JOURNAL OF THE EXPERIMENTAL ANALYSIS OF BEHAVIOR 1995, 64, 373–384 NUMBER 3 (NOVEMBER)

NORMALIZED DEMAND FOR DRUGS AND OTHER REINFORCERS

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The concepts of behavioral economics have proven to be useful for understanding the environmental control of overall levels of responding for a variety of commodities, including reinforcement by drug self-administration. These general concepts have implications for the assessment of abuse liability and drug abuse intervention and the formulation of public policy on drug abuse. An essential requirement is the ability to compare the demand for different drugs directly in order to assess relative abuse liability, and to compare demand for the same drug under different environmental and biological interventions to assess their ability to reduce demand. Until now, such comparisons were hampered by the confounding effect of varying drug doses and potencies that prevent quantitative comparisons of demand elasticity—sensitivity of consumption and responding to the constraint of price (effort). In this paper we describe a procedure to normalize demand-curve analysis that permits dose- and potency-independent comparisons of demand across drugs. The procedure is shown to be effective for comparing drug demand within and across the drug classes. The technique permits a quantitative ordering of demand that is consistent with the peak levels of responding maintained by the drugs. The same technique is generalized for the comparison of other types of reinforcers under different biological conditions.

Key words: behavioral economics, normalized demand, demand curve, elasticity, drug self-administration, cost, unit price, fixed-ratio schedule, overall response output, cocaine, alfentanil, nalbuphine, methohexital, phencyclidine, rhesus monkeys

Among the many advantages of behavioral economics is its ability to focus our attention on those environmental and biological variables that control an organism's level of performance to obtain specific reinforcers, apart from local patterns of performance or periodicities in consumption. This makes behavioral economics an ideal framework for analyzing behavior that occurs at such high levels in relation to the benefit it confers that it is considered to be "abusive"; an example is substance abuse (Brady & Lukas, 1984; Griffiths, Bigelow, & Henningfield, 1980; Johanson, 1978).

Behavioral economics has been shown to be a valuable tool for analyzing drug self-administration in animal models of drug abuse. Studies have applied economic concepts to the assessment of the level of consumption and its sensitivity to increases in effort to obtain the drug (Bickel, DeGrandpre, Higgins, & Hughes, 1990; Bickel, DeGrandpre, Hughes, & Higgins, 1991; Carroll, Carmona, & May, 1991; Winger, 1993b). Other studies have used these concepts to evaluate the effects of various variables that might alter maintenance of drug self-administration (Carroll et al., 1991; Comer, Hunt, & Carroll, 1994).

In several previous studies, Hursh (1991, 1993) has proposed that behavioral economics can be applied in four general domains for the analysis of drug abuse: (a) *abuse liability,* the assessment of a drug's potential to serve as a reinforcer and the strength of that reinforcer function in comparison with other drugs; (b) *drug interactions,* the capacity for consumption of one drug to either interfere with or enhance the level of performance to obtain another drug; (c) *drug abuse interventions,* the capacity for some change in the context of drug self-administration, including the administration of medications, to alter performance to obtain a drug; and (d) *public policy formulation,* the potential effects of public policy on the general demand for drugs,

The analysis reported here was conducted while the first author was assigned to the Walter Reed Army Institute of Research. The views of the authors do not purport to reflect the position of the Department of the Army or the Department of Defense (para 4-3, AR 360-5). The second author wishes to acknowledge support from U.S. Public Health Services Grants DA 00254, DA 04403, and DA 05951 for experiments described in this report. The research described in this report was conducted in compliance with the Animal Welfare Act and other federal statutes and regulations relating to animals and experiments involving animals and adheres to the principles stated in the *Guide for the Care and Use of Laboratory Animals,* NIH Publication 86-23, 1985 edition.

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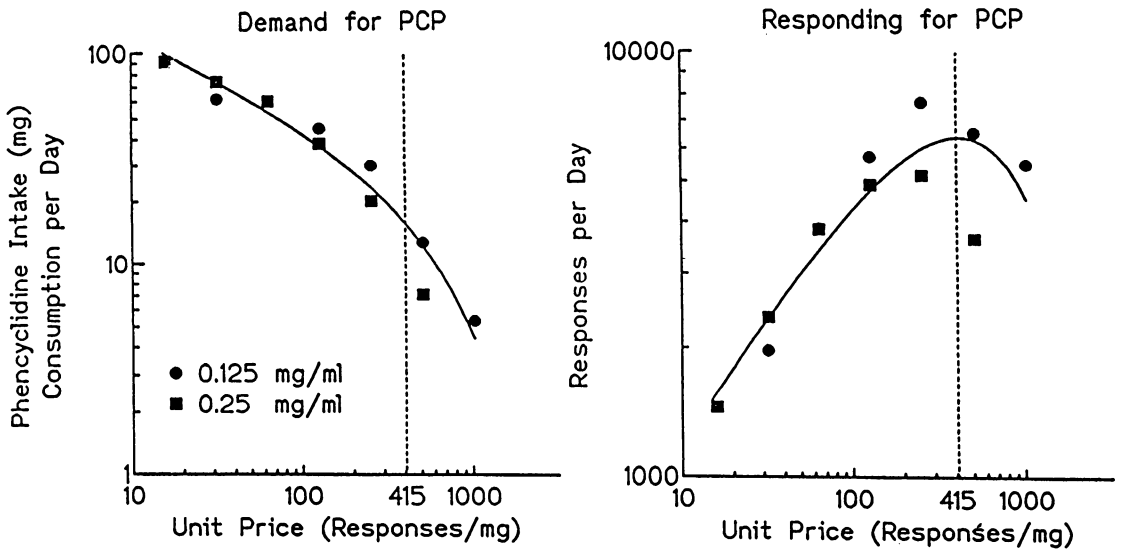

