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THREE PREDICTIONS OF THE ECONOMIC CONCEPT OF UNIT PRICE IN A CHOICE CONTEXT

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Economic theory makes three predictions about consumption and response output in a choice situation: (a) When plotted on logarithmic coordinates, total consumption (i.e., summed across concurrent sources of reinforcement) should be a positively decelerating function, and total response output should be a bitonic function of unit price increases; (b) total consumption and response output should be determined by the value of the unit price ratio, independent of its cost and benefit components; and (c) when a reinforcer is available at the same unit price across all sources of reinforcement, consumption should be equal between these sources. These predictions were assessed in human cigarette smokers who earned cigarette puffs in a two-choice situation at a range of unit prices. In some sessions, smokers chose between different amounts of puffs, both available at identical unit prices. Individual subjects' data supported the first two predictions but failed to support the third. Instead, at low unit prices, the relatively larger reinforcer (and larger response requirement) was preferred, whereas at high unit prices, the smaller reinforcer (and smaller response requirement) was preferred. An expansion of unit price is proposed in which handling costs and the discounted value of reinforcers available according to ratio schedules are incorporated.

Key words: behavioral economics, unit price, drug self-administration, delay discounting, matching law, plunger pull, humans

Two variables known to affect operant behavior are the number of responses required per reinforcer (e.g., Felton & Lyon, 1966; Ferster & Skinner, 1957) and the magnitude of the reinforcer (e.g., DeGrandpre, Bickel, Hughes, Layng, & Badger, 1993; Shettleworth & Nevin, 1965). From an economic perspective (i.e., labor-supply theory and consumer-demand theory) (e.g., Hursh, 1980; Kagel, Battalio, & Green, 1995) these variables are viewed as *costs* and *benefits,* respectively. Within economics, the ratio of costs over benefits (i.e., response requirement divided by reinforcer magnitude) is defined as the unit price of the good. Thus, the unit price of a single food pellet is 10 if three pellets are delivered contingent upon completing a fixed-ratio (FR) 30.

Economic labor-supply and consumer-demand theories (henceforth referred to as "economic theory") make predictions regarding the effects of unit price on response output, response allocation (choice), and consumption maintained by those reinforcers. First, increasing the unit price of a reinforcer decreases consumption of that reinforcer, all else being equal (e.g., Samuelson & Nordhaus, 1985). When plotted on logarithmic axes (Figure 1, top panel), consumption is typically a positively decelerating function of unit price increases, regardless of the species and reinforcer investigated (e.g., Bickel, DeGrandpre, Higgins, & Hughes, 1990; Collier, Hirsch, & Hamlin, 1972; Deaton & Muelbauer, 1980). The bottom panel of Figure 1 illustrates the relation between unit price and responding maintained under ratio schedules of reinforcement. As unit price is increased, responding increases to a maximum and further price increases decrease responding.

A second prediction made by economic theory is that unit price determines consumption and response output regardless of the specific values of the cost and benefit components of the ratio (Bickel, DeGrandpre, Hughes, & Higgins, 1991; Hursh, Raslear, Shurtleff, Bauman, & Simmons,

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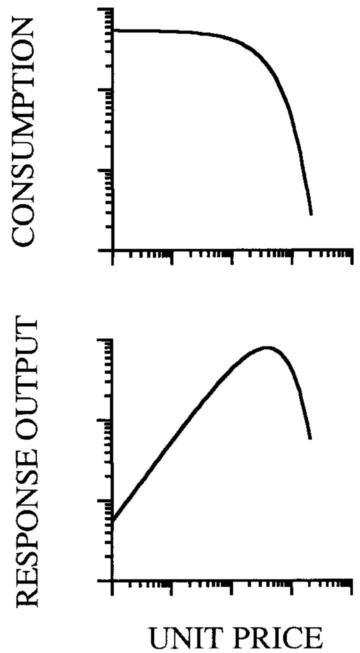

Fig. 1. Hypothetical data showing the relations typically observed between unit price and per session consumption (top panel) and total responding (bottom panel). Note the logarithmic axes in both panels.

1988; Kagel et al., 1995). For example, consumption and response output should be approximately equivalent under the following two contingencies because the unit price of a single food pellet is 10 responses in both cases: (a) three pellets delivered after completing an FR 30 and (b) five pellets delivered after an FR 50. Laboratory research with nonhuman food- and drug-maintained behavior has generally supported this prediction (Allison, Miller, & Wozny, 1979; Bickel et al., 1990; Carroll, Carmona, & May, 1991; Hursh et al., 1988; although see Nader, Hedeker, & Woolverton, 1993). Likewise, investigations of human drug (cigarette) consumption have also supported this prediction (e.g., Bickel et al., 1991).

From an economic perspective, these first two predictions are also applicable to total consumption and response output in a choice situation (Bickel & Madden, 1999). Specifically, if access to a commodity is unconstrained, total consumption and responding maintained by the commodity are, all else being equal, determined by the level of consumption at which satiation is reached (see Pearce, 1989, for an economic definition of satiation). From an economic perspective, the number of sources from which these commodities may be obtained is inconsequential; as long as the consumer is sated, further access to the commodity lacks utility. If access to the commodity is constrained (e.g., through a price increase), however, consumption and response output are affected by the obtained level of constraint (e.g., the price at which the commodity is actually purchased) and satiation is not a factor as long as the level of constraint is sufficient to reduce consumption below unconstrained levels. Again, whether the commodity is available from one or more sources is inconsequential; the important factor is the overall constraint placed on consumption (i.e., obtained unit price: total response output divided by total consumption).

Evidence supporting the first two economic predictions in a choice situation was gathered by Bickel and Madden (1999). Total consumption and response output were assessed in single- and concurrent-schedule conditions across a range of unit prices. The number of cigarette puffs obtained at each reinforcer delivery varied across single- and concurrent-schedule conditions, but obtained unit price (i.e., total response output divided by total puffs smoked per session) was yoked (and thus equated) across conditions. Consumption and response output were systematically affected by unit price, but few significant differences were detected between single- and concurrent-schedule conditions. Behavior was apparently unaffected by the different values of the cost and benefit components of unit price arranged across conditions.

A third prediction made by economic theory explicitly concerns choice: When choosing between two qualitatively identical reinforcers available at different unit prices (i.e., wage rates), behavior will be exclusively allocated to the alternative with the lower unit price (higher wage rate) (Becker, 1971; Samuelson & Nordhaus, 1985). Thus, if choosing between an FR 30 for three pellets (unit price = 10) and an FR 60 for three pellets (unit price = 20), steady-state behavior should be exclusively allocated to the first alternative. Experiments conducted with unequal variable-ratio (e.g., Herrnstein & Love-

Table 1

Demographic characteristics of subjects including scores on the Fagerström (1978) Tolerance Questionnaire (FTQ) and preexperiment exhaled carbon monoxide (CO) content.

Subject	Gender	Age	Cigarettes smoked per day	Years smoking	FTQ	Preexperiment CO (ppm)
S1	F	37	20	27	6	25
S2	M	24	30	10	6	35
S3	M	37	40	25	9	39
S4	F	24	20	9	8	29

land, 1975) or FR (e.g., Green, Rachlin, & Hanson, 1983) schedule values have verified this prediction. Likewise, in choice situations in which different reinforcer magnitudes are available at the same schedule value, behavior is nearly exclusively allocated to the alternative with the relatively larger amount of food (e.g., Neuringer, 1967) or the relatively larger dose of drug (e.g., Johanson & Schuster, 1975).

According to this third prediction of economic theory, given a choice between identical reinforcers (i.e., perfect substitutes), both available at the same unit price, behavior should be indifferent between them; that is, there should be no systematic allocation of behavior in favor of one or the other alternative. Applying the second prediction of economic theory to choices between alternatives of equal unit price, we would predict indifference regardless of the particular values of the cost and benefit components of unit price. The latter represents a more stringent test of economic theory than simple choices between small reinforcers versus large, or small work requirements versus large, because arranging different reinforcer magnitudes also requires that response requirement be manipulated. For example, if reinforcers are arranged according to an FR 50 for five food pellets on the left and on an FR 20 for two food pellets on the right (unit price = 10 in both cases), then behavior will be indifferent between the left and right alternatives if behavior is equally controlled by reinforcer magnitude and response requirement (as prescribed by unit price). If behavior is distributed systematically in favor of one of the alternatives, however, then one must conclude that the relative contributions of costs and benefits to unit price are not equal.

