*BEHAVIORAL ECONOMICS OF DRUG SELF-ADMINISTRATION.
II. A UNIT-PRICE ANALYSIS OF CIGARETTE SMOKING*

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In behavioral economics, the ratio of response requirement to reinforcer magnitude is referred to as unit price. Previous research with nonhuman subjects has demonstrated that (a) comparable amounts of food are consumed at the same unit price even though different response requirements and reinforcer magnitudes comprise that unit price and (b) increases in unit price decrease food consumption in a positively decelerating fashion. The present study assessed the generality of these findings to the cigarette smoking of 5 human volunteers. During approximately 18 3-hr sessions, various combinations of response requirement (fixed-ratio 200, 400, and 1,600) and reinforcer magnitude (1, 2, and 4 puffs per bout) were arranged. Consumption (i.e., the number of puffs) generally was comparable at the same unit price independent of the response requirement and reinforcer magnitude comprising that unit price. In addition, increasing unit price generally decreased consumption in a positively decelerating fashion. These results extend the generality of the unit-price analysis to human cigarette smoking. Moreover, these results further support the position that reinforcer magnitude and response requirement are functionally equivalent and interact to determine consumption. The concept of unit price, by integrating and summarizing the effects of those two operations, provides a more parsimonious explanation of the results than do separate evaluations of the effects of response requirement and reinforcer magnitude.

Key words: unit price, fixed-ratio schedules, reinforcer magnitude, cigarette smoking, behavioral economics, drug self-administration, humans

The study of drug dependence has been advanced by the observation that drugs of abuse can serve as positive reinforcers in human and nonhuman animals (Griffiths, Bigelow, & Henningfield, 1980; Young & Herling, 1986). Experimental study of the reinforcing effects of drugs has successfully delineated variables that both promote and modify drug self-administration (see Griffiths et al., 1980, and Young & Herling, 1986, for reviews). Two variables that reliably control drug self-administration are response requirement and drug dose (Griffiths et al., 1980). Response requirement refers to the amount of behavior required to obtain a given dose of a drug. Increasing response requirement typically decreases the amount of drug ingested and can be considered in terms of reinforcer magnitude (Griffiths et al., 1980; Young & Herling, 1986). Drug dose refers to the quantity of drug ob-

tained upon completion of a response requirement. As the drug dose increases, the number of self-administrations first increases and then decreases in an inverted U-shaped fashion (Griffiths et al., 1980).

According to behavioral economics, response requirement and reinforcer magnitude interact to determine consumption (Hursh, 1980). This interaction is quantified as unit price. With regard to drug self-administration, unit price is defined as response requirement divided by dose of the drug per ingestion (Bickel, DeGrandpre, Higgins, & Hughes, 1990). For example, a unit price of 10 is obtained when 10 responses are required to obtain 1 mg of a drug or 20 responses are required to obtain 2 mg of that same drug. According to this analysis, consumption should be comparable at the same unit price independent of the response requirements and reinforcer magnitudes comprising that unit price. Moreover, if unit price does determine consumption, then a single function relating consumption to unit price should be obtained when several unit prices are examined. In economic theory, the relationship between consumption of a commodity and its price is customarily

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Table 1
Subject characteristics.

Subject	Age	Sex	Fagerstrom	Cigarettes per day	Brand	Nicotine/tar (mg/cigarette)
KW	20	F	8	30	Winston Lights	0.6/10
TS	30	M	7	30	Marlboro	1.1/16
JL	49	M	6	30	Marlboro	1.1/16
MO	20	F	7	25	Camel Lights	0.6/10
MA	18	M	6	25	Marlboro Lights	0.8/11

referred to as demand (Lea, 1978; Samuelson & Nordhaus, 1985).

The notion of unit price has been supported by studies employing food as the reinforcer. For example, Collier, Johnson, Hill, and Kaufman (1986) manipulated unit price by presenting three sizes of food pellets (i.e., 22, 45, and 97 mg) according to several fixed-ratio (FR) schedules of reinforcement (i.e., FR 20, 40, 80, and 120). In that study, consumption (i.e., food intake and meal size) was generally the same at the same unit price regardless of the response requirement and reinforcer magnitude making up that unit price. In addition, increases in unit price decreased consumption in a positively decelerating fashion. Hursh and his colleagues extended the unit-price notion further by taking into account not only response requirement and reinforcer magnitude but also lever weight and probability of pellet delivery (Hursh, Raslear, Shurtleff, Bauman, & Simmons, 1988). The results of that study confirmed the equivalence of consumption at the same unit price and replicated the shape of the demand curve reported by Collier *et al.* (1986).

