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BEHAVIORAL ECONOMICS OF CONCURRENT ETHANOL-SUCROSE AND SUCROSE REINFORCEMENT IN THE RAT: EFFECTS OF ALTERING VARIABLE-RATIO REQUIREMENTS

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These experiments examined the own-price and cross-price elasticities of a drug (ethanol mixed with 10% sucrose) and a nondrug (10% sucrose) reinforcer. Rats were presented with ethanol-sucrose and sucrose, both available on concurrent independent variable-ratio (VR) 8 schedules of reinforcement. In Experiment 1, the variable ratio for the ethanol mix was systematically raised to 10, 12, 14, 16, 20, and 30, while the variable ratio for sucrose remained at 8. Five of the 6 rats increased ethanol-reinforced responding at some of the increments and defended baseline levels of ethanol intake. However, the rats eventually ceased ethanol-reinforced responding at the highest variable ratios. Sucrose-reinforced responding was not systematically affected by the changes in variable ratio for ethanol mix. In Experiment 2, the variable ratio for sucrose was systematically increased while the ethanol-sucrose response requirement remained constant. The rats decreased sucrose-reinforced responding and increased ethanol-sucrose-reinforced responding, resulting in a two- to 10-fold increase in ethanol intake. Experiment 3 examined the substitutability of qualitatively identical reinforcers: 10% sucrose versus 10% sucrose. Increases in variable-ratio requirements at the preferred lever resulted in a switch in lever preference. Experiment 4 examined whether 10% ethanol mix substituted for 5% ethanol mix, with increasing variable-ratio requirements of the 5% ethanol. All rats eventually responded predominantly for the 10% ethanol mix, but total amount of ethanol consumed per session did not systematically change. In Experiment 5, the variable-ratio requirements for both ethanol and sucrose were simultaneously raised to VR 120; 7 of 8 rats increased ethanol-reinforced responding while decreasing sucrose-reinforced responding. These data suggest that, within this ethanol-induction procedure and within certain parameters, demand for ethanol-sucrose was relatively inelastic, and sucrose consumption was independent of ethanol-sucrose consumption. Demand for sucrose, on the other hand, was relatively elastic, and ethanol-sucrose readily substituted for it. The results are discussed in terms of applying a behavioral economic approach to relationships between drug and nondrug reinforcers.

Key words: ethanol, sucrose, self-administration, behavioral economics, lever press, rat

A contemporary view of drug dependence posits that drug taking is choice behavior (e.g., Bickel, DeGrandpre, & Higgins, 1995; Herrnstein & Prelec, 1992; Heyman, in press-b; Jaffee, 1990; Vuchinich & Tucker, 1983, 1988), with every individual choosing to engage or not to engage in drug use. This choice is not made in isolation; rather, it is made in the presence of a multitude of other potential reinforcers such as family, friends, or hobbies. Drug addicts continuously choose to use drugs despite the deleterious impact this choice has on their lives. The developmental course of drug abuse may be intricately related to the mechanisms that govern these maladaptive choices (see Herrnstein & Prelec, 1992). Elucidating the factors that render drug taking dominant among these various alternatives may be important in understanding addiction and in designing novel treatment approaches to alleviate it.

Behavioral economics is one method that has been employed to examine relationships between drug and nondrug reinforcers (e.g., Hursh, 1991, 1993). In economics, the consumption or purchase of a particular commodity depends upon a number of variables. The factor that is most typically studied in relation to consumption is price (e.g., Samuelson & Nordhaus, 1985). A fundamental law of economics, the demand law, stipulates that all else being equal, total consumption decreases as price increases (Allison, 1983). If

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drugs act similarly to other reinforcers in this regard, then all else being equal, high rates of drug use should occur when the price of drugs is low. Conversely, a decline in drug use should result, all else being equal, when the price of a drug increases. In natural settings, however, all else is not equal: Drugs are bought and sold illegally with unregulated prices and in unknown dosages, the consequences of use seem to change as one engages in more and more drug taking (see Herrnstein & Prelec, 1992), and social factors strongly interact with drug taking. All of these factors render comparison of drug price and consumption difficult to quantify in natural settings.