The present experiment assessed these three predictions of unit price in human subjects using cigarette-smoking procedures similar to those employed when unit price has been found to determine cigarette consumption (e.g., Bickel et al., 1991). In all sessions smokers were allowed to choose between two concurrent schedules of cigarette access. Unit price was manipulated across at least a 10-fold range across sessions. The first prediction of economic theory was assessed by plotting total consumption and response output (i.e., summed across the concurrently available sources of reinforcement) across the unit price range. The second economic prediction was assessed by examining total cigarette consumption across the range of unit prices at which behavior was maintained. At each unit price, three different cost and benefit components of unit price were presented. The third prediction was assessed by examining choice between cigarette alternatives with equal and unequal unit prices. When cigarettes were available at the same unit price from both alternatives, the schedule of reinforcement and reinforcer magnitude were unequal across alternatives (e.g., FR 66 for three puffs [unit price = 22] vs. FR 198 for nine puffs [unit price = 22]). This allowed us to assess the combination of the second and third predictions, as discussed above. Preference between alternatives with equal and unequal unit prices was assessed at a range of unit prices.

METHOD

Subjects

Four human cigarette smokers were recruited via newspaper advertisements and consented to participate for $10 per hour in compensation. Demographic characteristics of each subject are presented in Table 1; in general, they were frequent smokers, in good health, with no current psychiatric or drug- or alcohol-abuse problems. Subjects were instructed to abstain from using psychoactive medications and illicit drugs during the experiment, but no drug screenings were conducted.

Apparatus

Participants worked alone in small rooms equipped with a response panel, computer, and monitor. Three Lindsley plungers (Gerbrands G6310) were mounted in a row, equidistant on the vertical face of the panel. Each plunger could be completely pulled with approximately 6 N of force. An Apple IIe® microcomputer collected data and presented stimulus events. A volumetric low-pressure transducer (Grass Instruments, Model PT5) was modified to measure the volume of cigarette smoke inhaled through a plastic cigarette holder fitted to the filter end of a cigarette. Participants smoked their preferred brand of cigarettes in all sessions (provided by the experimenter). Breath carbon monoxide (CO) levels were measured using a Bedfont EC50 Micro Smokerlyzer. Magazines, newspapers, and a radio were available during all sessions.

Procedure

Subjects completed one 3-hr session 5 days per week. Before the sessions, subjects abstained from smoking for 5 to 6 hr. Abstinence was verified by taking a breath sample that was analyzed for CO content (CO in expired air is correlated with amount of recent cigarette smoking; Henningfield, Stitzer, & Griffiths, 1980). To participate in a session, CO content had to be at or below 50% of a baseline reading taken at intake. If subjects failed to meet this criterion, the session was rescheduled. Next, a subject took one cigarette puff and waited 30 min before starting; this equated the time since the last cigarette across subjects (Henningfield & Griffiths, 1981). During this period, subjects were given an instruction sheet that specified response requirements and number of puffs that could be earned by responding on each plunger (see the Appendix).

The words LEFT, CENTER, and RIGHT appeared in their respective locations on the computer screen and corresponded to the three plungers. Below each of these words a number showed how many times puffs had been earned by completing the response requirement arranged on that plunger. At all times except when subjects were smoking, the text ''You may respond now'' appeared at the bottom of the screen. The time remaining in the session, in minutes, was shown in the upper left portion of the screen.

To decrease the probability that position preferences would develop, we prompted alternation between the center and right response plungers after each bout of cigarette smoking. Prompts consisted of an on-screen description of the response requirement and the number of puffs available on the center or right plunger. For example, the text ''X puffs for Y pulls'' appeared on the screen below the word CENTER when the computer prompted responding on the center plunger (the programmed number of puffs and FR value were substituted for X and Y, respectively). In addition, when prompted to respond on the center plunger, responding on the right plunger was ineffective.

Subjects were given the opportunity to override the computer prompts by completing an FR 5 on the left plunger. That is, if prompted to respond on the center plunger, subjects could deactivate the center plunger and activate the right plunger by pulling the left plunger five times. When the FR 5 was completed, the on-screen prompt was relocated to the other position on the screen. If the FR 5 was completed a second time, the prompts returned to their original configuration. An FR 5 was selected because it could be completed in about 1 or 2 s and it prevented accidental switching.

In the first session, subjects learned to smoke according to a standard puffing procedure. FR 6 schedules were programmed on the center and right plungers, and the computer prompted alternation after each round of puffs. Completing either ratio requirement allowed six puffs. This allowed us to assess position preferences beyond those controlled by the prompts to switch between alternatives. At the beginning of this session, the computer prompted S2 and S3 to begin on the center plunger, and S1 and S4 were prompted to begin on the right plunger. In subsequent sessions, the location of the first prompt alternated between the center and right positions.

When cigarette puffs were earned, a smoking interval began with two tones produced by the computer and an on-screen prompt to PUFF NOW. The tones prompted the subject to open the door so the smoking episode could be observed by the research assistant. Next, the subject lit a cigarette without inhaling, placed it in a holder connected by plastic tubing to the volumetric low pressure transducer, and inhaled until approximately 70 cc of smoke had been drawn. The cumulative volume of smoke inhaled (in cubic centimeters) was presented to the screen and the computer produced a brief tone when 60 cc had been inhaled. Subjects were instructed that if they stopped inhaling when they heard this tone, their puff volume would approximate 70 cc. Subjects held the smoke in their lungs until the computer produced a pair of tones 5 s after the 60-cc mark had been reached. The PUFF NOW message appeared on the screen 25 s after exhaling. When all puffs had been taken, the message NO MORE PUFFS was presented. At this time, in accordance with the instructions, the subject extinguished the cigarette. A series of three tones and the message ''You may respond now'' signaled the end of the smoking interval. The duration of the smoking interval was 45 s per puff. If the average puff volume in any session deviated from 70 cc by more than 5 cc or the standard puffing procedure was violated, the procedures were repeated at the next scheduled session.

In addition to observing subjects during the smoking intervals, the research assistant periodically observed participants to ensure that no unauthorized smoking occurred. The research assistant's room was close enough, and quiet enough, so that the sound of a lighter or match being lit could be heard even when the subject's door was closed. During those sessions in which cigarette puffs were available at high unit prices, research assistants were instructed to be particularly vigilant for unauthorized puffs or deviations from the standardized puffing procedure.

After the first session, subjects chose between earning different numbers of cigarette puffs on the center and right plungers according to different FR schedules (concurrent FR FR schedules). The numbers of puffs, FR values, and unit prices arranged in each session are shown in Table 2. Each of these contingencies remained in effect for a single session because prior research using similar smoking procedures has demonstrated replicable within-subject effects of unit price (e.g., Bickel, Hughes, DeGrandpre, Higgins, & Rizzuto, 1992; DeGrandpre, Bickel, Higgins, & Hughes, 1994).

Unequal unit prices. Preference between high and low unit prices was assessed in several sessions (see Table 2). Preference was assessed when (a) a fixed number of puffs could be obtained at high versus low FR values, (b) more versus fewer puffs could be obtained at the same FR value, and (c) puff amount and FR value both differed between alternatives. Preferences between high versus low FR values and between more versus fewer puffs were assessed at the lower and upper range of unit prices at which each subject responded. These sessions were conducted to ensure that preferences for the smaller FR and the larger number of puffs were not systematically affected by high and low unit prices. In other sessions the unit price of puffs on one plunger was double that arranged on the other. These sessions were conducted to determine whether the indifference prompts would yield response allocations that were insensitive to large differences in relative unit price across the range of prices assessed in the equal-unit-price conditions (see below).

Equal unit prices. In these sessions, subjects made choices between alternatives with equivalent unit prices but different numbers of puffs (three vs. six, three vs. nine, or six vs. nine puffs) and, thus, different response requirements (see Table 2). Sessions were conducted at three different combinations of puff amounts and response requirements for each puff. We planned to examine unit prices of 22, 230, 700, and 1,116, because this spans the range at which smokers in our laboratory typically respond to earn puffs (Bickel & Madden, 1999). S1 did not respond at unit prices higher than 230, and S3 continued to respond at unit prices as high as 4,500. To more thoroughly assess preference across the range of unit prices at which S1 would respond, response allocation was assessed at a unit price of 90 (three sessions). Likewise, to assess choice between alternatives with equal unit prices across the entire range at which S3 would respond, sessions were added in which puffs were available at unit prices of

Table 2

Conditions to which individual subjects were exposed.