Unit price has not been examined explicitly in drug self-administration. However, a reanalysis of results from drug self-administration studies that manipulated both response requirement and reinforcer magnitude revealed results highly consistent with the unit-price analysis (Bickel *et al.*, 1990). This finding was reliably obtained across drugs (e.g., methohexital, pentobarbital, ketamine, phenylcyclidine, and cocaine), routes of administration (e.g., oral and intravenous), and species (e.g., rhesus monkeys, squirrel monkeys, and rats). Further reanalysis of studies examining the influence of nicotine dose on human cigarette self-administration also obtained results consistent with a unit-price analysis (DeGrandpre, Bickel, Hughes, & Higgins, 1991).

Because the unit-price notion has not been

directly tested in drug self-administration research, the present study prospectively assessed the applicability of unit price to cigarette smoking. Specifically, the study examined (a) whether consumption would be comparable at the same unit price even though different response requirements and reinforcer magnitudes comprised that unit price and (b) whether increases in unit price would decrease consumption in a positively decelerating fashion.

METHOD

Subjects and Apparatus

Three male and 2 female cigarette smokers participated in this study. Subjects were recruited from newspaper advertisements, were in good health, and reported no medication usage or drug/alcohol abuse other than nicotine. To participate in the study, subjects had to score a minimum of 6 on the Fagerstrom's Tolerance Questionnaire, a self-report measure of nicotine dependence (Fagerstrom & Schneider, 1989). Subjects MA, TS, and JL had participated in a previous cigarette smoking study. Table 1 lists other relevant characteristics of the subjects.

The apparatus consisted of an Apple IIe® microcomputer-controlled response console (61 cm by 30 cm by 46.5 cm). The response console contained three Lindsley plungers (Gerbrands No. G6310) centered from left to right on the face of the response console. Subjects responded on the center plunger only. Responses made on the other manipulanda produced no programmed consequences.

Sessions were conducted in an isolated room that contained two response consoles. Subjects MA and TS were tested together, and the other subjects were tested individually. The experimental conditions for Subjects MA and TS were scheduled out of sequence. Subjects were instructed not to talk to each other during a

Table 2
Sequence of conditions (number of puffs and response requirement).

Subject		Ses- sions
KW	2 puffs (FR 1,600, 200, 400), 4 puffs (FR 200, 400, 1,600), 1 puff (FR 400, 1,600, 200)	18
TS	1 puff (FR 1,600, 200, 400), 2 puffs (FR 200, 400, 1,600), 4 puffs (FR 400, 1,600, 200), and 4 puffs (FR 100), 1 puff (FR 3,200)	20
JL	4 puffs (FR 1,600, 200, 400), 1 puff (FR 200, 400, 1,600), 2 puff (FR 400, 1,600, 200)	18
MO	2 puffs (FR 400, 1,600, 200), 4 puffs (FR 1,600, 200, 400), 1 puff (FR 200, 400, 1,600) and 2 puffs (FR 4,000)	19
MA	1 puff (FR 200, 400, 1,600), 2 puffs (FR 400, 1,600, 200), 4 puffs (FR 1,600, 200, 400)	18

session. When not smoking or responding on the plungers, subjects could read a newspaper or magazine. A research assistant was present in the room at all times.

Procedure

Subjects participated in approximately 18 3-hr sessions. Sessions were conducted 2 or 3 days per week with at least 1 day between sessions.

Subjects provided a breath sample during the initial interview that was analyzed for carbon monoxide (CO). Expired air CO is a direct function of the number of cigarettes smoked (Henningfield, Stitzer, & Griffiths, 1980). Prior to each session, subjects were required to provide CO values of 50% of their CO reading obtained during the initial interview. Subjects were instructed to abstain from cigarette smoking for 5 to 6 hr in order to meet this criterion. If this criterion was not met, the session was rescheduled. This occurred only once for 1 subject.

Next, subjects took one uniform puff on their preferred brand (all cigarettes were supplied by the experimenter). The session began 30 min later. This 30-min presession puff was used to equalize the time from last cigarette exposure across subjects (Henningfield & Griffiths, 1981).

