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REVIEW

Warren K. Bickel · R. J. DeGrandpre
Stephen T. Higgins

The behavioral economics of concurrent drug reinforcers: a review and reanalysis of drug self-administration research

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Abstract In economics, goods can function as substitutes, complements, or be independent of one another. These concepts refer to increases, decreases, or no change in the consumption of one item as the price of a second item increases. This review examined whether these economic terms can be used to describe relationships between concurrently available reinforcers in drug self-administration research. Sixteen drug self-administration studies that examined the effects of concurrent reinforcers were identified through a MEDLINE search. Across these studies, the following substances were employed: caffeinated coffee, cocaine, etonitazene, ethanol, heroin, food, methadone, morphine, nicotine cigarettes, pentobarbital, phencyclidine, sucrose and water. These studies were reanalyzed and the results were shown to be consistent with these economic notions. These analyses also showed that relationships among the concurrently available reinforcers were reliable within and across studies, that concurrently available reinforcers can affect each other asymmetrically, and that the relative price may determine the magnitude of effect for substitutes. These findings suggest that these economic concepts may be useful in characterizing the type and magnitude of interactions between concurrently available reinforcers and may suggest potential mechanisms that determine these relationships.

Key words Behavioral economics · Caffeinated coffee · Cocaine · Complements · Concurrent schedules of reinforcement · Cross-price elasticity · Ethanol · Etonitazene · Drug self-administration · Heroin · Food · Methadone · Morphine · Nicotine cigarettes · Pentobarbital · Phencyclidine · Reinforcer interactions · Substitutes · Sucrose · Water

Introduction

One contemporary view of drug dependence focuses on individuals giving a higher priority to drug use than to other behaviors that once had greater value (Jaffe 1990; Schuster 1990). This view suggests a functional approach in which understanding drug dependence requires the identification of factors that render drug taking the preferred choice relative to the larger number of alternative activities available to an individual (Vuchinich and Tucker 1988). Viewed as choice, drug dependence becomes an issue of understanding how qualitatively different reinforcers, when concurrently available, interact with one another.

One way to study how concurrently available reinforcers interact is to apply concepts employed by behavioral economics (Allison 1979; Hursh 1980). Behavioral economics is a research area developed within the field of behavior analysis that applies consumer demand theory to the study of behavior. Recent extensions of behavioral economics to drug self-administration research has demonstrated that the economic concepts of demand elasticity, income, and unit price pertain to drug reinforcement (Bickel et al. 1990, 1991; DeGrandpre et al. 1993a). However, the vast majority of these studies have examined arrangements where only a single reinforcer was available. Few studies have employed economic principles in studying concurrent schedules of drug reinforcement (e.g., Carroll et al. 1991; Bickel et al.

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Warren K. Bickel (✉) · R. J. DeGrandpre · Stephen T. Higgins
University of Vermont, Human Behavioral Pharmacology Laboratory, Department of Psychiatry, 38 Fletcher Place, Burlington, VT 05401, USA

1992), and therefore their utility in this area remains uncertain.

According to economics, concurrently available reinforcers interact in one of three ways that describe points along a continuum (Allison 1983; Hursh and Bauman 1987). At one end of the continuum, concurrently available reinforcers function as *substitutes*; that is, as the price of one reinforcer increases (e.g., Coca Cola) and its consumption decreases, the consumption of a second reinforcer with a constant price increases (e.g., Pepsi). At the other end of the continuum, concurrently available reinforcers function as *complements*; that is, as the price of one reinforcer increases (e.g., watching a motion picture in a theater) and its consumption decreases, the consumption of a second reinforcer with a constant price (e.g., popcorn) also decreases. Between these two extremes, two reinforcers may have no effect on one another, and therefore are defined as *independent*; that is, as the price of one reinforcer increases (e.g., Coca Cola) and its consumption decreases, consumption of a second reinforcer (e.g., watching a motion picture in a theater) with a constant price remains unchanged. These three relations are measured by cross-price elasticity coefficients. Cross-price elasticity is the proportional change in consumption of one reinforcer when there is a change in the price of another reinforcer. This coefficient is equivalent to the sign and the slope of consumption of the reinforcer with the unchanged price when plotted in log-log coordinates against the price of the reinforcer whose price has changed (Samuelson and Nordhaus 1985). More specifically, cross-price elasticity coefficients greater than zero, less than zero, and equal to zero, represent the quantitative definition of substitutable, complementary, and independent reinforcers, respectively (Hursh and Bauman 1987; Bickel et al. 1992).

In this paper, we addressed whether the three types of relationships between reinforcers can characterize the data from studies of drug self-administration where concurrent reinforcers were available.

Materials and methods

To identify research reports relevant for the reanalysis, a MEDLINE search from 1966 through 1992 was conducted using three key words: drug self-administration, drug interaction, and reinforcement schedule. The reference sections of the studies identified by the search were examined for additional relevant studies. All studies meeting four inclusion criteria were reanalyzed. The inclusion criteria were: (1) the presence of at least two programmed reinforcers in the experimental situation, (2) the drug dose or schedule associated with one reinforcer was varied, while simultaneously holding constant the drug dose or schedule of another concurrently available reinforcer, (3) the primary dependent variable, consumption (intake), or the independent variable, schedule parameter was reported, and (4) more than three changes of either dose or schedule value were examined. The last criterion was employed for reasons of statistical analysis (see below).