Numerous studies, however, have demonstrated the applicability of the demand law to the consumption of drug and nondrug reinforcers in controlled laboratory settings. Response requirements can be analogous to cost, and actual consumption can be objectively determined. Rats, monkeys, and humans all decrease responding for reinforcers such as food, sucrose, and electrical brain stimulation as the costs of these goods increase (e.g., Felton & Lyon, 1966; Hursh & Natelson, 1981). Likewise, both animals and humans decrease responding for drug reinforcers, such as nicotine, ethanol, heroin, and cocaine, as the response requirement for these commodities is increased (Catania & Reynolds, 1968; Griffiths, Bigelow, & Henningfield, 1980; Griffiths, Brady, & Snell, 1978; Yanigita, 1973; Young & Herling 1986).

The concept of *own-price elasticity* quantifies the relationship between consumption and price of a given commodity by representing the proportional change in consumption across price conditions (e.g., Hursh, 1980, 1991, 1993; Samuelson & Nordhaus, 1985). When consumption is plotted against price on log-log coordinates, the proportional change is equal to the slope of the best fitting line. At one extreme, increases in price markedly decrease consumption; this pattern is termed *elastic* consumption and is defined by own-price elasticities less than -1.0 (steep slopes). At the other end of the continuum, increases in price result in marginal decreases in consumption, or *inelastic* consumption. Inelastic consumption is defined by own-price elasticities greater than -1.0 (shallow slopes). Total insensitivity to cost is represented by elasticities of zero.

Own-price elasticity is not an inherent property of a reinforcer, however, because demand for a reinforcer varies in relation to other reinforcers in the environment. For example, the own-price elasticity of Coca Cola® may vary depending on the availability and price of Pepsi Cola®. A parallel can be demonstrated among drug and nondrug reinforcers in the laboratory. Rats, for example, will demonstrate elasticity of demand for food as long as another food source is available (e.g., Lea & Roper, 1977). Monkeys will consume large quantities of cocaine when it is the only experimenter-arranged reinforcer, but cocaine intake decreases markedly if a food alternative is introduced (Nader & Woolverton, 1991).

The concept of *cross-price elasticity* quantifies the relationship between consumption of one commodity and the price of another commodity by representing the proportional changes in consumption of the former across changes in price of the latter (e.g., Samuelson & Nordhaus, 1985). At one end of the spectrum, a reinforcer may substitute for another; as the price of Coca Cola® increases, the consumption of Pepsi Cola® increases. A reinforcer may also be a complement of another; as the price of Coca Cola® increases, consumption of potato chips diminishes. Between these extremes are *independents*; the price of Coca Cola® probably has little effect on the consumption of gasoline. Quantification of substitutes, complements, and independents is signified by cross-price elasticities greater than, less than, and equal to zero, respectively (Allison, 1983; Green & Freed, 1993; Hursh, 1980, 1991, 1993; Samuelson & Nordhaus, 1985).

A number of laboratory experiments have examined these economic relationships between two concurrently available reinforcers. Bickel et al. (1995) reviewed 16 published studies in which at least one of the concurrently available reinforcers was a drug and found that the data were consistent with these economic notions. They demonstrated that relationships among concurrently available reinforcers were reliable between and within studies, that concurrently available reinforcers can affect one another asymmetrically, and that relative price is important in determining the magnitude of effect for substitutes. In particular, in all four studies in which two doses of the same drug were available and the cost of one dose was systematically altered, the doses served as substitutes for one another (Bickel, Higgins, & Stitzer, 1986; Carroll, 1987; Iglauer & Woods, 1974; Meisch & Lemaire, 1988). Ethanol and sucrose were concurrently available and the unit price of the sucrose was altered in two other studies (Samson, Roehrs, & Tolliver, 1982; Samson, Tolliver, & Roehrs, 1983). In both of these studies, the drug served as a substitute for the nondrug reinforcer. Thus, when a nondrug reinforcer became more difficult to obtain, an escalation of drug taking was noted.

The present studies sought to investigate further the relationships between ethanol and sucrose reinforcement in the rat. We examined the changes in responding for and consumption of ethanol and sucrose as a function of alterations in response requirements for either or both.

GENERAL METHOD

Subjects

Six male (numbered 130 through 135) and 8 female (numbered 190 through 199) Wistar rats, weighing 295 to 365 g at the start of the experiment, served as subjects. They were individually housed in standard Perspex cages and were allowed 2 weeks to acclimate to the laboratory with food and water freely available before commencement of the experiment. Food was then rationed daily until each rat had reached 85% of its free-feeding body weight. These weights were then maintained throughout the remainder of the experiment, with daily food rations given approximately 30 min following the experimental sessions. The animals were housed in a room with a 12:12 hr light/dark cycle, with lights on and off at 6:00 a.m. and 6:00 p.m., respectively. The animals were studied daily at approximately the same time each day.