Fig. 1. Representative demand curve (left panel) and response output function (right panel) for phencyclidine (PCP) by monkeys (data from Carroll, 1987). Total daily consumption of drug and total response output are plotted as a function of unit price (responses per mg/ml/reinforcer) with logarithmic scales.

financial expenditures for drugs by the community, revenue potential for drug suppliers, and incentives to engage in criminal behavior to buy or sell drugs. As described previously (Hursh, 1991, 1993), all of these applications hinge on an analysis of demand for drugs and variables that alter demand, particularly elasticity of demand, which is the sensitivity of consumption to changes in price for a unit of drug reinforcement. In this article we describe an advance in the mathematical treatment of demand for drugs that will permit comparisons of elasticity of demand across drug doses and potencies, thereby advancing all four domains of drug abuse analysis using behavioral economics. In addition, we generalize this approach to the analysis and comparison of demand for any group of reinforcers.

Demand-Curve Analysis

The fundamental metric for an economic analysis of drug self-administration is the demand curve (Hursh, 1980, 1984; Hursh & Bauman, 1987; Lea, 1978; Raslear, Bauman, Hursh, Shurtleff, & Simmons, 1988). The demand curve describes the relationship between total consumption of a commodity and its price, expressed as effort per unit of reinforcement. Figure 1 displays a representative demand curve for phencyclidine (PCP) by rhesus monkeys. Two oral doses of drug (0.125 mg/ml and 0.25 mg/ml) were delivered under increasing fixed-ratio (FR) schedules (data from Carroll et al., 1991). The demand curve has two basic features—its initial level at the lowest price and its negative slope with increases in price. When plotted in log-log coordinates, the slope reflects proportional changes in consumption relative to proportional changes in price and is called elasticity of demand. If proportional changes in consumption are small in relation to proportional changes in price (the curve has a slope less negative than -1), then demand is said to be inelastic (Watson & Holman, 1977). In order to demonstrate inelastic demand, the subject must increase the total amount of responding with each increase in price (see Figure 1, right panel).

If proportional changes in consumption are large relative to proportional changes in price (the curve has a slope more negative than -1), then demand is said to be elastic and the corresponding response output function decreases with each increase in price. Most demand curves are nonlinear (as in Figure 1, left panel) and are inelastic across a range of low prices and elastic at higher prices. The accompanying response output function is an inverted U-shaped function (Figure 1, right panel). At the price the demand

curve passes through a slope of −1, the response output function reaches its maximum. This price is called P_{max} (vertical dashed lines in Figure 1) and sets the level of peak output, O_{max}.

The Demand Equation

Hursh has developed an equation that has proven to be very robust as a description of most demand curves (Hursh, Raslear, Bauman, & Black, 1989; Hursh, Raslear, Shurtleff, Bauman, & Simmons, 1988). This equation has three parameters: L for the initial level of demand at minimal price, b for the initial slope of the demand curve at minimal price, and a for the acceleration or increase in slope of the demand curve with increases in price. The equation is as follows, stated in the usual logarithmic units of price (P) and consumption (Q):

$$\ln(Q) = \ln(L) + b[\ln(P)] - a(P). \quad (1)$$

Elasticity of demand is the point slope (first derivative) of this function and is a linear function of price: Elasticity = $b - a(P)$. Price yielding maximal output, P_{max} is:

$$P_{max} = (1 + b)/a. \quad (2)$$

In most cases involving highly reinforcing commodities, the b parameter is negative and close to zero so that elasticity differences are manifest as changes in a. Movements of the entire curve in relation to the y axis (level shifts) are seen as changes in the L parameter. The equation accounts for 90% to 99% of the variance in consumption in studies conducted to date (DeGrandpre & Bickel, personal communication; Foltin, 1991; Hursh, 1991; Hursh et al., 1988, 1989).

Unit Price

A frequently used method for manipulating price in experiments concerned with assessing demand is to increase the value of an FR schedule that sets the number of responses per reinforcer. Hursh (1980), Hursh et al. (1988), and Bickel et al. (1990, 1991) have observed that price is more appropriately thought of as a cost-benefit ratio that sets the amount of effort required for each unit of reinforcement. Within this context, then, decreases in reinforcer magnitude, such as a reduction in drug reinforcer dose, would be functionally equivalent to an increase in effort or FR schedule. Studies have documented this equivalence for reinforcers such as PCP (Hursh, 1991), cigarette puffs (Bickel et al., 1991), food (Hursh et al., 1988), and pentobarbital and ethanol (Bickel et al., 1990). This permits comparison of demand across doses of the same drug.

Potency Differences

In a previous paper (Hursh et al., 1988), reinforcer "value" was shown to be an important factor determining measured demand. Value as used in that paper is more precisely understood to refer to all properties of the reinforcer that determine its magnitude, such as duration, size, and concentration. Magnitude of reinforcement participates in both the determination of total daily consumption (i.e., number of reinforcers × magnitude) and unit price, expressed as a cost-benefit ratio (i.e., responses ÷ magnitude). Magnitude is a general term that encompasses such properties as the size of a food pellet, the concentration of sucrose in a sweet solution, or the caloric density of food. When comparing demand between two commodities, factors that contribute to magnitude should be included in the computation of total consumption and price. For example, it would make no sense to compare demand for two candy bars that are not the same size without somehow equating the demand curves for unit price and total weight. Clearly, one would be willing to pay more for the larger bar but would probably consume fewer of them. In the context of drug reinforces, magnitude would include differences attributable to differences in dose as well as differences in the chemical properties of the drug that determine potency, such as bioavailability and receptor affinity. In order to compare two demand curves from different drugs directly, it would be necessary to account for differences in both dose and potency. Having accounted for these differences in magnitude, any residual differences in elasticity between the two drugs could then be fairly attributed to qualitative properties of the drugs, separate from dose and potency. Bickel et al. (1990) have shown that for a given drug, a dose-independent measure of demand can be easily computed with magnitude expressed in terms of weight of drug consumed. Daily consumption is defined as total weight of drug consumed