Sixteen studies were identified (see Table 1). Four studies had the same drug reinforcer concurrently available, five had two different drug reinforcers, and seven had a drug and a nondrug reinforcer concurrently available. Across the studies, ten different drug reinforcers (cocaine, caffeine via coffee, ethanol, etonitazene, heroin, methadone, morphine, nicotine via cigarettes, phencyclidine, and pentobarbital) were administered via three routes (inhalation, intravenous, and oral) to four species (baboons, humans, rats, and rhesus monkeys). Of these studies, four examined the effects of manipulating each reinforcer while holding the other constant, and thus provided two sets of data for the reanalysis (the effects of manipulating price of reinforcer A on consumption of B, and the effects of manipulating price of reinforcer B on consumption of A). These four studies permit an assessment of whether interactions between reinforcers are symmetrical.

The data for both the *manipulated* (schedule or dose parameter systematically varied) and the *unmanipulated* (schedule and dose parameter held constant) reinforcers were analyzed as a function of unit price (i.e., response requirement/reinforcer magnitude) of the manipulated reinforcer (Hursh et al. 1988). Unit price permits a wide variety of experimental operations to be incorporated into a single term, and thereby permits the effects of those operations to be examined in a uniform fashion (Bickel et al. 1993). Given that reviews of unit price are available elsewhere, it will not be repeated here (Bickel and DeGrandpre 1992; Bickel et al. 1993; DeGrandpre et al. 1993b).

Consumption was calculated by multiplying the number of infusions or drug deliveries by the drug dose (see original report to identify the units for drug dose). As noted above, the estimated slope of the consumption of the unmanipulated reinforcer when plotted as a function of the unit price of the manipulated reinforcer in log-log coordinates provides a measure of the cross-price

Table 1

Author	Date	Reinforcer	Subjects	Manipulation
Bickel et al.	1986	Methadone	Humans	Dose of methadone varied
Bickel et al.	1992	Cigarettes, coffee	Humans	FR varied for both coffee and cigerettes
Carroll	1987a	Ethanol, PCP	Rhesus monkeys	Dose varied for both PCP and ethanol
Carroll	1987b	PCP	Rhesus monkeys	Concentration varied for PCP
Carroll et al.	1991	Saccharin, PCP	Rhesus monkeys	FR varied for saccharin
Carroll et al.	1979	Etonitazene, water	Rats	Concentration of etonitazene varied
Dworkin et al.	1984	Morphine,food, water	Rats	Dose of morphine varied
Griffiths et al.	1981	Food, heroin	Baboons	Dose of heroin and number of food pellets varied
Iglauer and Woods	1974	Cocaine	Rhesus monkeys	Dose varied for cocaine
Meisch and Lemaire	1988	Pentobarbital	Rhesus monkeys	Dose varied for pentobarbital
Mello et al.	1987	Alchohol, cigarettes	Humans	Drinks per day varied
Mello et al.	1980a	Heroin, cigarettes	Humans	Number of doses per day of heroin varied
Mello et al.	1980b	Alchohol, cigarettes	Humans	Number of drinks of alcohol consumed varied
Roehrs and Samson	1981	Ethanol, water	Rats	FR for alcohol varied
Samson et al.	1982	Sucrose, ethanol	Rats	Concentration of sucrose varied
Samson et al.	1983	Sucrose, ethanol	Rats	FR for sucrose varied

elasticity between the concurrently available reinforcers. A linear regression analysis was used to derive an estimate of slope of the consumption data from the unmanipulated reinforcer for each study. The percent of variance (R^2) was also calculated for the unmanipulated reinforcer in each study (i.e., a comparison between the consumption values predicted by the linear equation and the obtained consumption values). Slopes, R^2 values and the associated statistically significant P values ($P < 0.05$) are presented in Tables 2, 3 and 4.

Data displayed graphically in the figures represent all the data from a study if the study reported only group means, or data from the subject with the lowest P value if individual subject data were reported (the subject that is in bold faced type in Tables 2, 3 and 4 is the one used for figures). If more than one subject's data shared the lowest P value, then the subject's data with both the lowest P value and the slopes closest to the mean slope for all subjects in that study were plotted.

Finally, the data are displayed in three figures (Figs 1, 2, and 3) and in three tables (Tables 2, 3, and 4) which correspond to the aforementioned three types of reinforcer interactions. Because obtaining zero slopes that define independence is unlikely (that is, nonsystematic changes in consumption may result in small magnitude slopes), we have arbitrarily defined for the purposes of this paper, positive slopes greater then 0.2 (increasing consumption), negative slopes less than −0.2 (decreasing consumption), and slopes between + 0.2 and −0.2 (unchanged consumption) as indicative of substitutable, complementary and independent reinforcers, respectively. Within each figure, the data were arranged by the sign and magnitude of the slope of the regression equation used to quantify changes in consumption of the unmanipulated reinforcer as a function of the unit price of the manipulated reinforcer. Note that although substitutability is measured, these studies manipulated the price of a reinforcer, but did not compensate for those effects on income (opportunity to obtain drug). Therefore, whether substitutability results solely from substitution effects or results also from income effects is not discernible.