Apparatus

Each rat was arbitrarily assigned to one of three operant conditioning chambers at the beginning of the study. Each chamber had two levers and two liquid dispensers mounted on the front wall. Responses on the right lever resulted in presentations of the right dipper and its associated solution, and responses on the left lever resulted in presentations of the left dipper and its associated solution. All dipper presentations provided a 1.5-s (unless otherwise stated) access to a 0.1-ml dipper. The fluid reservoirs were partially covered to minimize evaporation. During the session, a 1-W lamp was illuminated above each lever, and an exhaust fan provided air circulation for the chamber, which was housed inside a sound-attenuating outside chamber. The schedules were programmed in MED PC® (Tathum & Zurn, 1989).

Procedure

Training concurrent responding. After reaching their 85% body weights, rats were initially trained, via shaping, to lever press on a procedure that gave access to a 10% sucrose solution. This solution was prepared by mixing 10 g of sucrose with enough water to total 100 ml. Fresh solution was prepared each day. A 3-s period of access to both dippers was automatically provided at 30-s intervals. In addition, any lever presses were rewarded on a fixed-ratio (FR) 1 schedule. All rats learned to press within five 30-min daily sessions. In order to obtain responding on both levers, rats were then trained on a schedule that required them to press on both levers in order to obtain a reinforcement. This schedule was in operation for 15 sessions.

Introduction of ethanol. The rats were then placed on a concurrent variable-ratio (VR) 8 VR 8 (VR 8 on both levers) schedule. At this point, water was available on one side and a 10% sucrose solution on the other. The side at which the ethanol solution was available was alternated across sessions on a random basis at least once every 3 days. Gradually, ethanol was added to the sucrose solution (henceforth termed ethanol mix). Ethanol was first introduced in 2.5% by volume of the 10% sucrose solution. The ethanol concentration was then raised to 5, 7.5, 10, 15, 20, and 25%. Each concentration was in effect until responding became stable. Stability, throughout all experiments described in this paper, was defined as three consecutive sessions that showed neither a systematic increase or decrease nor an all-time high or low in responding for either alternative. A further constraint of a minimum of five sessions on any particular condition was also in effect. No maximum number of sessions per condition was set. Each session lasted 30 min.

Introduction of sucrose as an alternative. After completing all concentrations of the ethanol solution, the rats were then restabilized on a 10% alcohol/10% sucrose solution versus water, again on a concurrent VR 8 VR 8 schedule. Sucrose was gradually added to the water solution until the concentration of sucrose on both sides was equal at 10%. First, 2% sucrose solution was available concurrently with 10% ethanol/10% sucrose. The concentration of sucrose was increased in increments of 2% (2, 4, 6, 8, and 10%), and each concentration remained in effect until responding had stabilized at that concentration. When 8% sucrose was made available with 10% ethanol/10% sucrose, Rats 130, 131, 132, 190, 192, 193, 194, and 198 responded exclusively for the sucrose solution. The concentration of ethanol for these rats was decreased to 7.5% to ensure responding on both alternatives. However, this concentration also resulted in exclusive responding for sucrose. The concentration was then further lowered to 5% ethanol/10% sucrose. At this concentration of ethanol, responding reliably occurred for both reinforcers.

Data analysis. The individual rats' data for the last three sessions of a given condition are presented in terms of responses per minute and total reinforcers earned. In all experiments, the baseline condition was defined as the VR 8 versus VR 8 condition, and this was the condition to which the experimental conditions were compared.

The Appendices list the average number of reinforcers obtained in these last three sessions for each condition for the 14 rats. In order to facilitate within- and across-experiment comparisons of ethanol consumption in rats receiving 5% and 10% ethanol-mix reinforcers, the number of 10% ethanol-mix reinforcers obtained was multiplied by 2 in the Appendices. The volumes of solutions in troughs were occasionally measured before and after experimental sessions. The displaced volumes (measured in milliliters before and after the session) were highly correlated ($r^2 = 0.95$) with the calculated volumes (prior volume minus the number of earned reinforcers times 0.01 ml per reinforcer). Thus, the animals most likely had consumed all of their earned reinforcers.