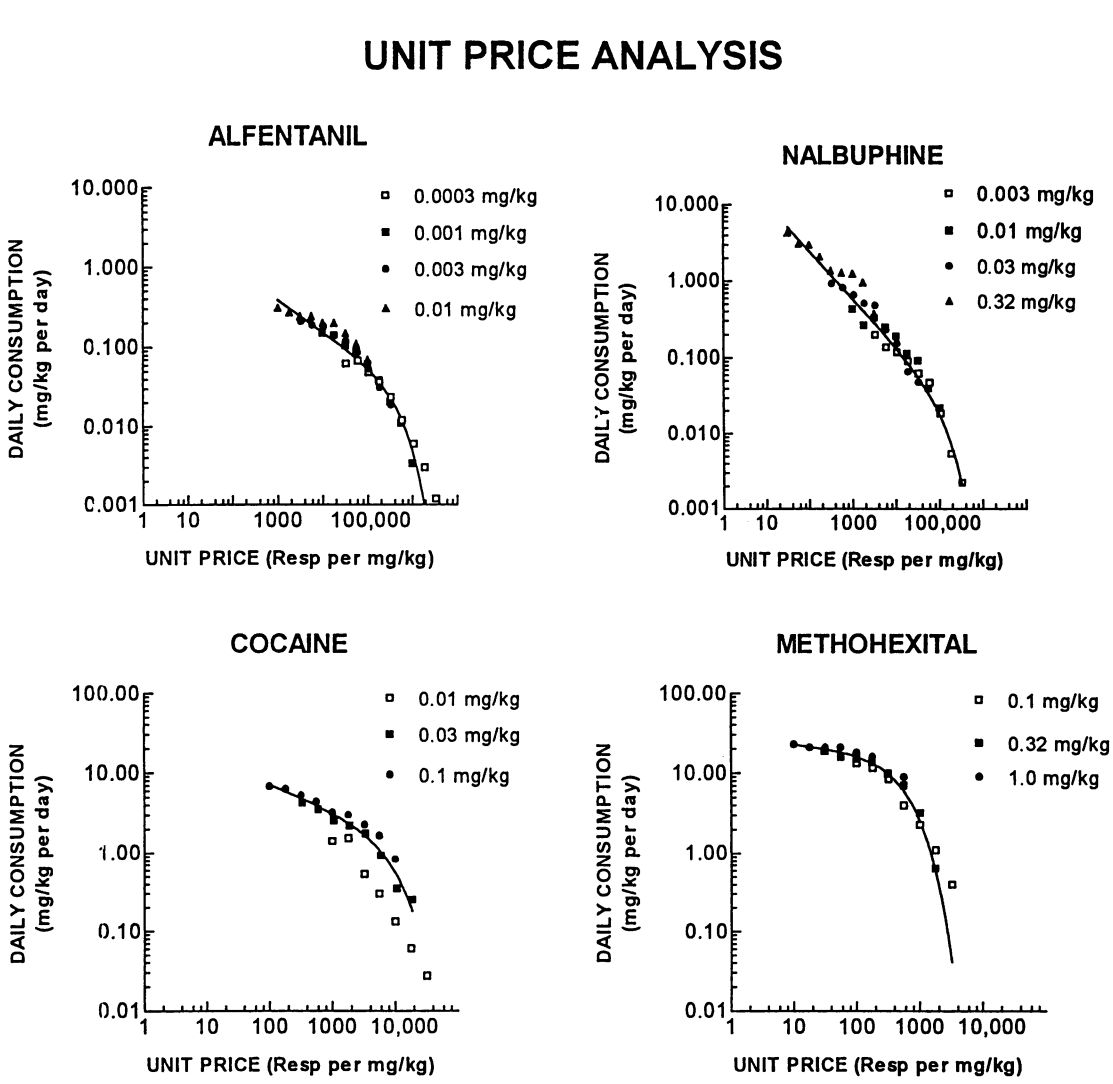

Fig. 2. Unit-price demand curves for cocaine and methohexital (bottom panel) (Winger, 1993a) and for alfentanil and nalbuphine (top panel) (Winger et al., in press). In each, total daily consumption of drug is plotted as a function of unit price (responses per mg/kg/reinforcer) with logarithmic scales.

(adjusted for body weight, e.g., mg/kg) per day, and unit price is number of responses per reinforcer divided by total weight of drug per reinforcer. For a variety of drug reinforcers, different doses yielded similar demand curves when plotted in these terms (Bickel et al., 1990). In other words, by accounting for differences in magnitude of reinforcement using unit price and total drug consumption, there were little or no residual elasticity differences between demand curves for the same drug given at different doses.

Demand curves defined in terms of unit price have two potential shortcomings. First, they cannot compensate for the other component of drug reinforcer magnitude, its potency. For example, when comparing demand for two opioid agonists nalbuphine and alfentanil, Winger, Woods, and Hursh (in press) showed that nearly 10 times as much nalbuphine was consumed at the lowest unit price as alfentanil, but the nalbuphine ceased to support responding at much lower unit prices compared to alfentanil (see Figure 2). As pointed out by Hursh et al. (1988), this pattern of results might be expected if nalbuphine has a lower reinforcer magnitude (such as lower potency) compared to alfen-

tanil, a conclusion that is supported by evidence that nalbuphine has lower potency and efficacy than alfentanil when their thermal analgesic affects were compared (Walker, Butelman, DeCosta, & Woods, 1993). A difference in magnitude does not necessarily indicate a basic difference in elasticity. As discussed above, one food pellet has lower reinforcer magnitude than two food pellets, but demand curves adjusted for this difference in size have identical elasticity of demand (Hursh et al., 1988). However, until now, no method existed to estimate potency differences among drugs to similarly adjust their demand curves so that they can be compared without the confounding effect of quantitative differences in magnitude.