Results

Eight sets of data met the definition of substitutes (see Fig. 1); that is, as the price of one reinforcer increased, consumption of a second reinforcer with a constant price increased. For the studies plotted in Fig. 1, the slopes of the data for the unmanipulated reinforcer ranged from 0.22 to 3.9. As would be expected, the four data sets with the greatest magnitude slopes (the strongest substitutes) had the same drug reinforcer concurrently available. For example, the study with the strongest substitution effect arranged two sources of methadone and manipulated the methadone dose for one of the two sources (Bickel et al. 1986). As the unit

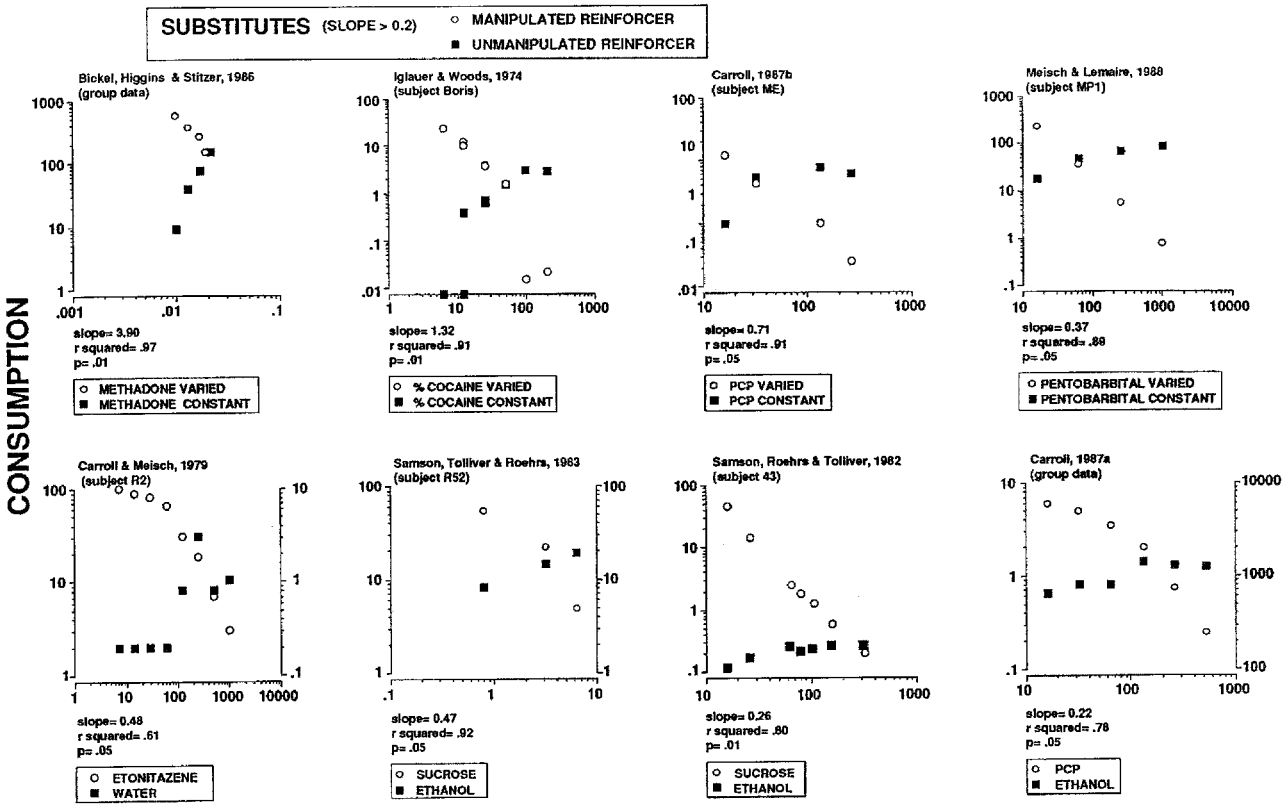

Fig. 1 Consumption of the two concurrent reinforcers that met the definition of substitutes as a function of the unit price (response requirement/dose of drug) of the manipulated reinforcer for eight reanalyzed data sets (see Table 1 for an outline of these studies). The studies are arranged from left to right in a descending order of the slope of the regression line for the unmanipulated reinforcer. When plotted on double-Y axes, the first and second axis refer to the manipulated and unmanipulated reinforcer, respectively. Data plotted on the X axis are instances where there was no consumption of the reinforcer (consumption=0.00). Note that the data are plotted on double-log coordinates

Table 2 Substitutes (slope > 0.2)