The data were also analyzed in terms of own-price and cross-price elasticity of demand, using the following equations derived from Allison (1983). For own-price elasticity,

$$E_{\text{own}} = [\log(Q_{A2}) - \log(Q_{A1})] \div [\log(P_{A2}) - \log(P_{A1})],$$

where Q is the quantity consumed of Reinforcer A at Price (P) 1 or 2. Elasticities above and below -1.0 are indicative of inelastic and elastic consumption, respectively (e.g., DeGrandpre, Bickel, Higgins, & Hughes, 1994; Hursh, 1991, 1993).

For cross-price elasticity,

$$E_{\text{cross}} = [\log(Q_{A2}) - \log(Q_{A1})] \div [\log(P_{B2}) - \log(P_{B1})],$$

in which Q is the quantity consumed of Reinforcer A at Price B1 or B2 (the two prices for Reinforcer B). Positive cross-price elasticities indicate that Reinforcer A is a substitute for Reinforcer B. Negative cross-price elasticities indicate that Reinforcer A is a complement of Reinforcer B. Values around zero indicate that Reinforcer A is independent of Reinforcer B. Because broad changes in price usually result in mixed elasticities (Hursh & Bauman, 1987), cross-price and own-price elasticities were calculated for each change in VR value compared to the baseline value.

EXPERIMENT 1: EFFECTS OF INCREASING THE VR REQUIREMENT FOR ETHANOL MIX

In this experiment, animals responded for an ethanol-sucrose mixture and sucrose when both were available initially at equal VR schedules. We then examined changes in response rates and consumption, as well as in own-price and cross-price elasticities, of ethanol mix and sucrose when the response requirement for the ethanol mix was systematically raised.

Method

After responding had stabilized at concurrent VR 8 VR 8, the VR requirement for the ethanol solution was gradually increased while the requirement for the sucrose remained at VR 8. The VR requirements for the ethanol mix were 10, 12, 14, 16, 20, and 30. The VR requirement for the ethanol mix was increased after stable responding had been established. The mean number of sessions per condition was 12.6 (range, 8 to 23). When rats demonstrated an exclusive, or near exclusive, preference for the sucrose-associated lever for 3 consecutive days, they began Experiment 2.

Results and Discussion

Figure 1 shows the overall response rates for both the ethanol mix and the sucrose solution for all 6 rats across the increasing VR requirements for the ethanol mix. Rats 130, 131, and 132 responded for 5% ethanol mix, and Rats 133, 134, and 135 responded for 10% ethanol mix. For 5 of the 6 rats, slight to moderate increases in VR requirements for the ethanol mix resulted in enhanced ethanol-mix-reinforced responding. For Rats 130 and 131, this increase occurred only when the ethanol-mix requirement was raised from 8 to 10. In those rats that consumed 10% ethanol, responding for the ethanol mix persisted until the response requirement was 1.5 to 2.5 times greater than the baseline of VR 8.

The average number of ethanol-mix and sucrose reinforcers earned in the last three sessions of each condition is shown in Appendix A. The number of 10% ethanol mix reinforcers is doubled in order to keep daily amounts of ethanol consumed consistent across rats. For some subjects, increased costs engendered increased response rates to such an extent that ethanol consumption exceeded baseline consumption. One possible explanation of this phenomenon may be related to the properties of the ethanol mix. The increased VR requirements may have lengthened the delay between consecutive reinforcers, which in turn may have altered the time course of action of ethanol's effects. Presumably, a given number of drug reinforcers dispersed in time would result in an attenuated pharmacological effect. Thus, if the pharmacological properties of ethanol control its consumption, then it is not surprising that the animals consumed more ethanol when it was temporally delayed.

As response requirements continued to increase, all rats eventually ceased responding for the ethanol mix. As ethanol-mix-maintained responding declined, responding continued only for the sucrose. However, no systematic change in sucrose-reinforced responding occurred across conditions. Even in those conditions in which responding was exclusively for the sucrose, only half of the rats demonstrated substantial increases in sucrose-reinforced responding compared to baseline. In the others, sucrose-maintained response rates remained similar to baseline.