Subject	Session	Unit price[a]	Puffs		Fixed ratio		Unit price		Obtained unit price
			Center	Right	Center	Right	Center	Right	
S1	1		6	6	6	6	1.0	1.0	1.0
	2	U	3	9	342	2,070	230.0	115.0	164.0
	3	E	9	6	2,070	1,380	230.0	230.0	230.0
	4	E	3	9	690	2,070	230.0	230.0	230.0
	5	E	6	3	1,380	690	230.0	230.0	230.0
	6	U	9	3	10,044	1,674	1,116.0	558.0	
	7	U	3	9	1,050	6,300	350.0	700.0	350.0
	8	E	6	9	4,200	6,300	700.0	700.0	
	9	U	9	6	99	132	11.0	22.0	11.0
	10	E	9	6	198	132	22.0	22.0	22.0
	11	E	3	6	66	132	22.0	22.0	22.0
	12	E	9	3	198	66	22.0	22.0	22.0
	13	E	6	9	2,520	3,870	420.0	420.0	
	14	E	6	3	1,980	990	330.0	330.0	
	15	E	6	9	540	810	90.0	90.0	90.0
	16	E	3	6	270	540	90.0	90.0	90.0
	17	E	9	3	810	270	90.0	90.0	90.0
	18	U	6	6	690	1,380	115.0	230.0	115.0
	19	U	6	6	66	132	11.0	22.0	11.0
	20	U	3	9	690	690	230.0	76.7	76.7
	21	U	9	3	66	66	7.3	22.0	7.3
S2	1		6	6	6	6	1.0	1.0	1.0
	2	U	3	9	33	198	11.0	22.0	19.2
	3	E	9	6	198	132	22.0	22.0	22.0
	4	E	3	9	66	198	22.0	22.0	22.0
	5	E	6	3	132	66	22.0	22.0	22.0
	6	U	3	9	345	2,070	115.0	230.0	146.4
	7	E	6	9	1,380	2,070	230.0	230.0	230.0
	8	U	6	3	1,380	660	230.0	220.0	230.0
	9	E	3	9	690	2,070	230.0	230.0	230.0
	10	U	9	3	6,300	1,050	700.0	350.0	525.0
	11	E	6	9	4,200	6,300	700.0	700.0	700.0
	12	E	9	3	6,300	2,100	700.0	700.0	700.0
	13	E	3	6	2,100	4,200	700.0	700.0	700.0
	14	U	3	9	1,674	10,044	558.0	1,116.0	558.0
	15	E	3	6	3,348	6,696	1,116.0	1,116.0	1,116.0
	16	E	9	3	10,044	3,348	1,116.0	1,116.0	1,116.0
	17	E	6	9	6,696	10,044	1,116.0	1,116.0	
	18	U	3	9	66	66	22.0	7.3	7.3
	19	U	6	6	132	198	22.0	33.0	22.0
	20	U	9	3	690	690	76.7	230.0	76.7
	21	U	6	6	1,380	690	230.0	115.0	115.0
S3	1		6	6	6	6	1.0	1.0	1.0
	2	U	3	9	345	2,070	115.0	230.0	161.0
	3	E	9	6	2,070	1,380	230.0	230.0	230.0
	4	E	3	9	690	2,070	230.0	230.0	230.0
	5	E	6	3	1,380	690	230.0	230.0	230.0
	6	U	9	3	10,044	1,674	1,116.0	558.0	744.0
	7	E	6	9	6,696	10,044	1,116.0	1,116.0	1,116.0
	8	E	6	3	6,696	3,348	1,116.0	1,116.0	1,116.0
	9	E	3	9	3,348	10,044	1,116.0	1,116.0	1,116.0
	10	U	3	9	1,050	6,300	350.0	700.0	445.0
	11	E	6	9	4,200	6,300	700.0	700.0	700.0
	12	E	9	3	6,300	2,100	700.0	700.0	700.0
	13	E	3	6	2,100	4,200	700.0	700.0	700.0
	14	U	9	6	99	132	11.0	22.0	11.0
	15	E	9	6	198	132	22.0	22.0	22.0
	16	E	3	6	66	132	22.0	22.0	22.0

Table 2

(Continued)

Subject	Session	Unit price[a]	Puffs		Fixed ratio		Unit price		Obtained unit price
			Center	Right	Center	Right	Center	Right	
	17	E	9	3	198	66	22.0	22.0	22.0
	18	E	6	3	18,000	9,000	3,000.0	3,000.0	3,000.0
	19	E	9	6	27,000	18,000	3,000.0	3,000.0	3,000.0
	20	E	3	9	9,000	27,000	3,000.0	3,000.0	3,000.0
	21	E	6	3	27,000	13,500	4,500.0	4,500.0	4,500.0
	22	U	9	3	66	66	7.3	22.0	11.4
	23	U	3	9	10,044	10,044	3,348.0	1,116.0	1,116.0
	24	U	6	6	132	198	22.0	33.0	27.9
	25	U	6	6	3,348	6,696	558.0	1,116.0	558.0
S4	1		6	6	6	6	1.0	1.0	1.0
	2	U	3	9	33	198	11.0	22.0	18.6
	3	E	9	6	198	132	22.0	22.0	22.0
	4	E	3	9	66	198	22.0	22.0	22.0
	5	E	6	3	132	66	22.0	22.0	22.0
	6	U	3	9	345	2,070	115.0	230.0	115.0
	7	E	6	9	1,380	2,070	230.0	230.0	230.0
	8	E	6	3	1,380	690	230.0	230.0	230.0
	9	E	3	9	690	2,070	230.0	230.0	230.0
	10	U	9	3	6,300	1,050	700.0	350.0	560.0
	11	E	6	9	4,200	6,300	700.0	700.0	700.0
	12	E	9	3	6,300	2,100	700.0	700.0	700.0
	13	E	3	6	2,100	4,200	700.0	700.0	700.0
	14	U	3	9	1,674	10,044	558.0	1,116.0	558.0
	15	E	9	6	10,044	6,696	1,116.0	1,116.0	1,116.0
	16	E	3	6	3,348	6,696	1,116.0	1,116.0	1,116.0
	17	E	9	3	10,044	3,348	1,116.0	1,116.0	1,116.0
	18	U	3	9	6,696	6,696	2,232.0	744.0	
	19	U	6	6	198	132	33.0	22.0	22.0
	20	U	6	6	6,696	3,348	1,116.0	558.0	
	21	U	9	3	66	66	7.3	22.0	7.3

[a] E = equal; U = unequal.

3,000 (three sessions) and 4,500 (one session).

RESULTS

In the first session, when six cigarette puffs could be obtained from the center and right plungers by completing an FR 6, all 4 subjects followed the computer's prompts to alternate between plungers. Only one session had to be repeated in the entire experiment because average puff volumes deviated from 70 cc by more than 5 cc.

The first prediction of economic theory is that as the unit price of a reinforcer increases, consumption should decrease. The functional relation between total cigarette puffs consumed per session (C) and unit price (P) was modeled using an equation proposed by Hursh et al. (1988):

$$C = LP^{b}e^{-aP}, \tag{1}$$

or restated in logarithmic coordinates,

$$\ln C = \ln L + b(\ln P) - aP, \tag{2}$$

where L is predicted consumption at Unit Price 1 and b and a are related to the initial slope and acceleration of the demand function, respectively. Puffs obtained from both schedules of reinforcement were summed to obtain total consumption (C). Parameter estimates for Equation 2 were derived using standard linear regression techniques (SAS® statistical software, PROC REG). Equation 2 was fit using the logarithmic transforms of unit price (P) and obtained consumption (C). For several subjects, high unit prices completely suppressed consumption. Data from these sessions were not used when deriving parameter estimates because zero is undefined in logarithmic coordinates. As prescribed by Hursh, Raslear, Bauman, and Black (1989), response-output functions were obtained by substituting $b + 1$ for b in Equation 2.

The left panels of Figure 2 show that for all subjects, cigarette puff consumption was a positively decelerated function of unit price. Equation 2 provided a good fit of the consumption data (see Table 3), accounting for an average of 90.7% of the variance across subjects ($SD = 2.2\%$).