Reinforcer magnitude and response requirement were manipulated by varying the number of puffs available and the FR value, respectively. Three baseline sessions were conducted for each puff condition (i.e., 1, 2, and 4 puffs). During these baseline sessions, puffs on a cigarette were available according to an FR 200 schedule of reinforcement. Once the three baseline sessions were completed, the FR value (i.e., FR 200, 400, and 1,600) was manipulated at that puff condition. Each FR pa-

rameter was in effect for a single session during each condition. The sequence of three baseline sessions followed by the manipulation of FR value continued until each puff condition was examined at each FR parameter (see Table 2 for the sequence of conditions). No trends in cigarette consumption were apparent during baseline sessions.

Assessment of the effect of the three response requirements at each of three puff amounts on cigarette consumption produced six unit prices (i.e., 50, 100, 200, 400, 800, and 1,600) (see Figure 1 for an outline of the composition of the unit prices). Three of these unit prices (i.e., 100, 200, and 400) were replicated via different combinations of response requirements and reinforcer magnitudes. Additional unit prices were employed for 2 subjects (i.e., a unit price of 2,000 for Subject MO and unit prices of 25 and 3,200 for Subject TS).

Puffing procedure. Upon completion of the response requirement, subjects lit their preferred brand of cigarette without inhaling. Subjects were required to take the specified number of puffs within a 5-min intertrial interval (ITI) according to a uniform-puff procedure in which the subject takes one uniform puff, inhales, retains the smoke in his or her lungs for 5 s, and then exhales (Griffiths, Henningfield, & Bigelow, 1982). Subsequent puffs were taken at 25-s intervals using the same procedure.

Instructions. Prior to the first session, the following instructions were read to the subject:

Your may earn puffs on a cigarette by pulling this lever (experimenter points to the center lever). During puffs you will be instructed to inhale and hold for 5 seconds and then to exhale. Each time you earn puffs on a cigarette the counter will increase by one. Prior to beginning each day you will be instructed as to

	1 PUFF	2 PUFFS	4 PUFFS
FR 200	200	100	50
FR 400	400	200	100
FR 1600	1600	800	400

Fig. 1. Number of puffs and response requirement making up the six unit prices that were examined. Two replications exist for unit prices of 100, 200, and 400. Each replication is composed of a different response requirement and reinforcer magnitude.

how many puffs you will get. When you have earned puffs you will have 5 minutes to take them. The screen before you will tell you how much time (in seconds) there is remaining in the 5-minute interval. During the interval, you may not earn any more puffs. When the interval ends, the screen will read "You may respond now." If another participant is working in this room it will be unrelated to what you are doing.

Subjects were also given the following daily instruction complete with the parameters for that session:

In this session you can earn — puff(s) on a cigarette. You may earn as many or as few sets of — puff(s) as you would like. Today you will need to pull the lever — times to obtain the — puff(s). When you complete the — responses you will have 5 minutes to take the — puff(s). Remember, you must smoke all your puffs during the 5-minute time-out period.

RESULTS

Figure 2 shows the number of puffs per session as a function of the three replicated unit prices (i.e., 100, 200, and 400). In general, comparable numbers of puffs were obtained at the same unit price, independent of the response requirements and reinforcer magnitudes that comprised that unit price. However, consumption in the one-puff condition tended to be lower relative to consumption in other puff conditions. This was especially true of Subject MO's consumption.

The unit-price demand curve for cigarette consumption is shown in Figure 3. Although the *X* and *Y* intercepts of the unit-price demand curve varied across subjects, they are similar in that consumption decreased as unit-price

increased. In order to test statistically whether the curves positively decelerated, the rate of change in slope of the demand curve was determined by applying a multiple regression equation originally presented by Hursh *et al.* (1988, Equation 4):

$$\log Q = \log L + b(\log P) - aP$$

where *Q* is the consumption of the reinforcer per session, *P* is unit price, *L* is an estimate of the level of consumption that would occur at a unit price of 1.0, *b* represents the initial slope of the demand curve, and *a* is the rate of change in the slope of the demand curve as unit prices increases. For further discussion of this equation see Hursh *et al.* (1988).

In our experiment, the rate of change in slope for Subjects TS, JL, KW, MA, and MO were 0.00024, 0.00006, 0.00017, 0.00038, and 0.00012. Values greater than zero indicate a positively decelerating curve (Hursh *et al.*, 1988). Although the rate of change in slope for all subjects was greater than zero, a statistical analysis indicated that it was significant only for Subject TS, $T(8) = -3.43$; $p = .009$, with Subject MA showing a near significant change in slope, $T(6) = -2.15$; $p = .076$.