The number of reinforcers obtained at each lever in the different conditions was used to determine own-price elasticity of the demand for ethanol mix and cross-price elasticity of the demand for sucrose; these values are shown in Table 1. Own-price values indicative of inelasticity are printed in italics, and values characteristic of elasticity are in standard print. This table demonstrates that demand for ethanol mix was inelastic in at least some of the changes in VR requirements, especially in the earlier conditions of VR 10 and VR 12. Rats responding for 10% ethanol mix demonstrated more point inelasticities than did rats responding for 5% ethanol mix.

Table 1 also shows cross-price elasticities of demand for sucrose. In 2 rats, sucrose was a substitute for ethanol mix when ethanol mix was elastic. Nonetheless, for most of the rats and across the majority of the conditions, sucrose was an independent commodity. In fact, in two thirds of all the comparisons, sucrose consumption was independent of the price of ethanol mix.

Figure 2 shows the average number of reinforcers earned across the varying VR requirements for the ethanol mix. Each reinforcer was considered to be one unit; thus, unit price was defined as the average number of responses required for each reinforcer. The average number of reinforcers earned refers to the last three sessions of a given condition. Log-log coordinates were used such that if lines were drawn connecting the baseline point with any of the experimental condition points, the slopes of these lines would be equal to the own-price or cross-price elasticities shown in Table 1. This figure demonstrates that, in 5 of the 6 rats, demand for ethanol mix was inelastic in at least some of the experimental conditions.

This experiment demonstrates that rats induced to obtain and drink ethanol in the manner described in this report will consume it at relatively high rates even when an alter-