The right panels of Figure 2 show responses per session at each unit price. For all subjects, response output increased with increases in unit price until a price was reached at which further price increases caused responding to decrease or stop (the latter are not shown in the figure because zero is undefined in logarithmic coordinates). No systematic differences in consumption or response output are apparent across sessions in which behavior was exclusively allocated to one of the concurrent-schedule alternatives or was distributed between alternatives.

The second prediction made by economic theory is that the amount of a reinforcer consumed is determined by its unit price, independent of the values of the cost and benefit components of the unit price ratio. Figure 3 shows cigarette consumption in the equal unit price sessions, in which response requirements (costs) and puff amounts (benefits) were varied across alternatives. Although consumption was rarely identical across the different cost and benefit components of a particular unit price, consumption was usually similar, and there was no systematic effect across these conditions. A repeated measures analysis of variance (ANOVA) was used to compare puffs smoked per session in the different puff magnitude conditions (i.e., three vs. six puffs, etc.) and across unit prices less than 3,000. The analysis revealed a statistically significant effect of unit price on the number of puffs smoked per session, $F(3, 38) = 27.2$, $p < .001$, but no significant effect of the puff magnitude condition, $F(2, 38) = 1.5$, $p = .30$, and no significant Price × Condition interaction, $F(6, 38) = 1.3$, $p = .31$.

The third prediction of economic theory is that preference should favor the alternative with the lower unit price. The upper panel in Figure 4 shows individual subjects' preferences between unequal unit prices when the number of puffs obtained per opportunity was constant across alternatives. Thus, in these sessions, subjects chose between high versus low FR values (FR values equal unit price times six puffs). With one exception (S3 at concurrent unit prices of 22 vs. 33), behavior was exclusively allocated to the relatively lower unit price. S4 did not respond at concurrent unit prices of 1,116 versus 558. The lower panel of Figure 4 shows preference between unequal unit prices when the number of puffs varied and the FR was held constant across alternatives. Again, with one exception (S3 at concurrent unit prices of 22 and 7.3), preference was exclusively for the lower unit price.

Figure 5 shows individual subjects' choices when the unit price of one alternative was always twice that of the other and different numbers of puffs (three vs. nine, or six vs. nine) and FR values were arranged across alternatives. Across subjects, preference was usually in favor of the alternative with the lower unit price. Exceptions occurred when choosing the lower unit price involved forgoing the relatively larger number of puffs (and the larger FR; open bars in Figure 5). In two sessions in which puffs were available at relatively low unit prices (11 vs. 22), S2 and S4 were indifferent. S1 and S3 exclusively preferred the lower unit price under comparable unit prices when the lower priced alternative delivered nine puffs. These data are not predicted by economic theory because unit price should determine preference independent of the particular values of the cost and benefit components of unit price.

Economic theory predicts indifference between identical reinforcers available at the same unit price. Figure 6 shows preference data from sessions in which different numbers of puffs were available at equal unit prices across the center and right plungers. In the lower range of unit prices, smokers preferred relatively more puffs for more responses. The exception was S2 in the six-versus-nine-puff condition in which indifference was observed at a unit price of 22. Across all subjects and all puff combinations, as unit prices increased, responses were, with few exceptions, increasingly allocated to the alternative with the relatively smaller number of puffs and smaller response requirement. At the highest unit prices at which behavior was

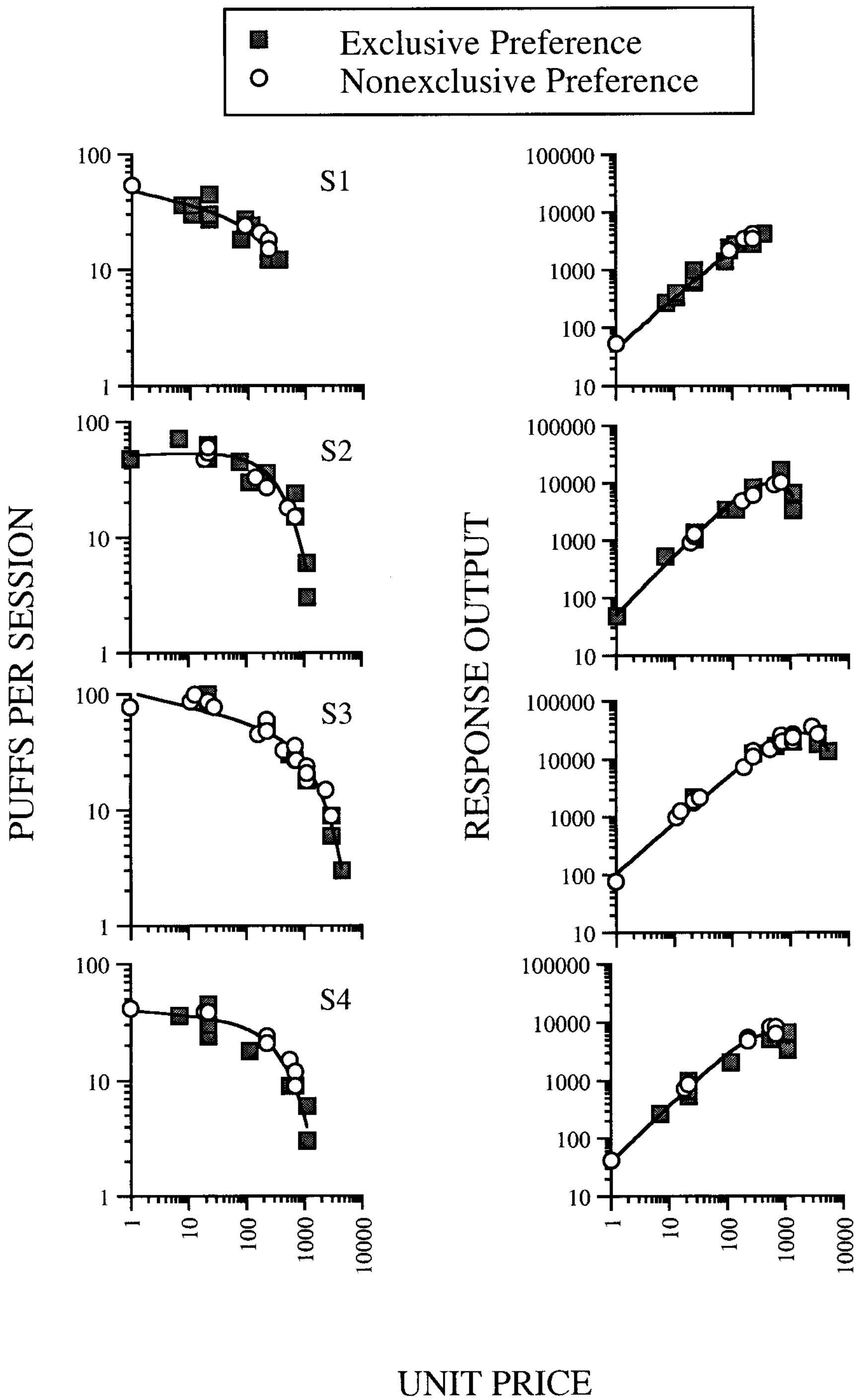

Fig. 2. Individual-subject data illustrating the relation between per session cigarette consumption (left column) and response output (right column) and obtained unit price. Data are included from sessions in which puffs were available at unequal and equal unit prices across alternatives, and the data from all sessions are included. Best fitting functions were derived using Equation 2. Solid squares correspond to sessions in which behavior was exclusively allocated to one alternative, and open circles show data from sessions in which both alternatives were chosen at least once.

