 20, 45, or 97 mg in size. Figure 14 shows pellet consumption for each size pellet across different size ratios. These three curves appear to be ordered in terms of elasticity with demand for small pellets being more elastic than demand for large pellets. This implies, perhaps, that small pellets maintain a weaker performance. Unfortunately, these three functions are not commensurate demand curves. For example, a 20-mg package of food costing 80 responses is a more expensive price for food than a 97-mg package costing 80 responses. Likewise, 10 20-

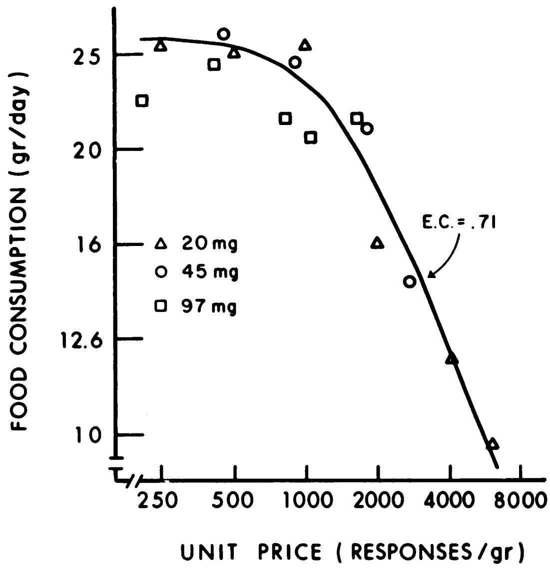

Fig. 15. Demand for food as a function of unit price across pellet sizes and consummatory ratios shown in Figure 14.

mg packages per day is a smaller consumption of food than 10 97-mg packages. To compare these three conditions, we must convert all prices to unit cost per gram of food and all quantities to grams of food per day. These curves would then be commensurate. Figure 15 shows that when converted to common units, all the points cluster about a common demand curve, the demand for food as a commodity class. Note that the x-axis is contracted for convenience and that the actual slope of the descending limb of the curve is less than 1.0 or *inelastic*.

The problem of units will not always be solved so easily. For example, if one commodity is obtained by pulling a chain and another is obtained by pressing a lever, it may be that the same number of responses per reinforcer would not represent equivalent functional prices. Perhaps this problem of units accounts for the difference between the demand curves obtained with interval compared to ratio supply schedules (see Figures 7 and 8). A similar problem has been discussed in relation to comparing generalization gradients (Blough, 1965).

True differences in demand elasticity can be revealed by a change in income. When income is reduced, one's consumption of luxuries is reduced while consumption of necessities is conserved. This may be explained by noting that when income goes down, all prices increase in terms of percent of income. If all prices go up, then consumption of elastic commodities will decline more rapidly than consumption of inelastic commodities. That effect has been described with concurrent performances for EBS and food (Hursh & Natelson, in press). As the VI schedules increased for both reinforcers, consumption of EBS declined while consumption of food was nearly constant (see Figure 11). Elsmore (Note 1) provides a more direct example of the effect of changing income on consumption of heroin and food by baboons in a 24-hr test situation. It had been observed previously that demand for heroin appeared to be more elastic than demand for food (see Figure 13). To test the effect of income, Elsmore gave each baboon a limited number of trials each day during which choice responses on one key would provide some food pellets or on another key would produce an infusion of heroin. Only one reinforcer was allowed per trial. Income was reduced by increasing the time between trials and reducing the number of trials during each day. Under those forced choice conditions, as trials per day were reduced, subjects gave up more heroin reinforcers than food reinforcers, suggesting again that demand for heroin was more elastic than demand for food. These results are summarized in Figure 16. On the x-axis are increasing intertrial intervals producing fewer trials per day. The y-axis is absolute choices for food and heroin. The broken lines show a smaller reduction in food choices than the steep decline in heroin choices shown as solid lines. As the number of trials declined an increasing proportion of this income was "spent" for food (a "necessity") while a constant proportion was "spent" for heroin (a "luxury"). This redistribution of choices among different commodities was the result of an interaction between different demand elasticities and changing income. In general, this implies that certain kinds of constraint applied uniformly to many reinforcers can produce redistributions of behavior that cannot be accounted for by a simple choice rule such as strict matching.