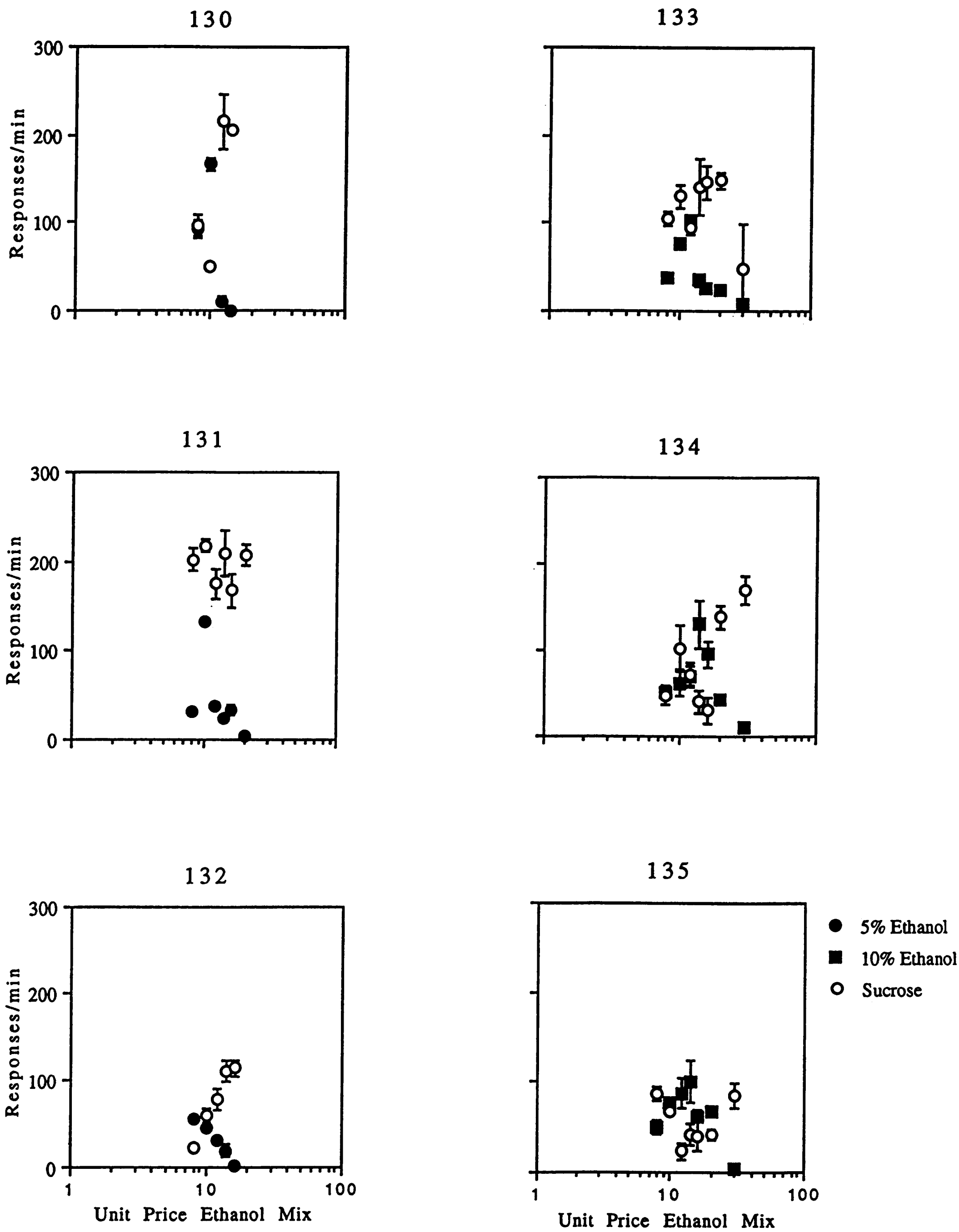

Fig. 1. Response rates for ethanol mix and sucrose across unit prices (increasing VR requirements) for ethanol mix. Each symbol represents the mean (±*SD*) of the last three sessions of a condition. Each graph is for a separate rat, identified by the number at the top. Note that the *x* axes are logarithmic. Rates were calculated exclusive of dipper-presentation times.