The second shortcoming of unit price is that it makes the strong assumptions that the relationship between dose and magnitude is linear (i.e., that a doubling of dose yields a doubling of reinforcer magnitude). Although this may be true within a range of effective reinforcing doses for most drugs, it is apparently not true for cocaine. Winger (1993b) showed that a unit price conversion of demand for cocaine did not result in a clear convergence to a single function; rather, three demand curves were evident, especially for the lowest dose compared to the higher two doses (see Figure 2, explained below).

The method for computing demand curves described below corrects for any differences in reinforcer magnitude. With drug reinforcers, this includes differences in the arranged dose per reinforcer and differences in potency. The method is essentially a normalization procedure. The average daily consumption observed with the smallest FR at each dose is taken as a reference level of consumption for that dose of the drug. This level is "defended" under the challenge of increasing prices or effort per reinforcer. The normalization procedure defines the demand curve in terms of percentage decreases from this reference level with increases in price. Elasticity of demand is the slope of this function in log-log coordinates and reflects the degree to which the subject emits increasing numbers of responses under increasing effort or response requirements (e.g., FR schedules) to prevent decreases from the average daily level of consumption at the lowest FR.

In order to carry out this normalization procedure, each drug dose is converted to a normalized unit that is this dose expressed as a percentage of the average total daily drug consumption of that dose at the lowest FR. For a drug with an average daily consumption of 100 mg/kg per day at the lowest FR, a dose of 1 mg/kg per reinforcer would be a normalized dose, q, of 1.0, expressed as a percentage computed as follows:

$$q = \frac{d}{(dB)} \times 100,$$

where q is the normalized dose, d is the dose per reinforcer (e.g., injection), and B is the average of reinforcers per day of that dose at the lowest FR. Because dose per reinforcer, d, cancels, we find that normalized dose is simply $q = 100 \div B$. Normalized consumption and price under each FR schedule are computed in terms of the q value for each dose: $P = FR \div q$, and $Q = Rq$. (FR is the fixed-ratio value, R is the number of reinforcers per day at an FR value, P is the normalized price, and Q is the normalized consumption.) Because q is in percentage units, dose and potency are no longer factors in determining the demand function. Also note that at the lowest FR value, Q will always equal 100; hence, all normalized demand curves have a starting level of 100.

Comparisons of Different Doses and Drugs

Data from two previous studies (Winger, 1993a; Winger et al., in press) were used to test the validity of the method. In the first study (Winger, 1993a), consumption of two drugs (cocaine and methohexital) was compared across a range of doses and FR schedules (FRs of 10, 17, 32, 56, 100, 178, 320, 560, and 1,000). In the second study (Winger et al., in press), two opioid agonists (alfentanil and nalbuphine) were compared across doses and a similar range of FR schedules. The subjects were adult rhesus monkeys (7 in Winger, 1993a; 11 in Winger et al., in press). Drug was dispensed through indwelling intravenous catheters. The primary data used for this comparison were the average number of injections per day of each drug and dose across subjects (shown in Table 1). For comparison to the more conventional method of plotting demand curves, Figure 2 displays daily consumption (dose per injection × injections per day) of each drug as a function of unit

Table 1

Mean number of injections per day under each FR schedule and normalized dose (q) for each drug.

Fixed	Alfentanil (mg/kg)				Nalbuphine (mg/kg)				Cocaine (mg/kg)			Methohexital (mg/kg)		
ratio	0.01	0.003	0.001	0.0003	0.32	0.03	0.01	0.00	0.10	0.03	0.01	1.00	0.32	0.10
10	31.0	70.0	151.0	209.0	13.60	31.00	43.10	66.30	69.10	144.13	141.90	23.00	59.00	132.00
18	27.0	63.0	142.0	226.0	9.80	27.50	26.50	45.50	63.80	117.90	153.80	21.00	50.00	115.00
32	24.0	61.0	105.0	163.0	9.30	22.00	33.00	39.20	53.70	85.40	53.30	0.21	47.00	84.00
56	24.0	47.0	91.0	123.0	6.50	17.00	24.90	30.40	44.17	74.00	30.30	21.00	43.00	40.00
100	20.0	40.0	62.0	79.0	4.30	16.00	19.00	20.80	32.17	58.40	13.30	18.00	31.00	23.00
178	20.0	29.0	38.5	40.0	4.00	7.70	11.20	15.80	30.10	31.00	6.10	16.00	22.00	11.00
320	15.0	18.0	20.7	20.0	3.90	5.10	9.20	6.20	22.75	11.70	2.75	10.00	10.00	4.00
560	11.0	10.5	11.2	10.0	3.00	2.20	4.00	1.80	16.50	8.50		9.00	2.00	
1,000	7.0	6.3	3.4	4.0	1.16	1.60	2.20	0.75	8.35			0.00		
q	3.22	1.43	0.66	0.48	7.35	3.23	2.32	1.51	1.45	0.69	0.70	4.35	1.69	0.76

price computed as responses per milligram per kilogram. Fitted demand functions were computed using Equation 1. For cocaine and methohexital (bottom two panels of Figure 2), much higher levels of methohexital were consumed compared to cocaine, but consumption of methohexital ceased at much lower unit prices (note the logarithmic scales). Because the functions are nonlinear and start at different levels, it is impossible to determine which drug supports the more inelastic demand. Similarly, for the two opioids (top two panels of Figure 2), nalbuphine was consumed in much larger quantities than alfentanil but ceased to support responding at lower prices. Within each drug, the computation of unit price yields a single demand curve, except for cocaine, which appears to support higher levels of demand at higher doses (the function was fitted to the higher two doses only).