Demand for a single commodity does not have a fixed elasticity. Economists have identified a variety of factors which alter demand and demand elasticity apart from income. An example is provided by a reinterpretation of

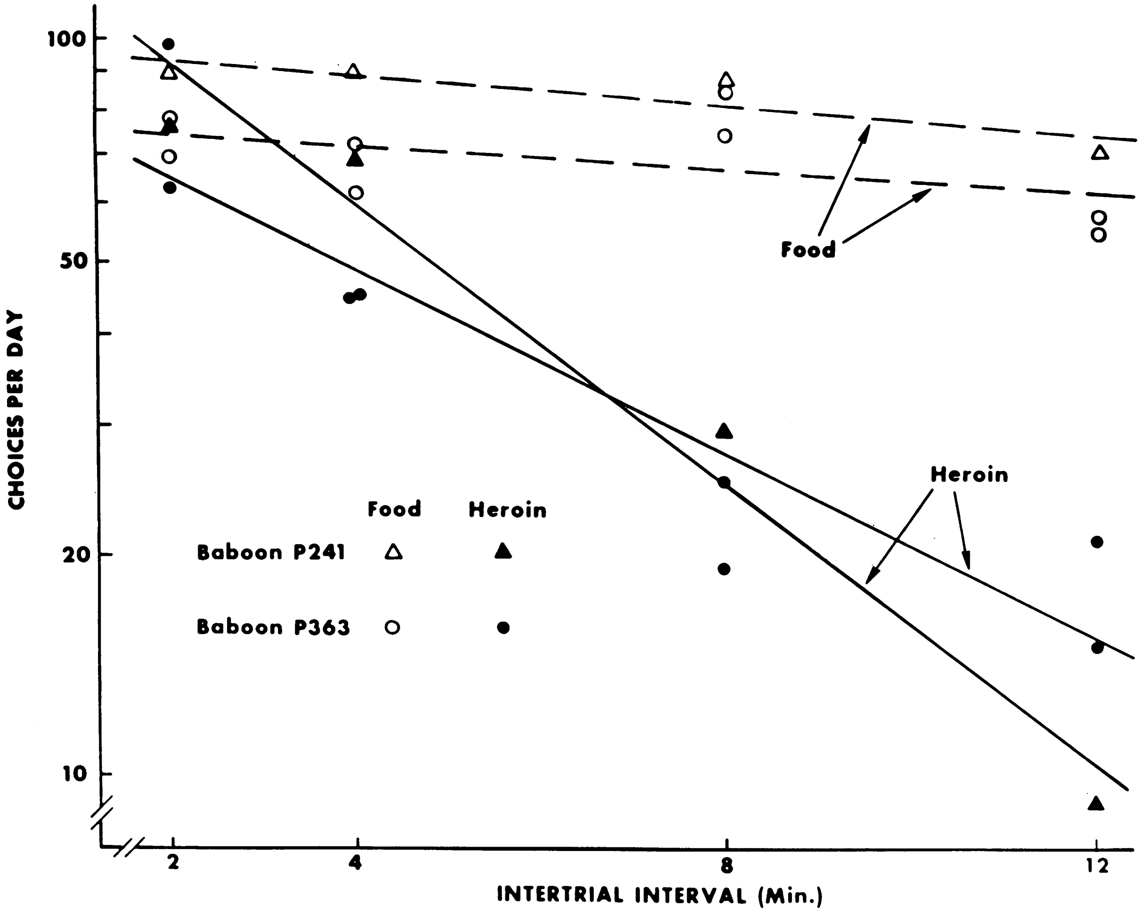

Fig. 16. Choices per day for food and heroin infusions as a function of intertrial interval (trials per day) by two baboons working 24 hrs per day. Data reported by Elsmore (Note 1).

an experiment reported by Roper (1975). Mice worked in short sessions for food pellets on FR schedules. Roper reported the quantities consumed (the demand curve) and the response rates. He introduced two unusual variables to this standard paradigm that altered demand elasticity. One factor, the distance between the lever and the food tray, may be conceptualized as a fixed tax per unit earned. The second factor was the amount of between-session feeding and length of deprivation. In Figure 17, top left panel, are demand curves for food with different bar-tray distances or "taxes." These curves were observed with 8 hrs of postsession feeding and 16 hrs of deprivation. The elasticity of demand—the degree of downward curvature—was increased by imposing larger bar-tray distances. With the largest distance, demand reached unity, on the verge of becoming elastic in qualitative terms. These different demand curves imparted different growth rates to the response rate functions (bottom left panel), with response rate increasing very little as a function of FR with the largest distance between bar and tray.

When Roper reduced the supply of substitutable food outside the session to 2 hrs, and increased deprivation to 22 hrs, the demand curves (Figure 17, top right panel) both increased in elevation to make up for the loss *and* decreased in elasticity at the intermediate bar-tray distance, converging with the other demand curve. The growth of response rate in the bottom right panel was increased also (note the y-axis units are doubled). So demand and demand elasticity are not immutable characteristics of a reinforcer, but are subject to change by other factors. What the