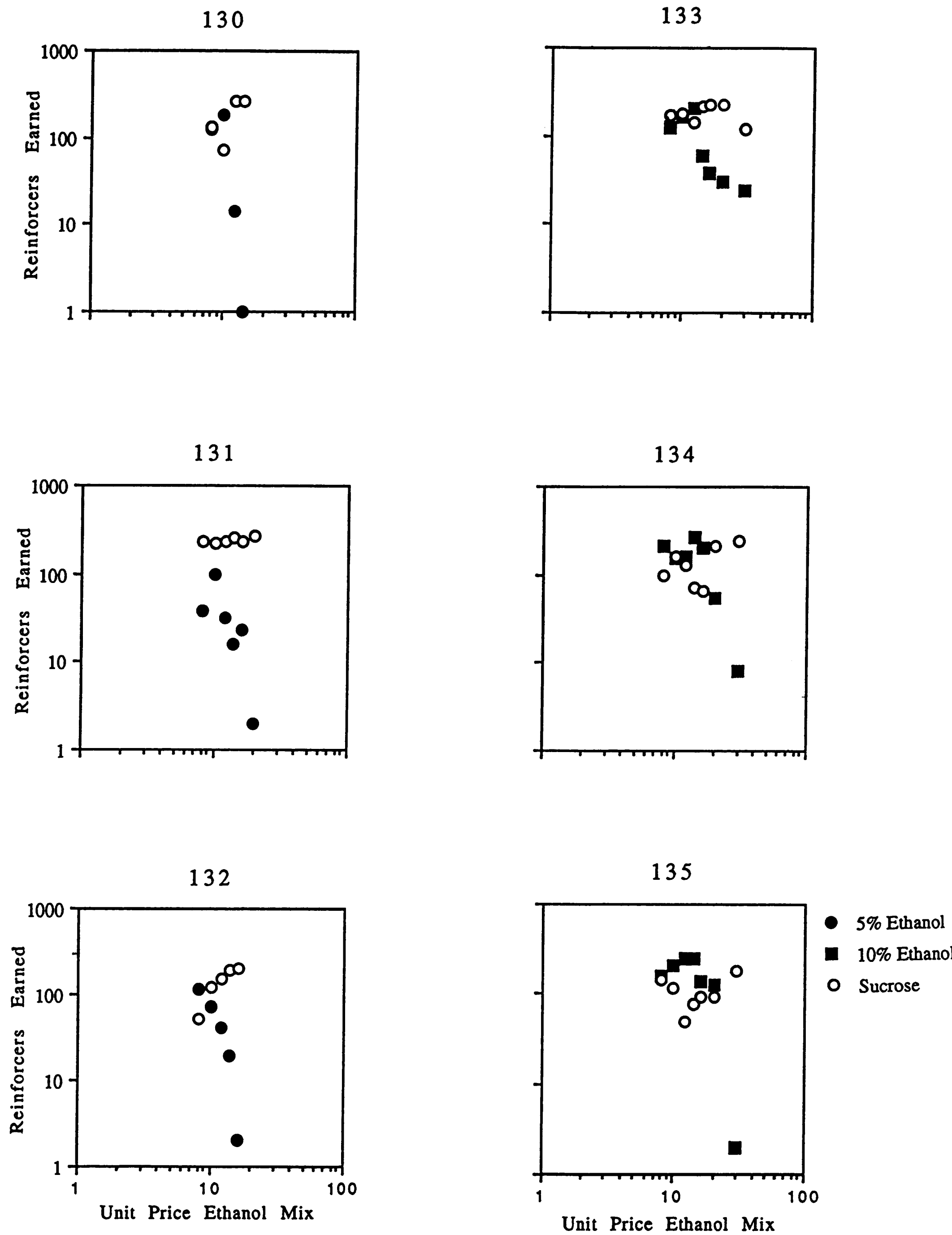

Fig. 2. Consumption of ethanol mix and sucrose as a function of unit price of the ethanol mix. Consumption was defined as average earned reinforcers in the last three sessions of a condition. Note that axes are logarithmic.

Table 1

Own-price elasticity of ethanol mix and cross-price elasticity of sucrose in Experiment 1.

	Rat 130		Rat 131		Rat 132		Rat 133		Rat 134		Rat 135	
VR	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price
10	*1.71*	−2.81	*4.25*	−0.27	−2.24	3.76	*1.25*	0.21	−1.52	2.17	*1.18*	−1.01
12	−5.40	1.67	*−0.42*	−0.08	−2.65	2.69	*1.23*	−0.42	*−0.65*	0.66	*1.08*	−2.61
14	−8.96	1.25	−1.55	0.13	−3.25	2.38	−1.30	0.42	*0.40*	−0.55	*0.80*	−1.12
16			*−0.72*	−0.04	−5.87	2.01	−1.71	0.40	*−0.05*	−0.59	*−0.19*	−0.66
20			−3.21	0.11			−1.55	0.32	−1.51	0.84	*−0.26*	−0.48
30							−1.24	−0.25	−2.49	0.69	−3.32	0.16

native reinforcer, equated in concentration of sucrose, is concurrently available. Rats in these studies consumed an average of 1.8 ± 0.9 g/kg daily in the baseline condition, an amount that exceeds the rate at which ethanol is metabolized (0.3 g/kg/hr; Wallgren & Barry, 1970).

These data further suggest that rats will increase ethanol-reinforced responding with increases in price in order to defend baseline intake levels. This finding is consistent with another report (Heyman & Oldfather, 1992) that demonstrated increases in ethanol-reinforced responding when these same alternatives were available on concurrent variable-interval (VI) 5-s schedules and the VI requirement for the ethanol mix increased. In the present experiment, all 3 rats that consumed 10% ethanol defended ethanol intake levels to a greater degree than did rats that consumed 5% ethanol. The greater inelasticity in the rats consuming 10% ethanol may be the result of a number of factors: greater caloric value of the more concentrated ethanol mix, genetic predisposition to consume ethanol, or degree of dependence on ethanol. However, as the increase in drug cost grew in magnitude, all rats reduced both drug consumption and drug-seeking behavior. Thus, in this experiment, demand for ethanol mix was mixed, tending to be inelastic at low prices and elastic at high prices. Sucrose consumption was typically independent of any changes in the price of ethanol mix.

EXPERIMENT 2: EFFECTS OF INCREASING THE VR REQUIREMENT FOR SUCROSE

Experiment 1 demonstrated that, within limited parameters, ethanol mix was an inelastic commodity and sucrose did not substitute for it. Sucrose consumption was generally independent of any changes in the price of ethanol mix. Although sucrose did not readily substitute for ethanol mix, this does not necessarily mean that ethanol will not substitute for sucrose. An asymmetry between reinforcers has been noted in a number of studies (see Bickel et al., 1995; Hursh, 1991). Thus, Experiment 2 examined the changes in responding for, and consumption of, sucrose and ethanol mix when the response requirement for the sucrose was systematically altered.

Method

Rats were restabilized on concurrent VR 8 schedules for 10% or 5% ethanol/10% sucrose versus 10% sucrose. The requirement for the sucrose solution was increased from VR 8 to 10, 12, 14, 16, 20, 30, 40, 50, and 60 responses. Each condition was kept in effect for at least five sessions and until stability requirements had been met.