Response rate generally increased as unit price increased but became asymptotic at higher unit prices (Figure 4). The response output of Subject TS and MO began to decrease at the higher unit prices, suggesting that an inverted U-shaped function may have been obtained if greater unit prices were examined. Subject MO's responses per session were generally lower for the one-puff condition relative to the other puff conditions. With other subjects, responses per session were generally comparable when unit prices were replicated with different response requirements and reinforcer magnitudes.

DISCUSSION

Previous behavioral-economic research with food-maintained behavior and a recent reanalysis of drug self-administration studies have demonstrated that unit price (i.e., the number of responses required per unit of the reinforcer) determines the consumption of reinforcers (Bickel *et al.*, 1990; Collier *et al.*, 1986; Hursh *et al.*, 1988). The present study extends this previous work by (a) prospectively dem-

Fig. 2. Consumption (number of puffs) at the three replicated unit prices (100, 200, and 400) for each subject. The response requirements and reinforcer magnitudes making up each unit price are shown on the x axis.

Fig. 3. Consumption (number of puffs) as a function of unit prices examined for each subject. Symbols indicate the number of puffs (reinforcer magnitude) that subjects received at that unit price. Replications at unit prices of 100, 200, and 400 are shown.

onstrating that consumption of a drug reinforcer is a function of unit price and (b) demonstrating that the unit-price notion is applicable to human drug self-administration. It is important to note that consumption was comparable at the same unit price independent

of the response requirement and reinforcer magnitude that comprised that unit price. This result indicates, at least with respect to consumption, that response requirement and reinforcer magnitude produce functionally equivalent effects. In addition, the shape of the

Fig. 4. Response output as a function of unit prices examined for each subject. Symbols indicate the number of puffs (reinforcer magnitude) that subjects received at that unit price. Replications at unit prices of 100, 200, and 400 are shown.

demand curve in the present study is similar to that obtained in previous studies (e.g., Hursh et al., 1988) and retrospective reviews (e.g., Bickel et al., 1990; DeGrandpre et al., 1991); that is, as unit price increased, consumption

tended to decrease in a positively decelerating fashion. The broad generality of the demand curve across reinforcers (e.g., food, cocaine, and tobacco cigarettes), routes of administration (e.g., inhalation, intravenous, and oral),

and species (e.g., rat, rhesus monkeys, and humans) suggests that this function describes the consumption of reinforcing stimuli when available according to a ratio schedule of reinforcement.

The functional equivalence of response requirement and reinforcer magnitude suggests that the same shaped function should be obtained if only reinforcer magnitude (i.e., drug dose) or response requirement were manipulated. Consequently, if only dose were manipulated, then the unit price could still be determined (i.e., the inverse of dose). This should permit the vast literature on drug self-administration to be reanalyzed via a common method. Such a reanalysis may permit previously unnoticed generalities or regularities to be discerned. For example, numerous studies have tested the nicotine regulation hypothesis, which specifies that smokers will maintain a characteristic level of nicotine intake when smoking cigarettes of varying nicotine yields. The results of those studies have been characterized as discrepant and contradictory. However, a unit-price analysis of those results showed the findings to be consistent (DeGrandpre *et al.*, 1991); that is, as unit price increased, consumption decreased in a fashion consistent with the data reported in the present study. This finding was obtained even though different manipulations to alter nicotine dose were used and different aspects of smoking behavior were measured. Application of the unit-price notion in this instance revealed regularities in the data that were not discernible by the traditional methods of data analysis and interpretation employed in those studies.

Although unit price generally determined consumption of cigarette puffs in this study, Subject MO's consumption was inconsistent with a unit-price analysis. This subject consumed less during the one-puff condition relative to the two- and four-puff conditions. This finding is similar to data reported by Marquis, Webb, and Moreton (1989; reviewed by Bickel *et al.*, 1990). In that study, three groups of 5 rats were trained to self-administer phencyclidine (0.125, 0.25, or 0.5 mg/kg) under FR 10, 20, 40, and 80 schedules of reinforcement. Consumption of phencyclidine was the same at the same unit price except at the lowest dose. The low-dose group generally consumed less drug at the same unit price than did the other groups self-administering the two higher doses. This result suggests that unit price may not

pertain to small reinforcer magnitudes even though these small reinforcer magnitudes were sufficient to maintain responding under at least some FR values in both our study and that of Marquis *et al.* (1989). Future research should examine whether the pharmacological actions of these drug doses functioned as reinforcers or whether conditioned reinforcing effects associated with their delivery maintained responding.