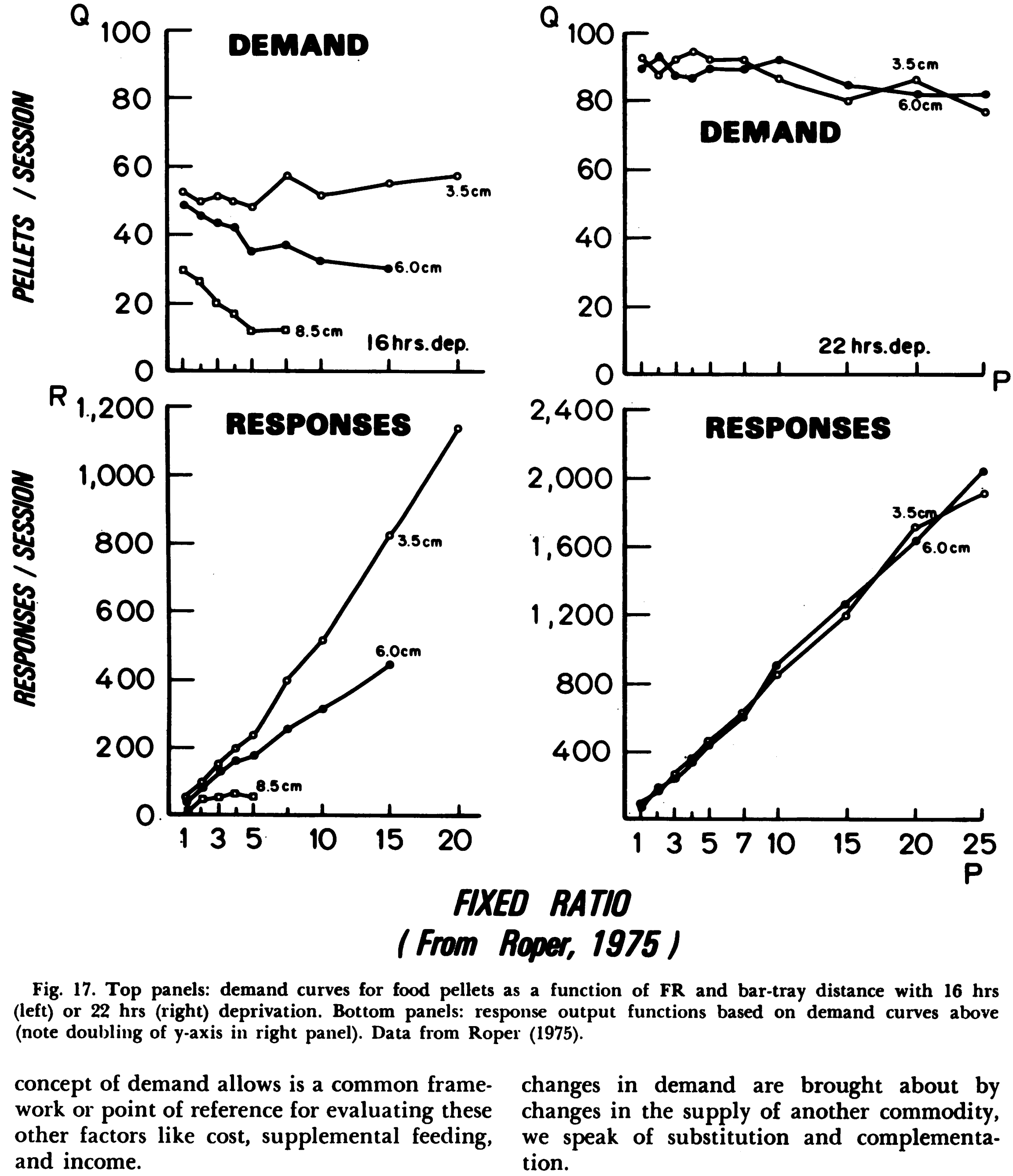

Fig. 17. Top panels: demand curves for food pellets as a function of FR and bar-tray distance with 16 hrs (left) or 22 hrs (right) deprivation. Bottom panels: response output functions based on demand curves above (note doubling of y-axis in right panel). Data from Roper (1975).

concept of demand allows is a common framework or point of reference for evaluating these other factors like cost, supplemental feeding, and income.

In summary, reinforcers can be distinguished by elasticity, apart from value inferred from response rate in a single situation. This feature can help to explain how response rate for different commodities can react quite differently to similar changes in supply or other environmental constraints, and how response rate for the same commodity may vary in sensitivity to environmental constraints. When these changes in demand are brought about by changes in the supply of another commodity, we speak of substitution and complementation.