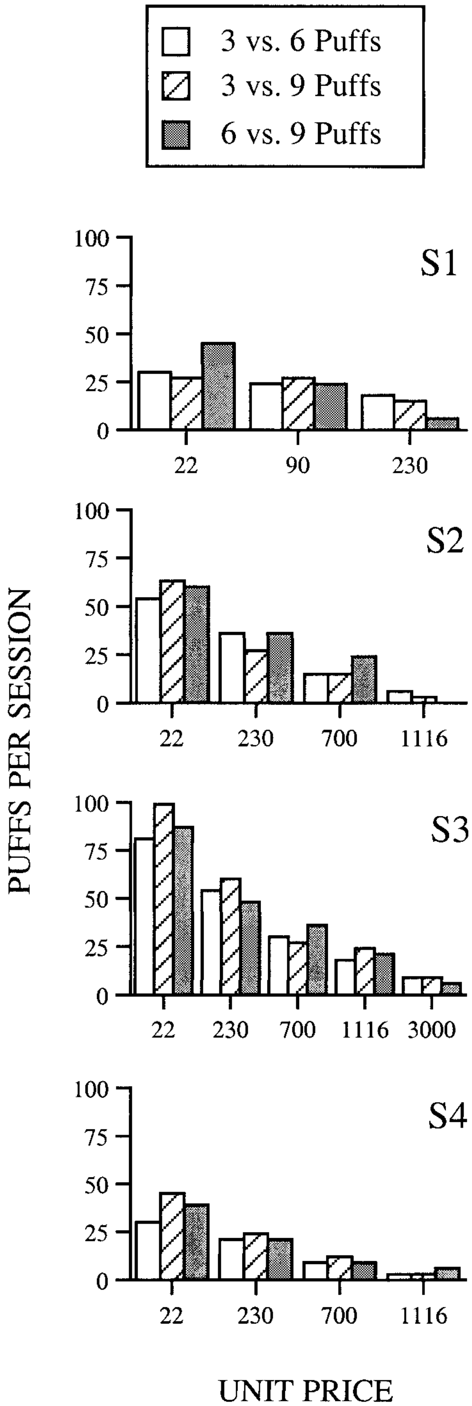

Table 3

Parameter estimates of Equation 2 derived from individual subjects' cigarette consumption curves.

Subject	L[a]	b[b]	a[c]	R^2 [d]
S1	50.3	−0.135	−0.00189	.85
S2	54.8	0.001	−0.00208	.90
S3	125.2	−0.163	−0.00052	.96
S4	40.5	−0.045	−0.00177	.92

[a] L gives the estimated number of cigarette puffs consumed at unit price 1.
[b] Initial slope of the demand curve.
[c] Acceleration of the demand curve.
[d] Percentage of variance accounted for by the demand curve.

maintained, responding was generally exclusively allocated to the alternative offering fewer puffs at a lower response requirement.

At very high unit prices, preference for the smaller number of puffs and smaller response requirements may have occurred because the 3-hr session was not long enough to complete the larger FR. To test this possibility, we used response rates from these sessions to estimate the time it would take to complete the larger FR. In no instance was the FR requirement for the larger number of puffs so large that it could not be completed within the 3-hr session (this included the session in which three vs. six puffs were available at a unit price of 4,500 for S3).

DISCUSSION

As predicted by economic theory, cigarette puff consumption was a decreasing function and response output was a bitonic function of unit price in the choice situations arranged in this experiment. The equation proposed by Hursh et al. (1988) accounted for a large portion of the variance in consumption across the range of unit prices investigated. A second prediction of economic theory was

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Fig. 3. Cigarette puff consumption in sessions in which different puff amounts were concurrently available at the same unit price. Consumption from S3's session with a unit price of 4,500 (three vs. six puffs) is not shown because sessions were not conducted at the other concurrent puff magnitudes shown in the legend. Fixed-ratio values may be obtained by multiplying the number of puffs by unit price.

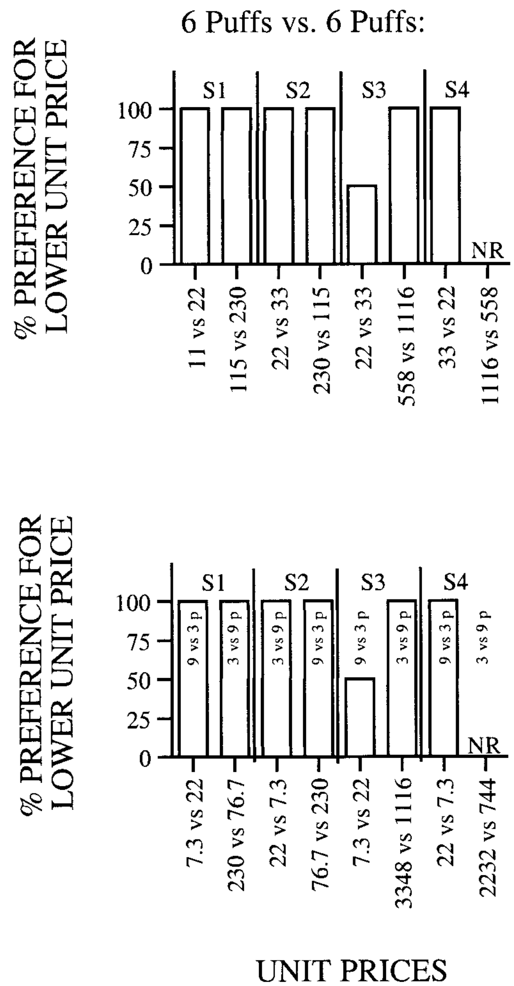
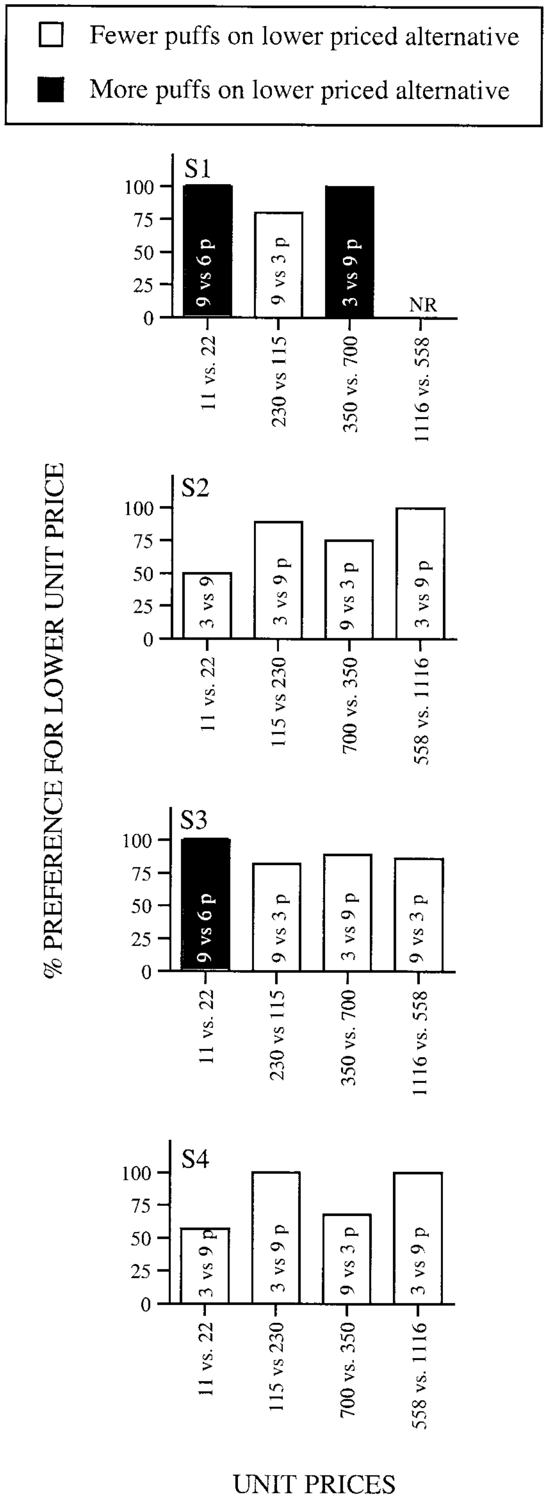


Fig. 4. Individual subjects' preferences between puffs available at unequal unit prices. The top graph shows preference for the lower unit price when the same number of puffs was available from both alternatives, but at different FR schedule requirements (these may be obtained by multiplying the unit prices shown along the *x* axis by six). The bottom graph shows preference for the lower unit price when different numbers of puffs were available across alternatives, but at the same FR requirement. In both graphs the first of the concurrent unit prices listed was arranged on the center response plunger and the second was arranged on the right plunger. Likewise, the first puff amount superimposed over the data was arranged on the center plunger and the second was arranged on the right. Fixed-ratio values may be obtained by multiplying the number of puffs by unit price. NR indicates that no responding occurred in the session.

supported when overall cigarette consumption (i.e., consumption summed across both alternatives) was affected by unit price but was not systematically affected by the cost (response requirement) or benefit (number of puffs) components of unit price. Evidence supporting the third economic prediction (i.e., preference for low unit prices over high) was obtained when subjects chose between large FR values over small (puffs held constant), or between more puffs over fewer (FR value held constant). However, in a second set of unequal unit price sessions, when choosing the alternative with the lower unit price involved selecting a small number of puffs over a relatively larger number of puffs, response allocation in some sessions indicated indifference or nonexclusive preference for the alternative with the lower unit price. When given a choice between alternatives with equal unit prices, behavior was differentially allocated to the larger number of puffs (and larger response requirement) at low unit prices and to the smaller number of puffs (and smaller response requirement) at high unit prices. These data suggest that choice is affected by the value of the cost and benefit components of unit price.