Another possible limitation of the unit-price analysis is whether consumption decreases in positively decelerating fashion as unit price increases. In the present study, although the rate of change in slope indicated that the slopes were all positively decelerating, the changes in slope were not significant for 4 subjects. Comparison of the curves obtained in the present study with those obtained in other unit-price analyses indicates that we may not have examined unit prices that were low enough to capture the flatter portion of the curve. This speculation could be easily examined in subsequent research. A final possible limitation of the unit-price analysis is the schedule of reinforcement. Although studies employing ratio schedules of reinforcement have produced results consistent with a unit-price analysis, it still remains to be determined whether the unit-price notion pertains to other schedules of reinforcement. For example, it is not clear whether responses per reinforcer, interreinforcement interval (IRI), or some combination of responses and IRI operate in interval schedules as response requirement does in FR schedules.

In drug self-administration studies, one important concern is whether response rate is affected by the direct effects of the drug being self-administered (e.g., the descending arm of the inverted U-shaped dose-effect curve; Griffiths *et al.*, 1980). In the present study, response rate was comparable at the same unit price even though different reinforcer magnitudes were employed. This suggests that either the direct effects of nicotine did not play a role or that only small nicotine doses were ingested. However, data from a study by Le-maire and Meisch (1985; reanalyzed by Bickel *et al.*, 1990) show the comparability of response rate at the same unit price more convincingly. In that study, a unit price of 4 was obtained by providing a different number of deliveries of a constant pentobarbital-ethanol solution (i.e., 2, 4, 8, 16, 32, 64, 128, and 256)

MA

Fig. 5. Consumption (upper panels) and responses per session (lower panels) as a function of the number of puffs obtained after completion of each response requirement (right panels) and as a function of unit price (left panels).

upon completion of different response requirements (i.e., 8, 16, 32, 64, 128, 256, 512, and 1,024). In general, the same response rates were obtained at that unit price. Of course, for each increase in dose there was a corresponding increase in response requirement, which, in turn, may have altered the sensitivity of the baseline behavior to drug effects. Thus, although the role of direct drug effects appears small, the results are not conclusive.

Ultimately, the adoption of the unit-price notion will depend on its utility in research. Three factors may favor the adoption of a unit-price analysis. First, behavioral economics stresses the notion that the multiple determinants of behavior act interdependently; that is, unit price describes and integrates what was

previously considered to be two functionally distinct operations. Figure 5 illustrates this point. Data on consumption and responses per session for Subject MA are shown as a function of reinforcer magnitude (left panels) and as a function of unit price (right panels). The traditional display of these data suggests little order. However, when plotted as a function of unit price, the data show an orderly function that accommodates the data from all conditions.

Second, unit price permits point predictions; that is, if consumption or response output is known at one unit price, then consumption or response output at different response requirements and reinforcer magnitudes that make up the same unit price should be predicted

Fig. 6. Hypothetical consumption data plotted as a function of unit price.

with accuracy (e.g., compare the ability to predict point consumption or response rates via traditional and unit-price curves displayed in Figure 5).

Third, the unit-price notion and the positively decelerating function may permit more accurate comparisons across different reinforcers. For example, consider a hypothetical study examining the effects of an antagonist on self-administration of two drug reinforcers, A and B (illustrated in Figure 6). Reinforcer A is studied at a very low unit price along the flat portion of the curve, and Reinforcer B is studied at a higher unit price near the point at which consumption declines rapidly. Typically, administration of an antagonist decreases the effectiveness of a given dose of drug, which is comparable to decreasing that dose. This, according to behavioral economics, is an increase in unit price. Now if the administration of an antagonist had the same functional effect of increasing unit price by a log unit for both reinforcers, then, although the effect of the manipulation was the same (i.e., increasing unit price by 1 log unit), the consumption of A (A1) would decrease little, whereas the consumption of B (B1) would decrease considerably. Ignoring the unit-price analysis could result in the erroneous conclusion that the effect of the manipulation was greater for Reinforcer B than for Reinforcer A when in fact the difference resulted from examining the two reinforcers at different points along their unit-price demand curves. By examining reinforcers at the same point along that curve (e.g., at Points B and C), the effects of an antagonist on those reinforcers could be assessed accurately.

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