SUBSTITUTES AND COMPLEMENTS

Most of the examples discussed so far have been from closed economies. In those situations, demand for food as a class is inelastic. Recall that in open economies in which food intake is held constant or supplemented, response rate for food declines with increases in price (see Figures 1 and 2). That would imply that in open economies, demand for food is elastic (see Figure 10). The change in elasticity brought about by the change in economic system leads to the next point. Demand is subject to change by alterations of the supply of other commodities. In the case of open economies, total consumption of food is usually the result of both the animal's performance during the sessions and some gratuitous supply provided by the experimenter —like a welfare check. That welfare check can substitute for earned food and will reduce demand. This interaction is called substitution. In the case of many open economies, substitution from other sources occurs to such a degree that demand for food in the session is elastic and response rate declines with increases in price or the VI schedule. For example, Hursh (1978) studied demand for food by monkeys in both closed and open economies. Response rate increased with increasing VI schedules in the closed economy and decreased with increasing VI schedules in the open economy. Figure 18 shows that those differences in response rate functions could be derived from the different demand curves in those two experiments. In the closed economy with no substitutable food outside the session, demand (d_2) was *inelastic;* in the open economy with constant food intake arranged by the experimenter, demand (d_1) was *elastic.* Figure 18 also shows a difference in *level* of demand with d_1 (open economy) higher at most points than d_2 (closed economy). This has less to do with the type of economies than with the specific session length chosen for the closed economy experiment. Had the experiment allowed less time for working, it is likely that greater demand in terms of reinforcers per hour would have been observed. The session length used (about 100 minutes) was just long enough so that at the lowest supply (VI 60-sec) a high rate of response would provide enough food to maintain good health.

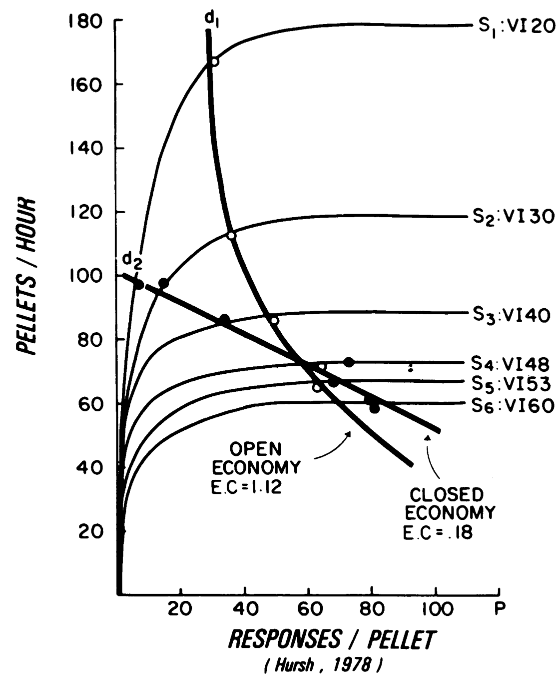

Fig. 18. Demand curves for food pellets determined with varying VI schedules in a closed economy (closed circles) and an open economy (open circles). Data are from Hursh (1978), Experiments I and II; computations are explained in legend of Figure 8.

These results illustrate demand interactions, the third point: *reinforcers can interact as substitutes and as complements.* Hursh (1978) reported a set of experiments in which two monkeys worked concurrently on two VI schedules for food and one VI schedule for water. One food schedule and the water schedule were constant at VI 60-sec. The value of the second VI food schedule was varied. A demand interaction would be indicated by changes in response rate under the constant food and water schedules as the supply of food from the third alternative, food source 2, was increased. Of interest was how this increasing supply of food from one schedule would change response rate for the alternatives on constant schedules. Responding for one food declined steeply as the supply from the alternative source was increased. This implied a reduction in demand for this source of food as food from a substitutable source increased. This interaction is called substitution (cf. Bernstein & Ebbesen, 1978; Rachlin, et al., 1976; Rachlin & Burkhard, 1978; Lea & Roper, 1977). On the other hand, response rate for water increased with the increased supply of food. Food and water are noted as complementary commodities. When food supply increased, water demand and response rate increased. This interaction is called complementarity (cf. Lea, 1978). For example, public officials hope to reduce commuting by private vehicle by increasing the supply of the *substitute,* public transportation,