Study	r^2	P	Slope
Bickel et al. (1986) (group data)			
Effect of methadone varied on methadone			
methadone	0.97	0.01	*3.90*
Iglauer et al. (1974) (individual subjects)			
Effect of cocaine varied on cocaine			
Bernadette	0.88	0.05	1.73
Boris B = 0.1	0.91	0.01	*1.32*
Boris B = 0.05	0.92	0.05	1.23
Rico	0.83	0.01	1.67
Willis	0.19	–	*0.70*
Mean			1.33
Carroll et al. (1987b) (individual subjects)			
Effects of PCP varied on PCP			
MA	0.88	–	0.35
MA1	0.88	–	0.86
MB	0.73	–	1.48
MB1	0.39	–	0.26
MB2	0.92	0.05	0.46
ME	0.91	0.05	*0.71*
MG2	0.93	0.05	1.01
MS	0.87	–	*1.38*
Mean			0.81
Meisch and Lemaire (1988) (individual subjects)			
Effect of pentobarbitol varied on pentobarbital			
First determination (dose in mgs.)			
MP1 dose = 0.0625	1.00	C	0.11
MP dose = 0.25	1.00	C	2.49
MP1 dose = 1	1.00	C	0.37
MP1 dose = 4	1.00	C	0.48
MP dose = 0.0625	0.58	–	0.51
MP dose = 0.25	0.74	–	1.22
MP dose = 1	0.92	–	1.76
MP dose = 4	0.62	–	0.22
MG2 dose = 0.0625	1.00	C	−0.64
MG2 dose = 0.25	1.00	C	0.00
MG2 dose = 1	1.00	C	2.29
MG2 dose = 4	1.00	C	0.24
MW dose = 0.0625	0.85	–	0.32
MW dose = 0.25	0.77	–	1.41
MW dose = 1	0.87	–	1.63
MW dose = 4	0.68	–	0.50
Second determination (dose in mg)			
MP1 dose = 1	0.89	0.05	*0.37*
MP1 dose = 4	0.74	–	0.01
MPdose = 0.25	0.81	0.05	1.29
MP dose = 1	0.90	–	1.09
MP dose = 4	0.78	–	0.26
MG2 dose = 1	0.69	–	0.81
MG2 dose = 4	0.57	–	0.15
MW dose = 0.25	0.94	0.05	1.03
MW dose = 1	0.66	–	0.90
MW dose = 4	0.55	–	*0.04*
Mean for each subject			
Mean MP1			0.64
Mean MP			0.98
Mean MG2			0.32
Mean MW			0.83
Mean for each dose			
Mean 0.0625			0.08
Mean 0.25			1.24
Mean 1			1.15
Mean 4			0.24

Table 2 Continued

Study	r^2	P	Slope
Carroll and Meisch (1979) (individual subjects)			
Effects of etonitazene varied on water			
R1	0.37	–	0.22
R2	0.61	0.05	*0.48*
R3	0.44	–	0.26
R4	0.37	–	*−0.27*
Mean			0.18
Samson et al. (1983) (individual subjects)			
Effect of sucrose varied on ethanol			
51	0.26	–	0.08
52	0.92	0.05	*0.47*
54	0.94	–	0.51
55	0.97	0.01	*0.22*
Mean			0.32
Samson et al. (1982) (individual subjects)			
Effects of sucrose varied on ethanol			
41	0.92	0.01	0.47
42	0.25	–	0.24
43	0.80	0.01	*0.26*
45	0.78	0.05	*0.38*
Mean			0.34
Carroll et al. (1987a) (group data)			
Effect PCP varied on ethanol			
ethanol	0.78	0.05	*0.22*
Effect of ethanol varied on PCP			
PCP	0.19	–	0.01

price for one source of methadone increased (i.e., the inverse of dose) and its consumption decreased, the consumption of another unmanipulated source of methadone increased dramatically (slope = + 3.9). The remaining studies had nonidentical reinforcers concurrently available and while these reinforcers exhibited weaker substitution effects, all correlations were statistically significant.

Replication of these types of relations across subjects within a study can be assessed by examining the data presented in Table 2 for the six studies reporting individual subjects data. Overall, the positive slope (definition of substitutes) for the unmanipulated reinforcer is identical across 49 of the 51 relevant data sets with only the magnitude of the slope showing individual differences. The two exceptions [subject MG2's consumption of the 0.625 pentobarbtial from Meisch and Lemaire (1988) and subject 4's consumption of water from Carroll and Meisch (1979)], had nonsignificant correlations. Overall, the substitutable interactions demonstrated across reinforcers in these studies are consistent across subjects.

Another eight sets of data met the definition of independence (see Fig. 2); that is, as the price of one reinforcer increases, consumption of a second reinforcer with a constant price remains unchanged. The slopes for the unmanipulated reinforcer ranged from 0.05 to −0.14, with statistically significant correlations in five of the eight data sets. All of these studies had nonidentical reinforcers concurrently available. For example, Carroll et al. (1991) increased the unit