Evidence Supporting Economic Predictions

The positively decelerated demand curve typically reported in previous experiments involving food and drug reinforcers (e.g., Bickel et al., 1990, 1991; Hursh et al., 1988) was observed in all subjects, thereby extending the generality of these findings to consumption summed across response alternatives in a choice situation. Consistent with findings reported by Bickel and Madden (1999), consumption was similar whether subjects responded on just one or both alternatives. Likewise, the bitonic response-output function typically observed across a range of unit prices was replicated in the choice context arranged here. Our results also extend the generality of Equation 2 as a quantitative account of consumption and response output under concurrent ratio schedules of reinforcement. These are important extensions of the generality of unit price as a summarizing variable given that behavior typically occurs in choice situations involving the concurrent availability of more than one source of reinforcement (Herrnstein, 1970).



The results of the present experiment also support the prediction of economic theory that the cost and benefit components of unit price are functionally equivalent in determining total consumption. This finding extends the generality of previous demonstrations (e.g., Bickel et al., 1991) to choice contexts. Prior reanalyses of published experiments that have investigated the effects of reinforcer magnitude and response requirement on response rate, consumption, or both have revealed that these variables may be more clearly and parsimoniously understood in terms of unit price manipulations rather than as separate variables (DeGrandpre, Bickel, Hughes, & Higgins, 1992; DeGrandpre et al., 1993). For example, DeGrandpre et al. (1993) reviewed a number of studies in which reinforcer magnitude and schedule requirement were manipulated. Systematic changes in these cost and benefit variables most often yielded puzzling, though replicable, results (e.g., Collier & Myers, 1961; Goldberg, 1973). DeGrandpre et al. (1993) demonstrated that if schedule requirement and reinforcer magnitude were expressed in terms of unit price, order was brought to data that otherwise appeared disorderly. That is, consumption and response output appeared to be unsystematically related to either schedule requirement or reinforcer magnitude when considered separately. Yet consumption and response output were orderly functions of those variables when they were expressed as values of unit price.

Evidence Failing to Support Economic Predictions

In sessions in which different numbers of puffs were arranged at the same unit price, systematic deviations from the indifference predicted by economic theory were observed in all subjects. At low unit prices, subjects tended to prefer more puffs and the larger

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Fig. 5. Individual subjects' preferences between unequal unit prices when the unit price of one alternative was twice that of the other. The puff amounts available on the center and right plungers are shown (from left to right) from each session. The FR values at which puffs could be obtained may be calculated by multiplying each unit price by the number of puffs available. NR indicates that no responding occurred in the session.

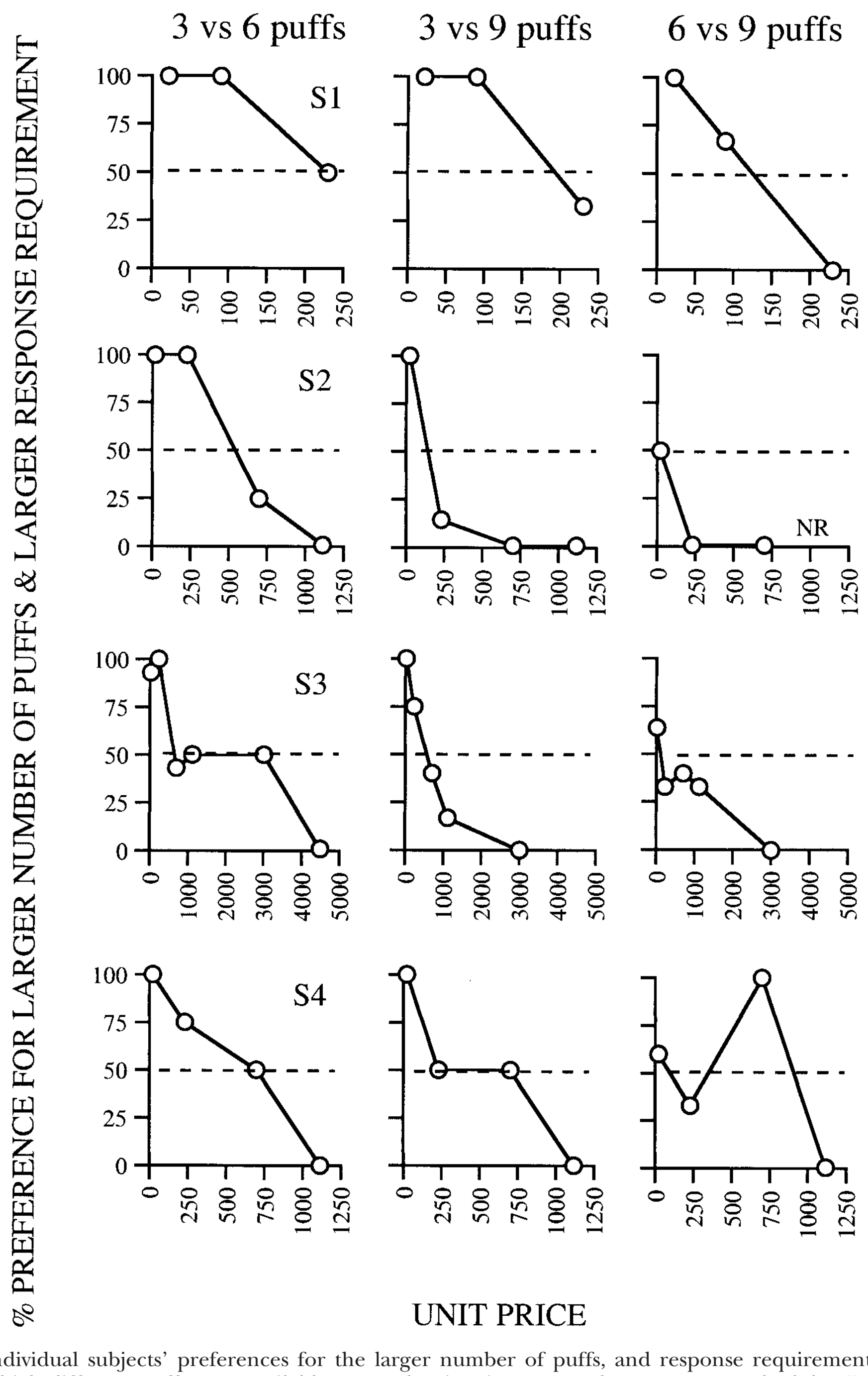

Fig. 6. Individual subjects' preferences for the larger number of puffs, and response requirement, from those sessions in which different puffs were available at equal unit prices across the concurrent schedules. Rows of graphs correspond to individual subjects, and columns correspond to the different pairs of puff amounts arranged across alternatives. The dashed line shows indifference, which is the relative response rate predicted by economic theory. NR indicates that no responding occurred in the session.

response requirement over fewer puffs and the smaller response requirement. This suggests that when both response requirements were relatively small, the difference in reinforcer magnitude outweighed the proportionally equivalent difference in response requirement. At higher unit prices, both FR values were increased while holding constant the proportional relation between the two response requirements and between response requirements and reinforcer magnitudes. Despite these equivalent increases in unit price, at high unit prices, preference was, with few exceptions, exclusively for fewer puffs and the smaller response requirement. These findings argue against the functional equivalence of the cost and benefit components of unit price when applied to predicting choice.