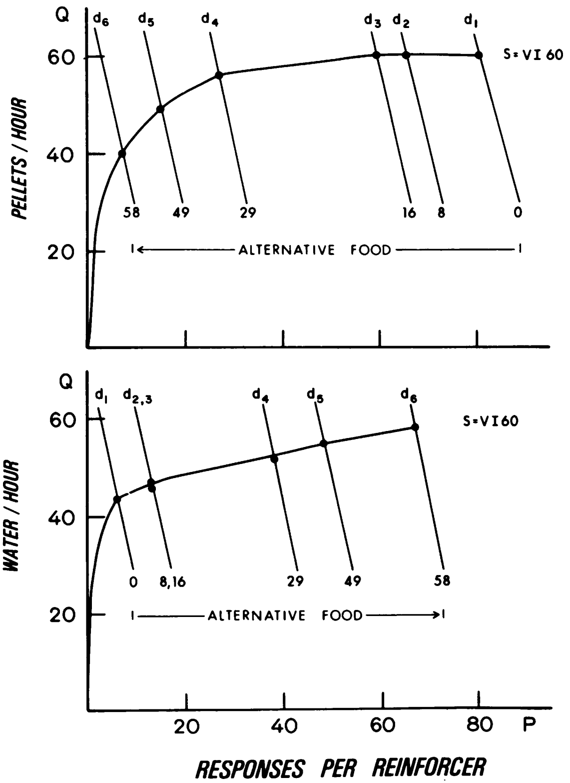

Fig. 19. Top panel: *Substitution*—reductions in demand for one food source (d_1, d_2, d_3, etc.) as a function of increases in the supply (and reductions in price) of a substitutable food source (8, 16, 29, etc. pellets per hr). Bottom panel: *Complementation*—increases in demand for water (d_1, d_2, d_3, d_4, etc.) as a function of increases in the supply (and reductions in price) of a complementary commodity—food. Data from Hursh (1978).

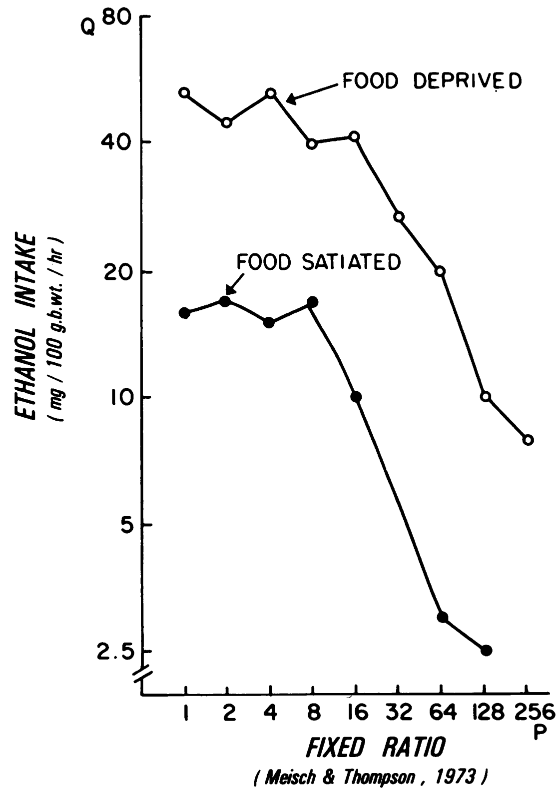

Fig. 20. Increase in demand for ethanol when shifted from a food satiated baseline to a food deprived baseline. Data from Meisch and Thompson (1973) replotted in log-log coordinates.

and by reducing the supply of the *complement,* cheap downtown parking.

Substitution and complementation are diagramed in economic terms in Figure 19. Substitution is shown in the top panel. The obtained quantity of Food 1 on the VI 60-sec supply schedule is plotted as a function of price paid. Each point represents a different equilibrium point resulting from intersections of the constant VI 60-sec supply schedule with different hypothetical Food 1 demand curves. The quantity of substitutable food available from the other food schedule is noted under each demand curve. As the substitutable supply increased, demand shifted to the left. The subject would not pay as high a price for food from this source when food at a lower price was available concurrently.

In the bottom panel of Figure 19, the very same scheme is presented for food's complement, water. In this case just the opposite change in demand occurred; as the supply of food, the complement of water, increased from zero to 58 pellets per hour, the demand for water moved to the right. The subject paid an increasing price for water to complement the increasing supply of food. The same commodity that substituted for food and reduced demand, complemented water and increased demand. This is a third case in which two responses under similar schedules of reinforcement (but for different commodities) were affected differently by a common variable—in this case, a change in a third schedule of reinforcement.

In these diagrams, the complete demand curves were entirely hypothetical. The equilibrium was observed only at one point. An application of this concept to some other data can provide a more complete illustration of substitution (Figure 20). These data are from Meisch and Thompson (1973) replotted in log-log coordinates to permit comparisons of elasticity. They studied rats drinking ethanol under FR supply schedules. When food satiated, the subject's demand was low as in the filled circles. When access to food was restricted, demand for ethanol increased uniformly. Here, the calories from the ethanol substituted for calories lost from food so that a restriction in food led to an increase in demand for the substitute ethanol. Note that elasticity of demand (the slope) in this case was not altered. Generally, in open economies where a supplemental supply is provided, this supply will alter demand in the test session by substitution. This can reduce demand. When the amount of a substitutable supply is varied across conditions to maintain constant weight or intake, there will be an apparent increase in elasticity of demand within the test situation. This explains the decreasing response rate functions found by Felton and Lyon (1966) and Catania and Reynolds (1968) shown in the first two figures. They provided a substitutable source of food between sessions that made demand for food in the sessions elastic.