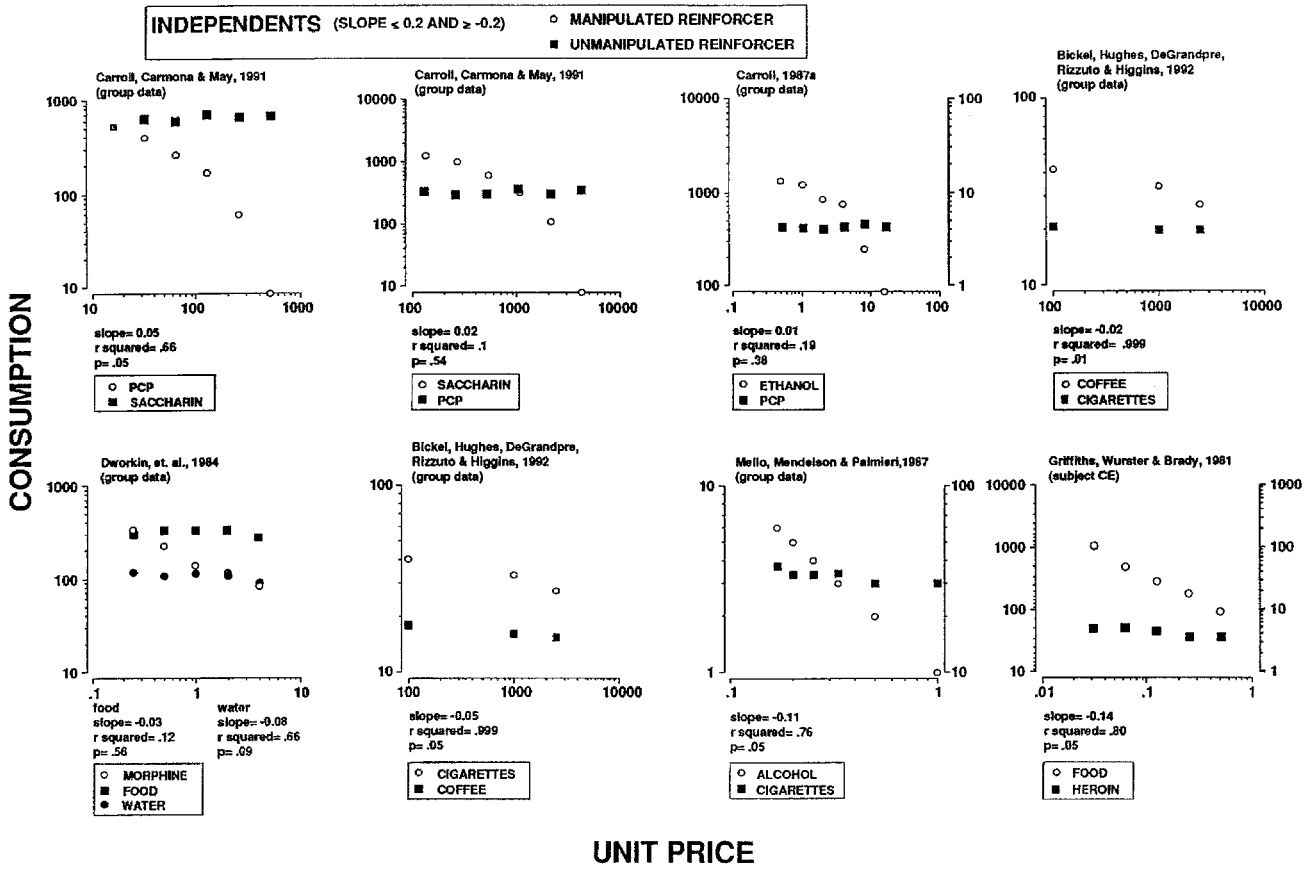

Fig. 2 Consumption of the two concurrent reinforcers that met the definition of independent reinforcers as a function of the unit price of the manipulated reinforcer for the eight data sets. Note that these eight sets of data were obtained from six studies because two of these studies (Carroll et al. 1991; Bickel et al. 1992) manipulated the unit price of both reinforcers separately. See Fig. 1 caption for other details

price of phencyclidine and examined its effects on saccharin consumption. Overall, the effect on saccharin consumption was negligible, with a slope of 0.02.

Only one study meeting the definition of independent reinforcers reported individual subject data (Griffiths et al. 1981). The two subjects in that study exhibited negative slopes close to zero when the number of food pellets was varied and the unit price of heroin was held constant (see Table 3). Thus, this study showed across subject replication of independent interactions consistent with that noted above for substitutes.

Four sets of data met the definition of complements (see Fig. 3); that is, as the price of one reinforcer increases, consumption of a second reinforcer with a constant price also decreases. The slopes for the unmanipulated reinforcer ranged from −0.27 to −1.35 with statistically significant correlations in all four data sets. Each study employed nonidentical reinforcers for the two alternatives. For example, one study (Mello et al. 1980b) examined the effects of providing subjects with concurrently available alcohol and cigarettes. As the unit price of ethanol increased and its consumption decreased, cigarette smoking decreased significantly, with a slope of −0.47.

Three of the latter studies reported the data on multiple individual subjects (see Table 4). As noted above regarding across subject replications of the substitution and independent relationships between reinforcers, negative slopes consistent with a complementary interaction was found in all subjects.

The symmetry or asymmetry of these interactions can be assessed with four studies that examined the effects of manipulating each of the two reinforcers separately (Griffiths et al. 1981; Carroll 1987; Carroll et al. 1991; Bickel et al. 1992); that is, the effects of manipulating price of reinforcer A on consumption of B, and the effects of manipulating price of reinforcer B on consumption of A. Two of the studies (e.g., Carroll et al. 1991; Bickel et al. 1992) showed similar symmetrical effects consistent with independent interactions (see Table 4). For example, weak complementary interactions were obtained with coffee consumption when the unit price of cigarettes was increased (a significant slope of −0.02) and with cigarette smoking when the unit price of coffee was increased (a significant slope of −0.05) (Bickel et al. 1992). Note that in the published report, the data were analyzed economically using point cross-price

Table 3 Independents (slope ≤ 0.2 and ≥ −0.2)