Noneconomic Predictions

Because of these prediction failures, we were interested in the predictions of noneconomic models of choice. We assessed predictions of the matching law (Herrnstein, 1970), because this quantitative model (and its derivatives, e.g., Baum, 1974; Logue, Rodriguez, Peña-Correal, & Mauro, 1984) is the most frequently investigated model of human and nonhuman choice (see reviews by Bradshaw & Szabadi, 1988; Davison & McCarthy, 1988). In the following version of the matching law,

$$\frac{B_L}{B_R} = k\left(\frac{A_L}{A_R}\right)^{S_A}\left(\frac{F_L}{F_R}\right)^{S_F}\left(\frac{D_R}{D_L}\right)^{S_D}, \qquad (3)$$

B refers to behavior allocated to the left (L) and right (R) sources of reinforcement, and A, F, and D represent reinforcer amount, frequency, and delay, respectively. The derived parameter k is a measure of position bias not accounted for by differences in reinforcer amount and frequency, and the exponents S_A, S_F, and S_D are derived parameters affected by sensitivity to changes in reinforcer amount, frequency, and delay, respectively. Like unit price, Equation 3 holds that response allocation (B_L/B_R) is a function of the ratio of obtained amounts and frequencies of reinforcement (when delay ratio is ignored). Thus, the absolute values of the amount, frequency, and delay components of the right side of Equation 3 should not affect preference (the relativity assumption of the matching law).

Predictions about preference between alternatives with equal unit prices may be derived from Equation 3 by substituting reinforcer amounts and frequencies into the right side of the equation. Frequency of reinforcement may be estimated for predictive purposes by assuming a constant response rate on each FR schedule. For these predictions we assumed no response bias ($k = 1$) and unit sensitivity to reinforcer amount and frequency ($S_A = S_F = 1.0$). Interestingly, at all unit prices, reinforcer magnitudes, and frequencies employed in our experiment, Equation 3 makes the same predictions as unit price: Responding should be indifferent between alternatives with equal unit prices, and when choices are between unequal unit prices, preference should exclusively favor the lower priced alternative. In light of the failure of unit price to predict response allocation in the equal unit price choice conditions of our experiment (i.e., when the ratios of reinforcer amounts and frequencies were equivalent across alternatives but the values of the reinforcer amounts and frequencies were varied across sessions), it is not surprising that empirical tests of the relativity assumption of the matching law have usually not supported matching (e.g., Chung & Herrnstein, 1967; Fantino, Squires, Delbrück, & Peterson, 1972; Logue & Chavarro, 1987; Snyderman, 1983; although see Ito & Oyama, 1996).

Additional Variables That May Affect Unit Price

Handling costs. Additional variables derived from two conceptual models of choice may help us to understand our observed deviations from the response allocations predicted by economic theory. First, in Rapport's model of optimal foraging (e.g., Rapport, 1971), the time required to handle and prepare a prey for consumption is factored into the decision to stay in or leave a particular patch in favor of another concurrently available patch. In terms of the unit price (P) of cigarette puffs in our experiment, an optimal foraging model suggests that

$$P = \frac{\text{FR} + H}{A}, \qquad (4)$$

where FR is the fixed-ratio schedule at which reinforcers of amount A are available, and H corresponds to the handling cost *per unit of* *cigarette puffs* (given in instrumental response units). In our experiment, the work required to remove a cigarette from the pack, light it, place it in the plastic holder, and eventually extinguish it was the same regardless of the number of puffs obtained. Thus, handling cost per puff was greater when fewer puffs were earned. For example, in one condition, to accumulate nine puffs, subjects were required to handle the cigarette once (nine puffs earned), 1.5 times (six puffs earned), or three times (three puffs earned). The total savings in handling costs afforded by choosing the relatively larger number of puffs should have been pronounced at low unit prices because consumption was relatively high at this end of the price continuum.

Equation 4 may help us to understand preference for more puffs over fewer at low unit prices, but it fails to explain the preference reversal toward the smaller number of puffs (and smaller work requirement) observed at higher unit prices. At high FR values, when unit price is calculated according to Equation 4, the price of the larger number of puffs is still lower than the unit price of fewer puffs. Thus, handling costs alone cannot account for the systematic deviations from economic predictions observed in this study.

Hyperbolic discounting. A second model that may help us to understand these deviations is the temporal discounting model proposed by Mazur (1987). According to this model, the value of a reinforcer is hyperbolically discounted with increases in the delay to its delivery. According to Mazur's equation,

$$V = \frac{A}{1 + kD}, \tag{5}$$

where V is the present value of the reinforcer of magnitude A delivered following delay D. The empirically derived parameter k measures rate of discounting. If we substitute Mazur's equation for the denominator of Equation 4 (i.e., the benefit component of unit price), unit price becomes

$$P = \frac{\mathrm{FR} + H}{V}, \tag{6}$$

where V is given by Equation 5. This substitution is supported by Bauman's (1991) finding that interval schedules with values yoked to the times required to complete ratio schedules produce similar effects on food consumption, and by Grossbard and Mazur's (1986) demonstration that reinforcer value is a decreasing hyperbolic function of increasing ratio schedule values.

Figure 7 illustrates the relation between modified unit price calculated according to Equation 6 and unit price as originally proposed (FR/A). To obtain the modified unit prices shown on the y axis, handling costs were estimated to be equivalent to 75, 112.5, and 225 instrumental responses for nine, six, and three puffs per self-administration, respectively. A handling cost of 75 was selected per nine-puff self-administration because the average time to complete an FR 75 (20 s) approximated the time it takes, on average, for a subject to remove a cigarette from the pack, light the cigarette, place it in the plastic holder before puffs may be taken, and eventually extinguish it. Handling costs were set at 112.5 and 225 for six and three puffs, respectively, because obtaining nine puffs via these puff amounts required handling cigarettes 1.5 and three times. A k value of 0.001 was selected because it approximates the average k value observed in humans choosing between immediate and delayed hypothetical monetary rewards (for a review, see Kirby, 1997). Delays were the times individual subjects took to complete each ratio value (when more than one ratio was completed in the session, average delays were used).

The three panels for each subject in Figure 7 correspond to sessions in which different puff amounts were both available at the same unit price. In all three panels, at low unit prices on the x axis, the larger magnitude reinforcer is the lower priced source of puffs on the y axis (where price is calculated according to Equation 6). As unit price on the x axis increases, relative modified unit prices on the y axis are gradually reversed. If Equation 6 is a valid modification of unit price, then, according to economic theory, subjects should have exclusively preferred more puffs at low unit prices, should have been indifferent at some of the moderate prices (where modified unit prices are approximately equal), and should have shifted to exclusively preferring the smaller number of puffs at higher prices. These predictions are quantitatively correct in only half of the preferences plotted in Figure 6. However, a majority of the incor-