ECONOMICS AND CHOICE

The concepts of substitution and complementarity are more than just useful tools for explaining shifts in demand and differences

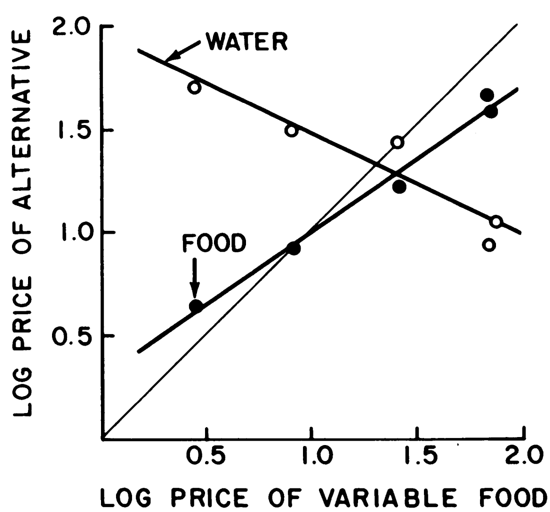

Fig. 21. In logarithmic units, the price paid for food (filled circles) and water (unfilled circles) both on VI 60-sec schedules as a function of changes in the price paid for a second food available on various VI schedules. Data from Hursh (1978).

between open and closed economies. The very fact that commodities can interact in these quite opposite ways has important implications for any general theory of choice. It will be shown that *no simple, unidimensional rule of choice such as strict matching can explain interactions between reinforcers if some interact as substitutes and others interact as complements* (cf. Herrnstein, 1970). Perfect matching can *only* occur when choice is between perfect substitutes; for example, between two members of a single class of commodities such as between two similar foods. The following simple equations substantiate that assertion. The ratio form of the matching law (Baum, 1974) states that the ratio of choice responses equals the ratio of consumptions:

$$\frac{R_1}{R_2} = \frac{Q_1}{Q_2}$$

By simple algebra this implies that responses per reinforcer for one is equal to responses per reinforcer for the other:

$$\frac{R_1}{Q_1} = \frac{R_2}{Q_2}$$

Since, by definition, responses per reinforcer is the same as price this means that the prices paid for the two commodities are always equal in any situation. Only if the two commodities interact as perfect substitutes will the prices paid always be equal. The equality of price, or probability of reinforcement, under situations of strict matching has been noted before (e.g., Revusky, 1963; Herrnstein & Loveland, 1975). The essential point here is that this equality of price is a special case of choice between perfect substitutes.

The data from Hursh (1978, Experiment 1) with two foods and one water will illustrate this conclusion. In Figure 21, I have plotted the price of the food from the constant schedule, filled circles, as a function of the price for the substitutable food on the varied schedule (log-log coordinates). The results are means of two monkeys' data. If the subjects matched prices the points would fall on the diagonal. The subjects did not precisely match prices for food; they were not perfect substitutes but a strong correlation in prices was noted ($r = .98$), a form of imperfect substitution (and matching). Other cases of "under-matching" on concurrent variable-interval schedules also may be indicative of less than perfect substitution between the alternatives (Lobb & Davison, 1975; Myers & Myers, 1977).

I have also plotted in Figure 21 the prices paid for water, unfilled circles, as a function of the price of the variable food. In this case, prices were inversely correlated ($r = -.95$); the subjects did not match. Instead, the complementary interaction between food and water produced the opposite of matching.

The cross-price relation has many of the features of the log-ratio relation proposed by Baum (1974) for evaluating the matching law. The cross-price relation has the added advantage of clearly denoting the dependent nature of both the x and y variables. In the economic context, the cross-price relation is a simple method for evaluating the nature of a demand interaction (substitute, complement, or independent) between two commodities. Figure 21 is based on the cross-price relations in a closed economy (Hursh, 1978, Experiment 1). The cross-price relation between food and water is somewhat different in an open economy. When the consumptions of food and water were arbitrarily held constant (Hursh, 1978, Experiment 2), the price of water was independent of (did not match) the price of the variable food. The cross-price relation between the two foods was unaffected.

The failure of matching to extend to another class of reinforcers suggests that matching is only a valid choice rule for mutually substitutable commodities. When considering choice among a broad set of commodities, no simple rule based on a single quantity such as "value" will describe all choices. All interactions are not homogeneous. In particular, it would not be generally valid to lump all alternatives into a single summed class (e.g., Herrnstein, 1970) when computing the outcome of a choice among a variety of alternatives. One could retain the concept of a unitary choice rule if one assumes that the subject chooses among various psychological "values" or "marginal utilities" rather than concrete commodities (Rachlin, 1971; Samuelson, 1976, pp. 432-437). This approach, however, merely moves the interaction concepts of substitution and complementarity back one step to the point of determining "value" or "marginal utility." Preservation of a unitary choice rule introduces an additional hypothetical concept and does not eliminate heterogeneous interactions.

SUMMARY

1. The economic system arranged by the experimenter can determine the results. The two general systems defined are open and closed economies. In closed economies, the subject's consumption is a direct result of the equilibrium of his demand with the environment's supply.