Study	r^2	*P*	Slope
Carroll et al. (1991) (group data)			
Effects of saccharin varied on PCP			
PCP	0.10	–	*0.02*
Effects of PCP varied on saccharin			
saccharin	0.66	0.05	*0.05*
Carroll et al. (1987a) (group data)			
Effects of PCP varied on ethanol			
ethanol	0.78	0.05	0.22
Effects of ethanol varied on PCP			
PCP	0.19	–	*0.01*
Bickel et al. (1992) (group data)			
Effects of coffee varied on cigarettes			
cigarettes	0.999	0.01	*−0.02*
Effects of cigarettes varied on coffee			
coffee	0.999	0.05	*−0.05*
Dworkin et al. (1984) (group data)			
Effect of morphine varied on food and water			
food	0.12	–	*−0.03*
water	0.66	–	*−0.06*
Mello et al. (1987) (group data)			
Effects of alcohol varied on cigarettes			
cigarettes	0.76	0.05	*−0.11*
Griffths et al. (1981) (individual subjects)			
Effects of food varied on heroin			
CE	0.80	0.05	*−0.14*
ST	0.60	–	−0.03
Effect of heroin varied on food			
CE	0.90	0.05	−0.78
ST	0.48	–	*−0.39*
Mean food varied			−0.09
Mean heroin varied			−0.39

Table 4 Complements (slope < −0.2)

Study	r^2	*P*	Slope
Mello et al. (1980a) (individual subjects)			
Effects of heroin varied on cigarettes			
2HA1	0.99	0.05	*−0.27*
Mello et al. (1980b) (individual subjects)			
Effects of the alcohol varied on cigarettes			
3MA5	0.89	0.01	*−0.47*
4MA5	0.76	0.05	−0.15
3MA6	0.98	–	−0.54
1MA3	0.04	–	*−0.12*
Mean			−0.32
Griffths et al. (1981) (individual subjects)			
Effect of varied on heroin			
CE	0.80	0.05	−0.14
ST	0.60	–	−0.03
Effects of heroin varied on food			
CE	0.90	0.05	−0.14
ST	0.48	–	−0.39
Mean food varied			−0.09
Mean heroin varied			−0.39
Roehrs et al. (1981) (individual subjects)			
Effect of ethanol varied on water			
R6	0.68	0.01	−1.35
R8	0.85	0.01	−1.35
Mean			−1.35

elasticities and statistically using analysis of variance procedures. The differences in methods resulted in similar magnitudes of cross-price elasticity coefficients, but differences in statistical significance with the published manuscript. The published study reported statistical significance for the effects of changes in cigarette price on coffee consumption as opposed to both interactions being significant as presented above. In using these different techniques, differences in outcome would be expected particularly at that point of the continuum close to independence where the type of interaction between reinforcers would be considered weak. The remaining studies show evidence of asymmetry (Carroll 1987a; Griffiths et al. 1981). In the Carroll (1987a) study, when the unit price of phencyclidine was increased and its consumption decreased, ethanol consumption increased (significant slope of + 0.22), meeting the definition of a substitute. In contrast, when the price of ethanol increased and its consumption decreased, phencyclidine consumption remained relatively unchanged (nonsignificant slope of 0.01),

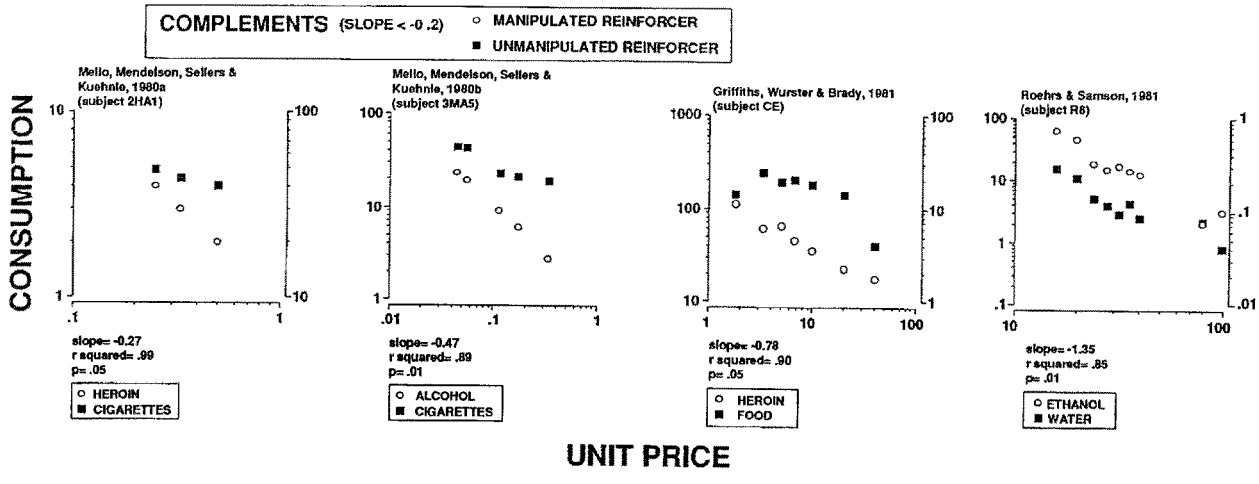

Fig. 3 Consumption of the two concurrent reinforcers that met the definition of complements as a function of the unit price of the manipulated reinforcer for the four data sets. See Fig. 1 caption for other details

meeting the definition of independence. In the Griffiths et al. study (1981), increasing the number of food pellets had no effect on heroin consumption indicative of independence, while decreasing the dose of heroin decreased the consumption of food meeting the definition of a complement. Thus, these studies show that both symmetrical and asymmetrical relationships among the reinforcers are possible.