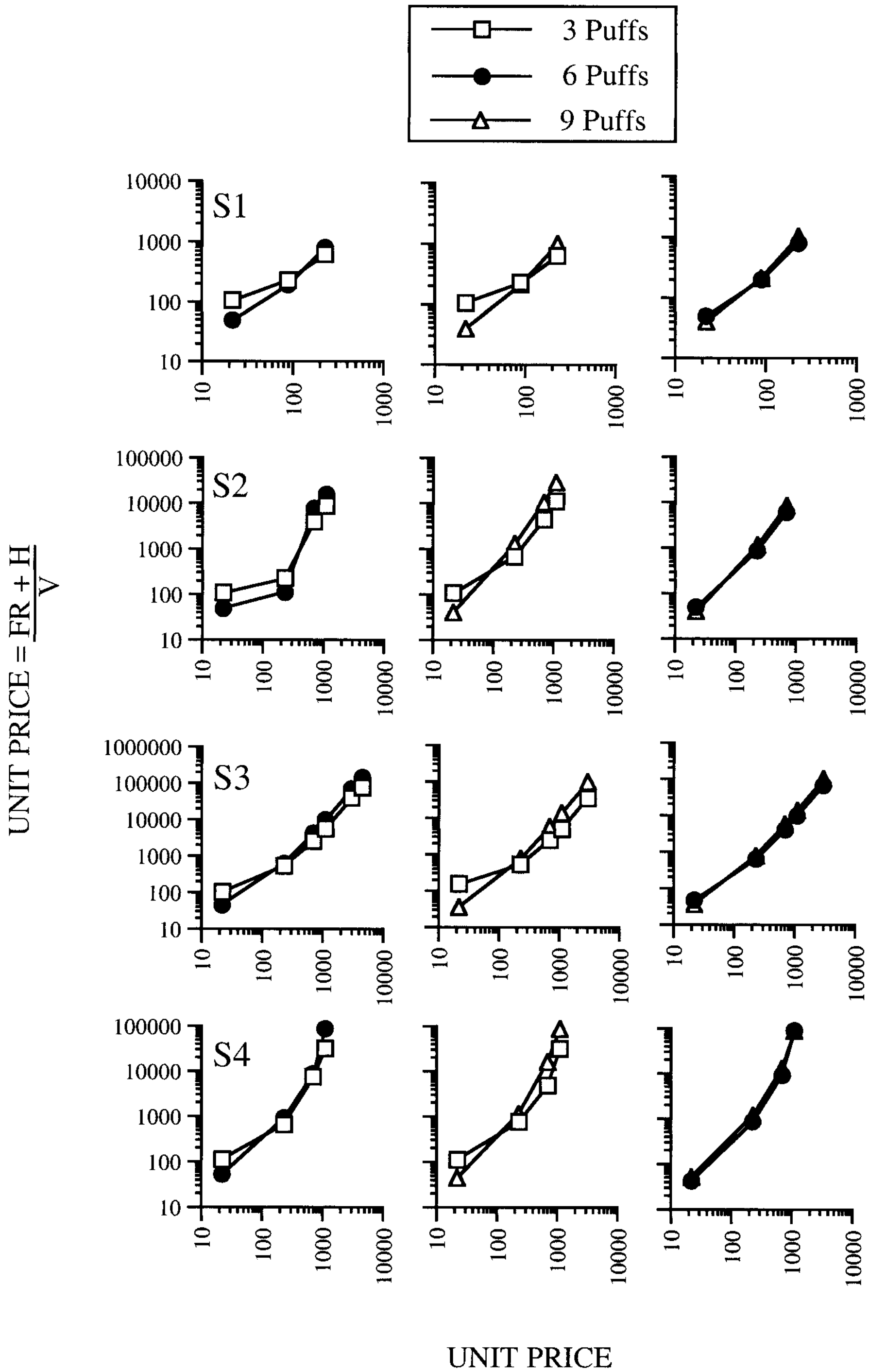

Fig. 7. The relation between the original unit-price ratio and modified unit price (Equation 6). The three columns compare the relative unit prices of three versus six puffs (left), three versus nine puffs (center), and six versus nine puffs (right). Note the double-logarithmic axes.

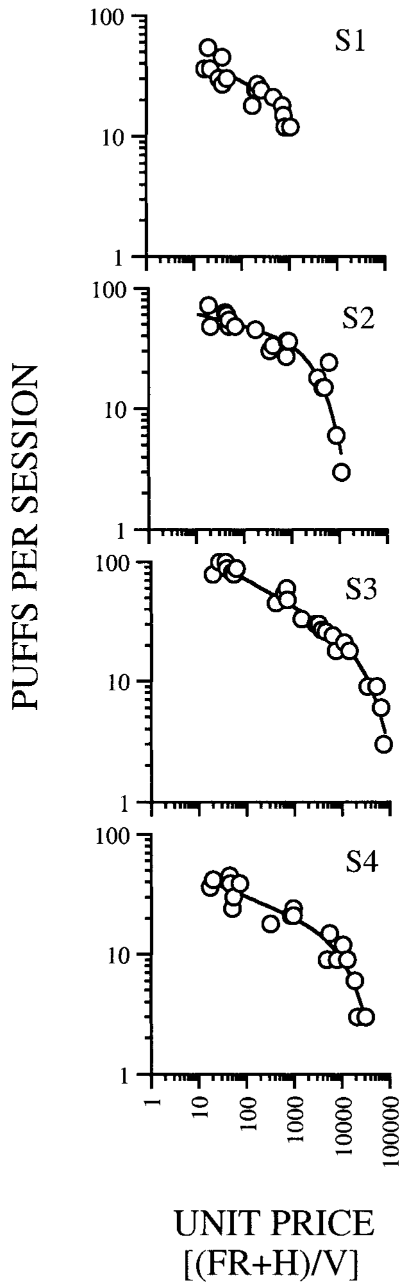

Fig. 8. Demand curves fitted to per-session cigarette consumption using Equation 6 as unit price.

rect predictions were qualitatively correct (i.e., preference was in the direction predicted, but subjects did not show exclusive preference). Whether exclusive preference would have been more frequently observed had subjects completed more than one session at each unit price configuration is unknown.

Table 4

Parameter estimates of Equation 2 derived from individual subjects' cigarette consumption curves using Equation 6 to calculate unit price. Parameters of the demand curve are the same as those described in Table 3.

Subject	*L*	*b*	*a*	R^2
S1	65.4	−0.174	−0.00043	.83
S2	76.4	−0.097	−0.00018	.91
S3	197.1	−0.223	−0.00002	.97
S4	64.2	−0.164	−0.00004	.91

A criticism of Equation 6 is that costs and benefits are no longer independent (i.e., as the FR is increased, reinforcer value is discounted). When unit price is calculated as total response output divided by total number of puffs obtained in the session, consumption is predicted to be equivalent across sessions in which the same unit price is arranged, regardless of the particular values of the cost and benefit components of unit price. This prediction has been widely supported. For example, in our Figure 3 we compared consumption across three different cost-benefit configurations when the obtained unit price (i.e., total response output divided by total number of puffs smoked) at each was identical. If Equation 6 is used to calculate unit price, then the obtained unit prices shown in Figure 3 are no longer equal, and we would no longer predict equal consumption. A one-way ANOVA was conducted to determine whether Equation 6 would yield obtained modified unit prices that were significantly different across the three cost-benefit configurations shown in Figure 3. Obtained modified unit prices were calculated by multiplying the two modified unit prices that were concurrently available by the number of times puffs were obtained from that alternative and dividing the sum of the obtained values by the total number of times puffs were earned in the session. For the analysis, the modified unit price was treated as a nominal variable with three cost-benefit configurations at each price. No significant difference between obtained modified unit prices was detected across the three configurations, $F(2, 29) = 1.57$, $p = .22$.

Another test of Equation 6 is shown in Figure 8. Here cigarette consumption for individual subjects is plotted as a function of obtained modified unit price, and demand curves are fit to these data using Equation 2 (derived parameters of the demand curves are provided in Table 4). Variance accounted for by these demand curves was similar to that observed when unit price was calculated as FR/A (see Table 3).

From these analyses, factoring handling costs and discounting of delayed reinforcers into unit price apparently shifts the choice from two alternatives with equal unit prices to a choice between alternatives with unequal prices. When total consumption (i.e., consumption summed across both alternatives) was examined as a function of obtained unit price (i.e., total response output divided by total number of puffs obtained in the session), however, calculating unit price according to Equation 6 made predictions that accorded well with those of original unit price. Thus, in a choice situation, preference may favor the lower of two concurrently available unit prices, but total consumption can be relatively insensitive to the subtle (and nonsignificant) changes in obtained unit price introduced when Equation 6 is employed.

Although these post hoc analyses offer some support for Equation 6, we should note that each should be viewed cautiously because handling costs and discounting rates were estimated rather than empirically assessed. Prospective analyses are necessary before sufficient evidence supporting or refuting Equation 6 can be accumulated.

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APPENDIX

Instructions Given to Participants Prior to Each Session

In this study you can earn cigarette puffs by pulling the center and right-hand plungers. The computer will prompt you to alternate between the center and right-hand plungers. That is, after earning puffs on the center plunger, the computer will prompt you to pull the right plunger in order to earn your next round of puffs. The number of pulls that are required and puffs available on the center and right-hand plungers are shown on this page below. *It is completely up to you to determine how often you pull, or if you want to pull at all.*

Although the computer prompts you to switch between the center and right-hand plungers on every other trial, you can override these prompts. That is, if the computer prompts you to pull the right plunger, but you would rather pull the center plunger, you may override the computer by pulling the left plunger 5 times. Pulling the left plunger 5 times will allow you to pull the plunger that the computer would previously not let you pull. Pulling the left plunger is not required before pulling the other two plungers. You should only pull the left plunger if you prefer one puffing alternative over another and want to override the computer's prompt. If you have no preference between the center and right-hand alternatives, then do not pull the left plunger.

Prior to beginning each day, you will be provided with this sheet which tells you how many pulls you must make on each plunger to earn puffs. When you earn puffs, you will have 45 seconds per puff to take them. The computer will count down this time and will tell you when you may start pulling again to earn more puffs.

Daily conditions:

Left plunger: 5 pulls switches plunger in operation

Center plunger: — puffs for — pulls

Right plunger: — puffs for — pulls