2. Different reinforcers can be distinguished by elasticity of demand which is independent of reinforcer value. Inelastic commodities show small changes in consumption with large increases in price. In closed economies, demand for some reinforcers will be inelastic and demand for others will be elastic. In open economies, demand tends to be more elastic for all commodities because the experimenter provides a substitutable source of supply.

3. Reinforcers may interact as substitutes and as complements. An increase in supply (or reduction in price) of one commodity will lead to a reduction in demand for substitutes and an increase in demand for complements.

4. Heterogeneous interactions imply that no simple, unidimensional choice rule can account for all choice behavior. Strict matching is a special case of choice between perfect substitutes.

APPENDIX A

The relationship between the demand curves and the response rate functions shown in Figure 10 can be explained mathematically. Consider the first three cases of demand curves that are linear in logarithmic coordinates:

$$\log Q = b - a \log P \tag{1}$$

where P is price, a is the elasticity coefficient (E.C.), b is the y-intercept and Q is the quantity consumed. Since response rate (R) is the unit price (P) times the quantity consumed (Q), we have the following equation for response rate in logarithmic coordinates:

$$\log R = \log P + \log Q \tag{2}$$

Substituting the value of $\log Q$ from equation (1) into equation (2) and rearranging terms, we have the following linear expression for response rate:

$$\log R = b + (1 - a) \log P \tag{3}$$

When demand is inelastic and the elasticity coefficient of the demand curve, a, is less than 1, then the slope of the response rate function is positive. When demand is elastic and a is greater than 1, then the slope of the response rate function is negative. When a is equal to 1 (unit demand), then the response rate function is equal to the constant, b.

Consider now the case of linear demand in arithmetic coordinates:

$$Q = b - a\,P \tag{4}$$

Response rate in arithmetic coordinates is the following:

$$R = P \cdot Q \tag{5}$$

Substituting the value of Q from equation (4) into equation (5) we have:

$$R = b\,P - a\,P^2 \tag{6}$$

This quadratic equation for response rate is bitonic with the price yielding maximum rate depending on the y-intercept, b, and the slope of the demand curve, a, in arithmetic coordinates. The ascending limb of the response rate function corresponds to the inelastic portion of the demand curve; the descending limb corresponds to the elastic portion of the demand curve.

REFERENCE NOTES

1. Elsmore, T. Evaluating the strength of heroin-maintained behavior. Invited address, meeting of the Association of Behavior Analysis, Dearborn, Michigan, 1979.
2. Hill, W. L., & Collier, G. H. The economics of response rate as a feeding strategy. Paper presented at the meeting of the Eastern Psychological Association, Washington, D.C., 1978.

REFERENCES

Allison, J., Miller, M., & Wozny, M. Conservation in behavior. *Journal of Experimental Psychology: General,* 1979, **108,** 4-34.

Barofsky, I., & Hurwitz, D. Within ratio responding during fixed ratio performance. *Psychonomic Science,* 1968, **11,** 263-264.

Baum, W. M. The correlation-based law of effect. *Journal of the Experimental Analysis of Behavior,* 1973, **20,** 137-153.

Baum, W. M. On two types of deviation from the matching law: Bias and undermatching. *Journal of the Experimental Analysis of Behavior,* 1974, **22,** 231-242.

Bernstein, D., & Ebbesen, E. Reinforcement and substitution in humans: A multiple-response analysis. *Journal of the Experimental Analysis of Behavior,* 1978, **30,** 243-253.

Blough, D. S. Definition and measurement in generalization research. In: D. I. Mostofsky (Ed.), *Stimulus generalization.* Stanford: Stanford University Press, 1965.

Catania, A. C., & Reynolds, G. A quantitative analysis of the responding maintained by interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior,* 1968, **11,** 327-383.

Collier, G. H., Hirsch, E., & Hamlin, P. H. The ecological determinants of reinforcement in the rat. *Physiology and Behavior,* 1972, **9,** 705-716.

Collier, G., & Jennings, W. Work as a determinant of instrumental performance. *Journal of Comparative and Physiological Psychology,* 1969, **68,** 659-662.

Felton, M., & Lyon, D. O. The post-reinforcement pause. *Journal of the Experimental Analysis of Behavior,* 1966, **9,** 131-134.

Findley, J. D. Behavior output under chained fixed-ratio requirements in a 24-hour experimental space. *Journal of the Experimental Analysis of Behavior,* 1959, **2,** 258.

Graft, D. A., Lea, S. E. G., & Whitworth, T. L. The matching law in and within groups of rats. *Journal of the Experimental Analysis of Behavior,* 1977, **27,** 183-194.

Hamilton, C. L., & Brobeck, J. R. Hypothalamic hyperphagia in the monkey. *Journal of Comparative and Physiological Psychology,* 1964, **57,** 271-278.