Finally, one study permitted an assessment of factors that determine the magnitude of substitutability among reinforcers (Meisch and Lemaire 1988). Concurrent pentobarbital solutions were arranged and the dose of one source of pentobarbital was systematically varied, while the dose of the second source of pentobarbital was kept constant. The response requirement for delivery of either source of pentobarbital was 64 for all subjects, except subject MP, for whom the requirement was 16. Importantly, the dose of the unmanipulated reinforcer was held constant within each replication, but was varied across replications. The systematic change in dose across replications translates to changes in the unit price of the unmanipulated reinforcer across replications. This then permits an assessment of whether substitutability is affected by the relative unit price of the unmanipulated reinforcer.

Figure 4 presents the consumption data from the manipulated and unmanipulated reinforcer from this study, plotted as a function of the unit price of the manipulated reinforcer. The unit prices of the unmanipulated reinforcer are indicated by dashed vertical lines. First, when the unit prices of the manipulated and unmanipulated reinforcers were the same, the levels of consumption for both reinforcers were about the same (shown by vertical dashed line). Second, when the unit price of the unmanipulated reinforcer is less than the unit price of the manipulated reinforcer (data to the right of the dashed lines), the level of consumption of the unmanipulated reinforcer is above that of the manipulated reinforcer and the slope is close to zero (e.g., subject MG2, left-most panel). Third, when the unit price of the unmanipulated reinforcer is higher than that of the manipulated reinforcer (data to the left of the dashed lines), consumption of the unmanipulated reinforcer is lower than that of the manipulated reinforcer, and its slope tends to either increase (e.g., subject MW, right-most panel) or be near zero (subject MG2, the two right-most panels). Overall, the slope of the unmanipulated reinforcer was greatest when the unit price of the unmanipulated reinforcer was in the middle of the range of unit prices determined for the manipulated reinforcer, and least when the respective unit prices did not overlap. Importantly, these data suggest that the magnitude of substitution effects are a function of the relative unit prices of the manipulated and unmanipulated reinforcers, at least with identical reinforcers.

Discussion

The main findings from the present review and reanalysis are as follows: first, relations between concurrent reinforcers, when quantified and examined across studies, indicate that drug reinforcers can function as substitutes, complements, or be independent of the price of one another (Hursh and Bauman 1987). Second, the types of relations exhibited generally were consistent across subjects for those studies reporting individual subjects' data. Third, these relations were not necessarily symmetrical. Fourth, the relative unit prices of the manipulated and unmanipulated reinforcers are factors that may determine the magnitude of the interaction.

The fact that each type of interaction was observed across different experimental arrangements, species, and drug reinforcers suggests that these economic concepts may have broad generality in concurrent drug self-administration studies. The generality of these notions are further supported by reports of similar types of relations in studies of nondrug reinforcers (Allison 1983; Allison and Mack 1982; Green and Freed 1993; Rachlin and Krasnoff 1983). Together these observations support the utility of these concepts for identifying and quantifying the type and magnitude of interactions between concurrent reinforcers.

The metric of cross-price elasticity also may be usefully employed to quantify how other independent variables may affect the magnitude of these interactions. For example, the effects of satiation or deprivation, other drugs, or brain lesions on the type or magnitude of particular interactions could be assessed. Such research may, in turn, suggest mechanisms that result in these types of relations. For example, do these interactions result from the history of availability of the substances involved or does the type of interaction result from some biological relationship among them? Such analyses may be particularly useful in explaining asymmetrical relationships.

One factor noted in this reanalysis that affects the magnitude of these relationships between concurrent reinforcers was the relative unit prices of the two alternative reinforcers. In the study by Meisch and Lemaire (1988), reviewed above, the magnitude of the interaction was determined by the relative unit prices of the concurrent reinforcers. More specifically, the data indicated that substitutability was determined by whether the price of the unmanipulated reinforcer was within or outside of the range of prices used with the manipulated reinforcer. Indeed, substitution appeared to be defined by the increase in consumption of the unmanipulated reinforcer that occurred as the unit price of the manipulated reinforcer moves from below to above the unit price of the unmanipulated reinforcer. This supports an essential point that these interactions are not inherent properties of the reinforcing events, but are instead effects determined by the circumstances in which they occur (Hughes et al. 1988).