Normalization for dose. Figure 3 displays these same results in terms of normalized demand curves. The normalized curves all start at a baseline level of 100%. The curves decline at different rates that reflect different rates of change in consumption relative to consumption at the lowest FR as a function of increasing normalized price.

The function fitted to the data was a simplified version of Equation 1. Because normalization resulted in an adjustment of the initial level of consumption to 100%, the level parameter, L, in Equation 1 was replaced with the constant 100:

$$\ln(Q) = \ln(100) + b[\ln(P)] - a(P). \quad (3)$$

Although Equation 3 is a two-parameter function, the overall model continues to have three parameters because normalized dose, q, used to transform price and quantity consumed, is an empirically derived parameter based on the average number of injections under each drug dose at the lowest FR. The equation was fitted to the pooled data for each drug across all doses, except the lowest dose of cocaine. The values for normalized dose, q, used for the analysis are shown in Table 1. The results of the regression analysis are shown in Table 2. This normalized version of the demand equation accounted for 92% to 96% of the variance in the data shown in Figure 3. The average R^2 was .935, slightly better than that found with the analysis of unit price shown in Figure 2 (mean R^2 of .933). The fit to various doses of alfentanil was superior with normalization compared to unit price, with R^2 of .94 and .89, respectively; fits were approximately equal for the two techniques with methohexital and nalbuphine, and the fit was worse for cocaine with normalization compared to unit price, with R^2 of .92 and .95, respectively. The point of maximal output (elasticity of -1), P_{max}, was computed using Equation 2 and is shown in Table 2 and Figure 3 as a vertical dotted line. It can be seen that P_{max} is higher for alfentanil and cocaine than for nalbuphine and methohexital. This indicates greater inelasticity of demand for alfentanil and cocaine in this behavioral procedure.

The normalization procedure was successful in correcting for dose differences, such

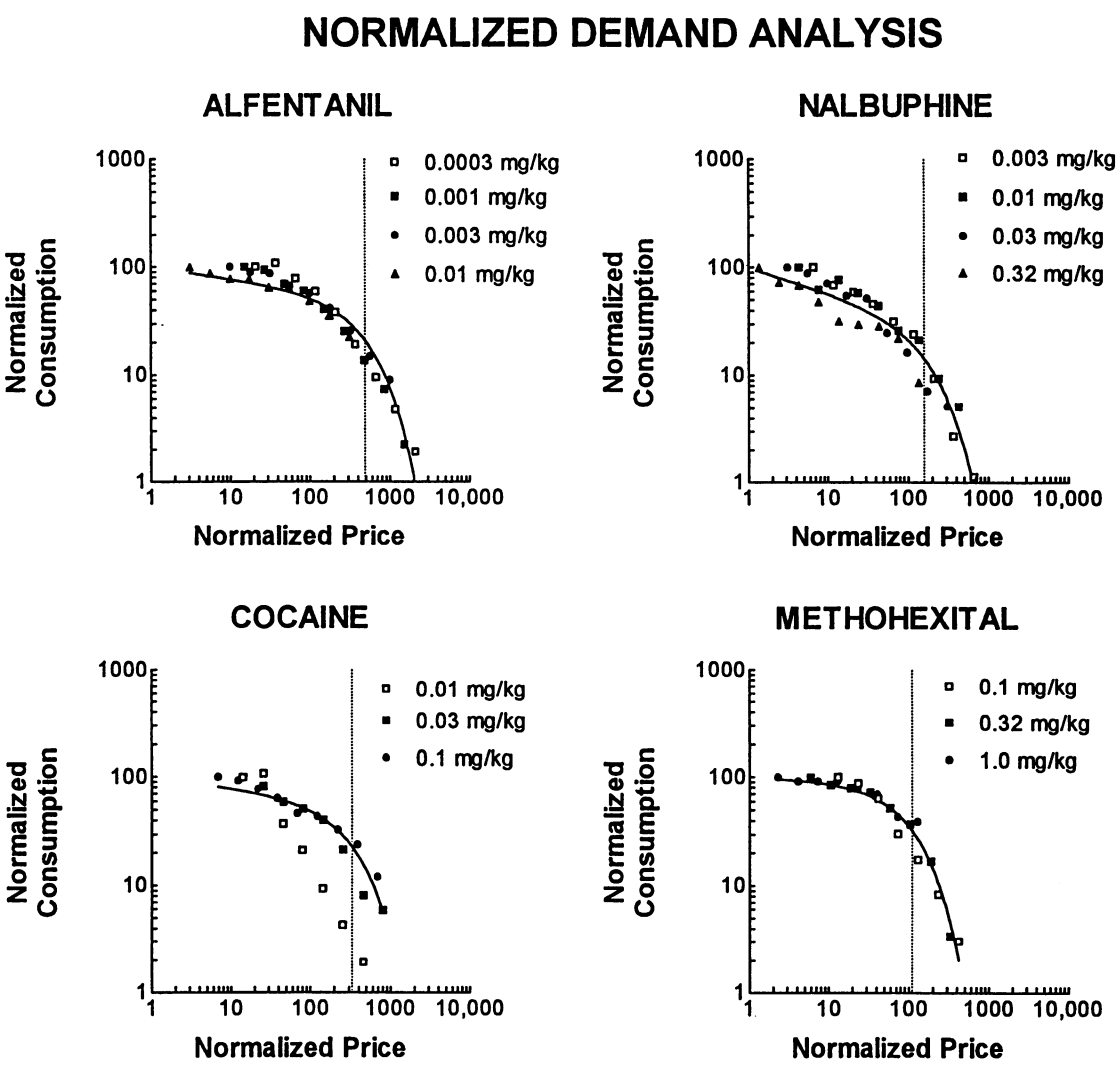

Fig. 3. Normalized demand curves for the drugs analysis, nalbuphine, cocaine, and methohexital (Winger, 1993a; Winger et al., in press) by monkeys. Normalized consumption is plotted as a function of normalized price with logarithmic scales (see text for explanation). The dotted line represents the point of peak responding, P_{max}.