Hearst, E., Koresko, M. B., & Poppen, R. Stimulus generalization and the response-reinforcement contingency. *Journal of the Experimental Analysis of Behavior,* 1964, **7,** 369-380.

Herrnstein, R. J. Relative and absolute strength of response as a function of frequency of reinforcement. *Journal of the Experimental Analysis of Behavior,* 1961, **4,** 267-272.

Herrnstein, R. J. On the law of effect. *Journal of the Experimental Analysis of Behavior,* 1970, **13,** 243-266.

Herrnstein, R. J. Derivatives of matching. *Psychological Review,* 1979, **86,** 486-495.

Herrnstein, R. J., & Loveland, D. H. Maximizing and matching on concurrent ratio schedules. *Journal of the Experimental Analysis of Behavior,* 1975, **24,** 107-116.

Heyman, G. M., & Luce, R. D. Operant matching is not a logical consequence of maximizing reinforcement rate. *Animal Learning and Behavior,* 1979, **7,** 133-140.

Hogan, J. A., & Roper, T. J. A comparison of the properties of different reinforcers. *Advances in the Study of Behavior,* 1978, **8,** 155-255.

Hollard, V., & Davison, M. D. Preference for qualitatively different reinforcers. *Journal of the Experimental Analysis of Behavior,* 1971, **16,** 375-380.

Hursh, S. R. The economics of daily consumption controlling food- and water-reinforced responding. *Journal of the Experimental Analysis of Behavior,* 1978, **29,** 475-491.

Hursh, S. R., & Natelson, B. J. Electrical brain stimulation and food reinforcement dissociated by demand elasticity. *Physiology and Behavior,* in press.

Lea, S. E. G. The psychology and economics of demand. *Psychological Bulletin,* 1978, **85**, 441-466.

Lea, S. E. G., & Roper, T. J. Demand for food on fixed-ratio schedules as a function of the quality of concurrently available reinforcement. *Journal of the Experimental Analysis of Behavior,* 1977, **27**, 371-380.

Lobb, B., & Davison, M. C. Performance in concurrent interval schedules: A systematic replication. *Journal of the Experimental Analysis of Behavior,* 1975, **24**, 191-197.

Logan, F. A. The free behavior situation. In D. Levine (Ed.), *Nebraska Symposium on Motivation* (Vol. 12). Lincoln: University of Nebraska Press, 1964.

Mazur, J. The value-averaging model: An alternative to "conservation in behavior." *Journal of Experimental Psychology: General,* 1979, **108**, 43-47.

Meisch, R. A., & Thompson, T. Ethanol as a reinforcer: Effects of fixed-ratio size and food deprivation. *Psychopharmacologia,* 1973, **28**, 171-183.

Moran, G. Severe food deprivation: Some thoughts regarding its exclusive use. *Psychological Bulletin,* 1975, **82**, 543-557.

Myers, D. L., & Myers, L. E. Undermatching: A reappraisal of performance on concurrent variable-interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior,* 1977, **27**, 203-214.

Nevin, J. A. Response strength in multiple schedules. *Journal of the Experimental Analysis of Behavior,* 1974, **21**, 389-409.

Premack, D. Reinforcement theory. In D. Levine (Ed.), *Nebraska Symposium on Motivation* (Vol. 13). Lincoln: University of Nebraska Press, 1965.

Rachlin, H. On the tautology of the matching law. *Journal of the Experimental Analysis of Behavior,* 1971, **15**, 249-251.

Rachlin, H., & Burkhard, B. The temporal triangle: Response substitution in instrumental conditioning. *Psychological Review,* 1978, **85**, 22-47.

Rachlin, H., Green, L., Kagel, J. H., & Battalio, R. C. Economic demand theory and psychological studies of choice. In G. H. Bower (Ed.), *The Psychology of Learning and Motivation* (*Vol. 10*). New York: Academic Press, 1976.

Revusky, S. H. A relationship between responses per reinforcement and preference during concurrent VI VI. *Journal of the Experimental Analysis of Behavior,* 1963, **6**, 518.

Roper, T. J. Nest material and food as reinforcers for mixed-ratio responding in mice. *Learning and Motivation,* 1975, **6**, 327-343.

Samuelson, P. A. *Economics* (10th ed.). New York: McGraw-Hill, 1976.

Skinner, B. F. *Science and Human Behavior.* New York: The Free Press, 1953.

Staddon, J. E. R. Operant behavior as adaptation to constraint. *Journal of Experimental Psychology: General,* 1979, **108**, 48-67.

Staddon, J. E. R., & Motheral, S. On matching and maximizing in operant choice experiments. *Psychological Review,* 1978, **85**, 436-444.

Watson, D. S., & Holman, M. A. *Price theory and its uses* (4th ed.). Boston: Houghton Mifflin, 1977.

Received November 26, 1979
Final acceptance April 18, 1980