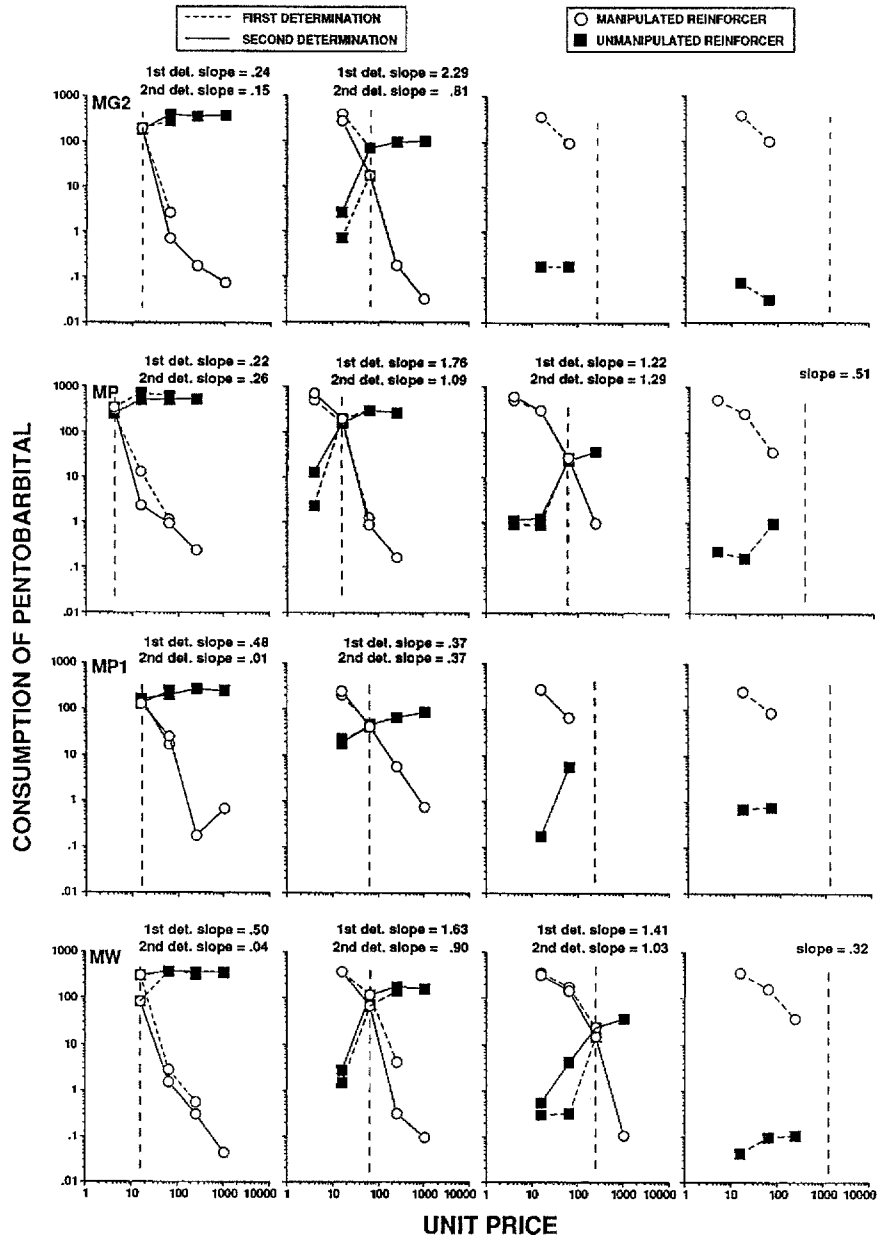

Fig. 4 Consumption of the two concurrent sources of pentobarbital for individual subjects as a function of the unit price of the manipulated source of pentobarbital from Meisch and Lemaire (1988). Note that the *vertical dashed line* indicates the unit price of the unmanipulated reinforcer. Slopes were determined when more than two data points were available

An important point that remains to be determined empirically is whether replications of the same unit prices with different constituent values would still lead to the same type and magnitude of interactions. One characteristic of unit price is that consumption should be the same at the same unit price even when composed of different values (Bickel et al. 1990). All the studies reviewed here manipulated either the response requirement or the dose of drug, and thereby prevented an assessment of whether unit prices derived from different values of response requirement and dose of the drug reinforcer produced the same effect. Studies would need to be conducted that simultaneously manipulate response requirement and dose for each of the two concurrent reinforcers in order to demonstrate conclusively that these interactions are dependent on the unit price and not the specific individual values that make up the unit price. For example, would the same effects be observed if a unit price of 10 for one of the reinforcers resulted from 10 responses per 1 mg drug, 20 responses per 2 mg drug, or 30 responses per 3 mg drug?

The analysis presented here stands in contrast with the most prevalent behavioral view of choice offered by the matching law. The matching law was developed to address identical reinforcers. Green and Freed (1993) note that the matching law's assumption of perfect substitutability between alternative sources of reinforcement is denied by the economic concept of substitutability as a continuum of interactions among reinforcers. Indeed, Hursh (1980) has noted that the matching law is derivable from these economic

concepts, but these economic concepts are not derivable from the matching law. These observations, along with those of the present paper, indicate that the continuum of interaction suggested by behavioral economics may accommodate a broader range of observations.

Importantly, the successful application of these operationalized concepts provides a systematic way to organize the existing data on reinforcer interactions in drug self-administration research and to quantify the magnitude of those interactions. The organization and quantification afforded by these economic concepts may set the occasion for research with clinical relevance. For example, determining the factors that lead to these observed interactions may permit us to begin to understand how drugs can become substitutes for other prosocial reinforcers, which may impact our understanding of the development of drug dependence. Further, this may suggest a means to explore potential pharmacological and nonpharmacological therapies (Bickel and DeGrandpre 1995). For example, perhaps the magnitude of substitution between a drug of abuse (e.g., heroin) and a therapeutic agent (e.g., methadone or naltrexone) will determine its efficacy in clinical situations (Bickel et al. 1993). With respect to nonpharmacological treatments, application of these notions may suggest alternative activities (e.g., employment, attending family functions) that may successfully compete with drug use (Higgins et al. 1991, 1993). Additionally, this conceptualization of reinforcer interactions can address whether suspected complements to drug taking (e.g., drug using friend) increase the likelihood of drug use and perhaps lead to relapse. Such findings would have immediate clinical significance by suggesting which activities or events patients should avoid (e.g., drug using friends) and which patients should access.

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