Table 2

Results of regression analysis of data in Table 1 and Figure 3 using Equation 3 applied to normlized prices and consumptions pooled across doses of each drug. Values of q used for normalization are shown in Table 1. Shown are parameter estimates, R^2, and P_{max} values for each drug.

Parameter	Alfentanil	Nalbuphine	Cocaine	Methohexital
a	0.00184	0.00486	0.00273	0.00883
b	−0.1071	−0.2287	−0.09729	−0.02946
R^2	0.94	0.92	0.92	0.96
P_{max}	485.8	158.7	331	110

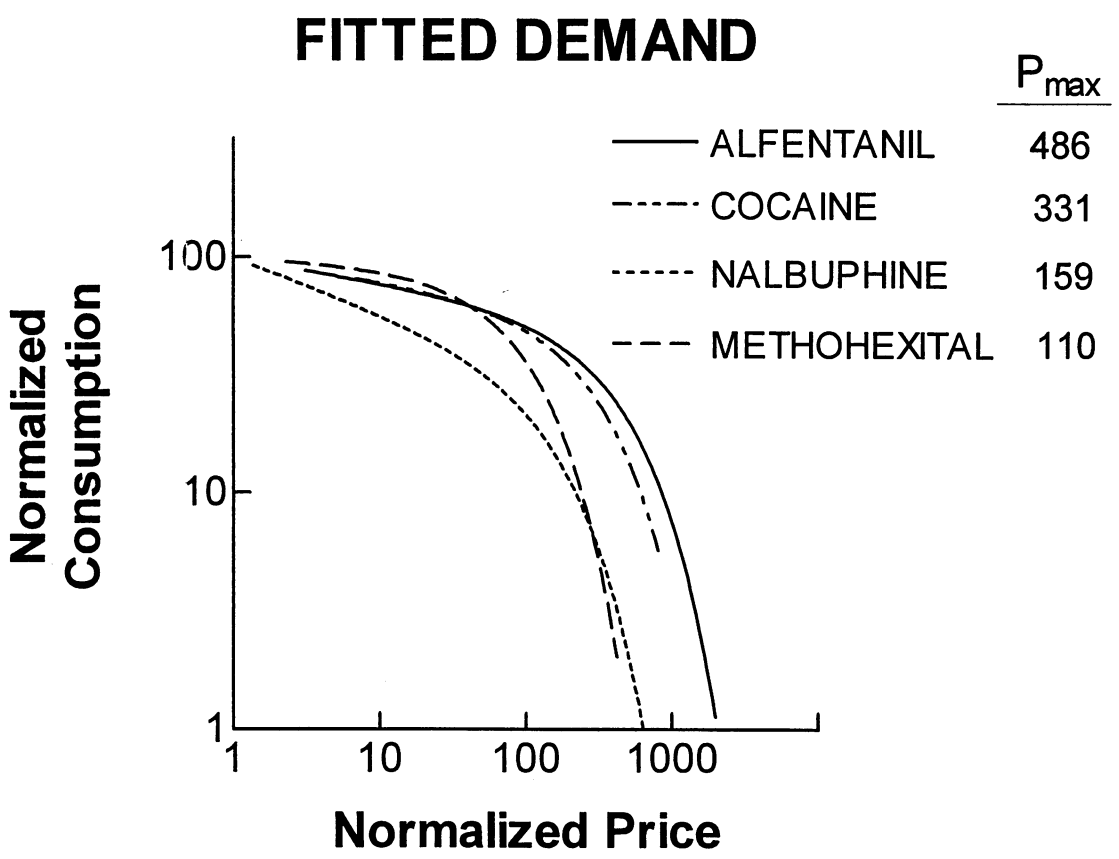

Fig. 4. Fitted functions to the normalized demand curves in Figure 3. Values of P_{max} for each drug are shown as one metric for ordering level of demand. See text for explanation.

that the data for a single drug converge to a single function, except for the lowest dose of cocaine; this appears to support a much more elastic and linear demand curve, not unlike the results with the analysis of unit price in Figure 2. This persistent difference between demand for the lowest dose of cocaine and higher doses supports one of two conclusions: (a) that normalization is no better than unit price in correcting for nonlinearities between dose and magnitude, or (b) that the lowest dose of cocaine differs qualitatively from higher doses and represents more than a quantitative magnitude shift.

It is difficult to discriminate firmly between these two conclusions; however, normalization certainly uses the subjects' own evaluation of the drug in terms of total consumption to correct for dose differences. One would expect that this would reduce, if not eliminate, any nonlinearities between dose and magnitude. The fact that the difference between the lowest dose and higher doses appears to be unchanged under these conditions seems to support the second conclusion that more than a magnitude shift is involved. One interpretation is that the lowest dose of cocaine is only a marginally effective primary reinforcer and derives its strength as a reinforcer from some form of conditioned reinforcement due to sensory similarities to the effects of higher doses. It might not be surprising that a conditioned reinforcer supports qualitatively different demand compared to primary reinforcers. See Bickel, DeGrandpre, and Higgins (1993) for further discussion of this issue.

Normalization for potency. The correction for potency can be seen most clearly in Figure 4, in which the fitted functions were plotted together for comparison. The demand curves for alfentanil and cocaine were very similar

and showed the least elasticity of the group. Methohexital showed a small initial slope that rapidly increased such that it showed the lowest consumption at the highest normalized prices. Nalbuphine had the greatest initial slope (b in Equation 3) but an acceleration parameter (a in Equation 3) about half that of methohexital.

A convenient way to compare elasticity across demand curves that have continuously varying slopes and elasticities is in terms of the point on the price dimension at which they each reach a slope of −1.0. This happens to be the point at which responding reaches its peak, the defined boundary between inelastic and elastic demand. The greater the general elasticity of a demand curve, the lower the price that generates peak response output. This point is the price with maximum output, P_{max}, and is shown in Table 2 and Figure 4. Alfentanil showed peak responding at the highest price of 486, followed by cocaine at 331. Nalbuphine and methohexital had P_{max} values less than half those of the other two drugs (159 and 110, respectively). Assessment of demand based on comparison of elasticities indicated by P_{max} values gives an ordering as follows: alfentanil > cocaine ≫ nalbuphine > methohexital.

One drawback of comparing demand entirely in terms of differences in elasticity is that it ignores differences in *level* of consumption that could significantly affect the total amount of performance emitted per day to obtain the reinforcer. Another approach to assessing demand that considers both elasticity and level of demand is in terms of area under the normalized demand curve. By inspection, this leads to a slightly different ordering as follows: alfentanil ≅ cocaine ≫ methohexital > nalbuphine. The area method gives an ordering consistent with the peak amounts of responding maintained by each drug. This is not surprising. If one draws a rectangle under each curve bounded on the x axis by P_{max} and bounded on the y axis by the level of demand at P_{max}, the area of that rectangle in arithmetic units is mathematically equal to the peak amount of responding, as illustrated in Figure 5.

If FR_{max} is the FR value at P_{max}, R_{max} is the number of reinforcers at P_{max}, and O_{max} is the peak response output at P_{max}, then

$$\text{area} = \frac{FR_{max}}{q} \times qR_{max}.$$

The q values cancel, reducing to: area = $(FR_{max}) \times (R_{max}) = O_{max}$. Because the units of FR are responses per reinforcer and the units of consumption (R) are reinforcers, the reinforcer units cancel, giving the response level at P_{max}, which is O_{max} or maximum output of responding. Maximum output is sensitive both to changes in elasticity that alter P_{max} and to changes in the level of consumption, reflected in R_{max}. Also, the calculation of this area and O_{max} does not include a term for q, the normalized dose. This means that the area defined by P_{max} under the demand curve and its mathematical equivalent, O_{max}, peak response output, are dose- and potency-independent metrics for comparing demand. These features of O_{max} make it a sensitive tool for direct comparison and quantitative ordering of demand, both within and across the drug classes (stimulant, sedative, and opioid) represented by these four drugs.

The procedure reported here for computing normalized price is mathematically similar to an earlier proposal by Timberlake and Peden (1987). They transformed each response requirement to reward density, which was mathematically equivalent to q/FR, the inverse of normalized price as presented here. They proposed that all response-rate functions should converge to a single curve when plotted as a function of reward density. By implication, this predicts that all normalized demand curves should overlap and have equal P_{max}. The results shown in Figures 3 and 4 confirm this prediction for different doses of a single drug but contradict the prediction across different drugs.

Other Reinforcers

The method described here may be used to compare elasticities of any reinforcers. For example, in Hursh et al. (1988), demand for food by normal monkeys was compared to demand by monkeys with lesions of the ventromedial nuclei of the hypothalamus (VMH) which produce hyperphagia and obesity (data from Hamilton & Brobeck, 1964). Compared to normal monkeys, obese VMH monkeys eat much more food at low FRs and less food at high FRs. This has led to a two-factor theory of how this lesion alters food regulation. First,

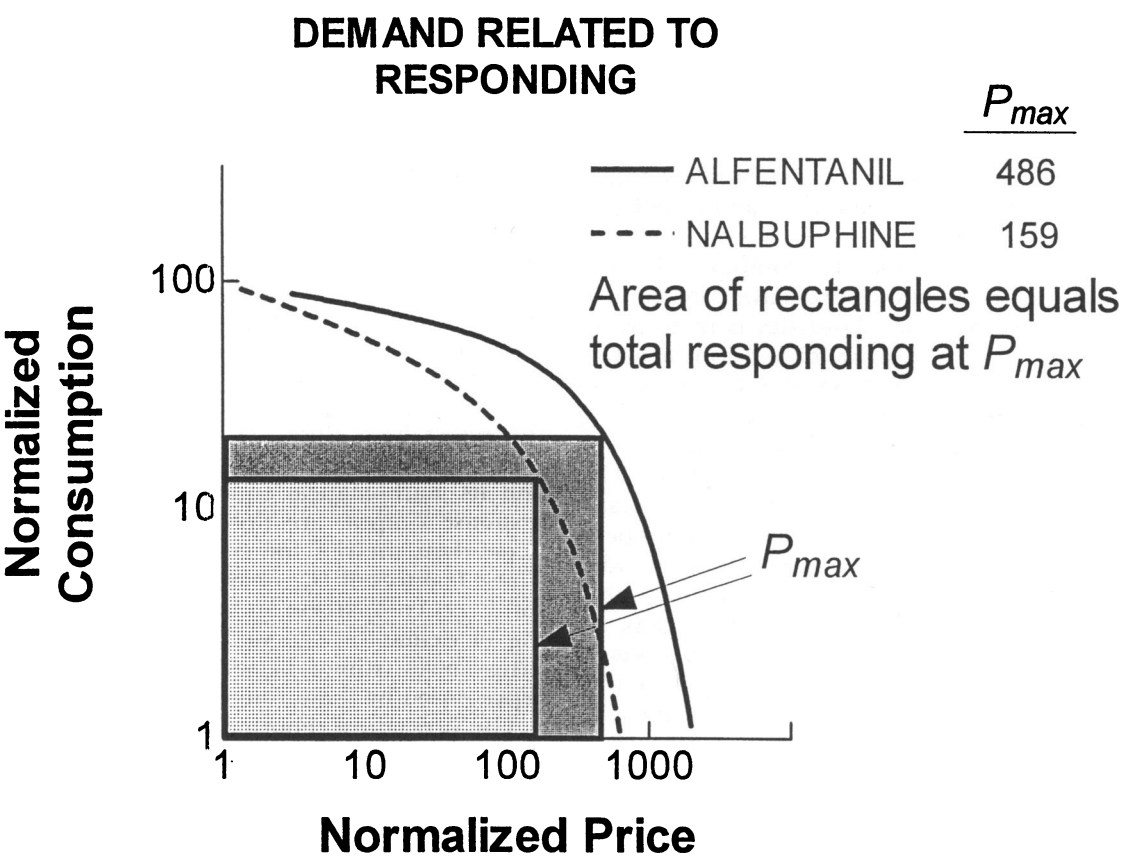

Fig. 5. Illustration of the relationship between area under the demand curve, as bounded by P_{max} and the level of demand at P_{max}, and the total level of responding at P_{max}, known as O_{max}. This area under the demand curve is an alternative metric for ordering level of demand and is consistent with the peak level of responding maintained by the drug.

it increases the baseline set point for satiety. Second, it reduces overall drive for food, leading to greater sensitivity to constraints such as FR schedules. Hamilton and Brobeck tested monkeys under a series of FR schedules that ranged from FR 1 to FR 1,024 in a closed economy (Hursh, 1980, 1984). Obese subjects ate 2.7 times as much food as normal subjects at FR 1 but consumed less food at FR values greater than FR 64.

Hursh et al. (1988) proposed that a quantitative magnitude difference in the food as processed by the two groups could account for both aspects of consumption. To test this hypothesis, we applied the normalization procedure to those data; the results are displayed in Figure 6. Normalization treats consumption at FR 1 as 100% for both groups. Each food pellet represented a different proportion of each group's normal intake. For the normal group, each food pellet was 1.25% of baseline consumption (q = 1.25). For the obese subjects, each pellet was only 0.46% of daily intake (q = 0.46). Thus, for obese animals, each pellet was worth only about 37% as much as a pellet for a normal monkey. This represents a quantitative magnitude difference that must be taken into account to compare demand by the two groups fairly. In particular, equivalent FR values had functionally larger cost-benefit ratios for the obese animals. This magnitude difference is compensated for when the demand curves are plotted in normalized units. Figure 6 shows that when equal prices represent equivalent cost-benefit ratios, the two demand curves show equal sensitivity to price increases and converge to a single function. In other words, the

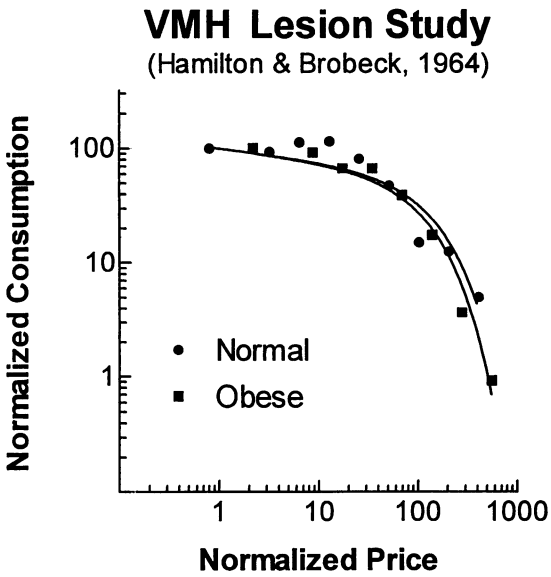

Fig. 6. Normalized demand for food by normal and obese monkeys with VMH lesions. Fitted demand curves to the data from the two groups are nearly identical, indicating similar elasticities of demand in the face of increasing normalized prices (data from Hamilton & Brobeck, 1964).

normalized demand curves reveal nearly identical elasticities across the range of prices. Both normal and obese animals defended their baseline levels of consumption to the same degree in the face of equivalent increases in the normalized price of food. One can infer from this, then, that the lesion has only one effect on food consumption: It alters the set point for satiety represented by the differences in the maximum daily consumption at the lowest FR. This, in turn, alters the functional magnitude of each pellet in terms of its contribution to satiety and, further, alters the functional cost of each FR schedule.

Implications

If one can draw an analogy between this lesion study and strategies to alter demand for drugs biologically, the normalization procedure will permit researchers to determine if such interventions merely alter baseline potency, analogous to the level shift in food consumption produced by VMH lesions, or truly alter elasticity of demand, as seen in the differences between, for example, demand for cocaine and methohexital in Figure 4. In particular, it would be valuable to compare the effectiveness of antagonists that reduce the potency of the target drug to interventions that provide substitute agonists, which, based on the analysis in Hursh (1991), would be expected to produce an increase in demand elasticity for the target drug. The normalized demand procedure described here would permit a fair comparison of interventions independent of quantitative shifts in reinforcer magnitude of the target drug. Only those interventions that increase elasticity and reduce either P_{max} or the area under the demand curve would be expected to reduce the peak level of performance to obtain the drug and remediate the adverse social consequences that attend such excessive behavior.

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Received January 12, 1995
Final acceptance June 27, 1995