Results and Discussion

Figure 3 shows average response rates for the last three sessions across conditions for the 6 individual rats. Baseline responding had changed from the previous experiment. Four of the 6 rats decreased ethanol-mix-reinforced responding, and 5 rats increased sucrose-reinforced responding in comparison to baseline rates in Experiment 1. Increased price for sucrose resulted in systematic decreases in sucrose-reinforced responding. Sucrose-reinforced responding diminished from baseline rates even when the requirement increased only marginally, from VR 8 to VR 10 (except for Rat 132), and it continued to decrease as the requirement rose. In con-

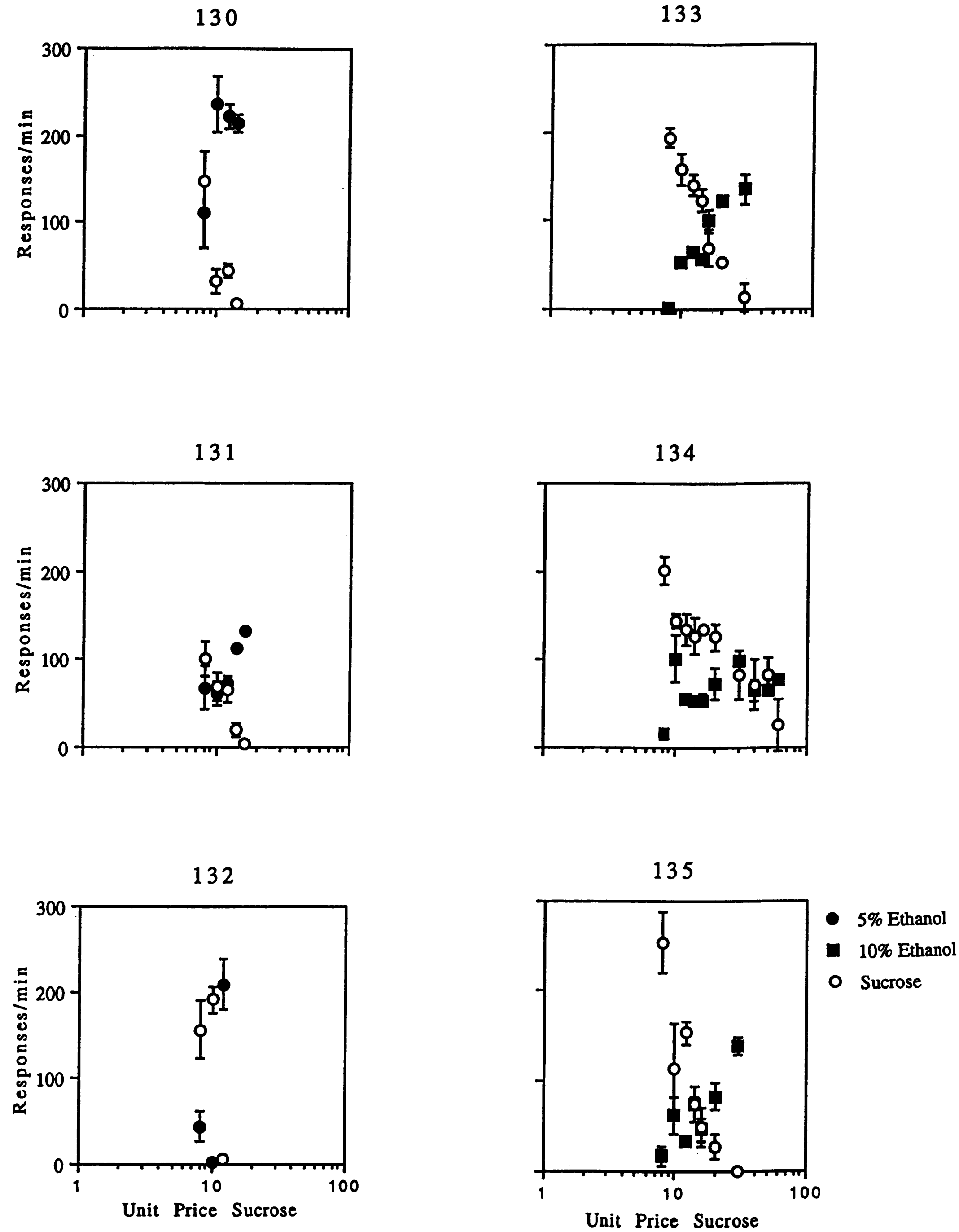

Fig. 3. Response rates for ethanol mix and sucrose across increasing VR requirements for sucrose in the 6 individual rats. See Figure 1 for further details.

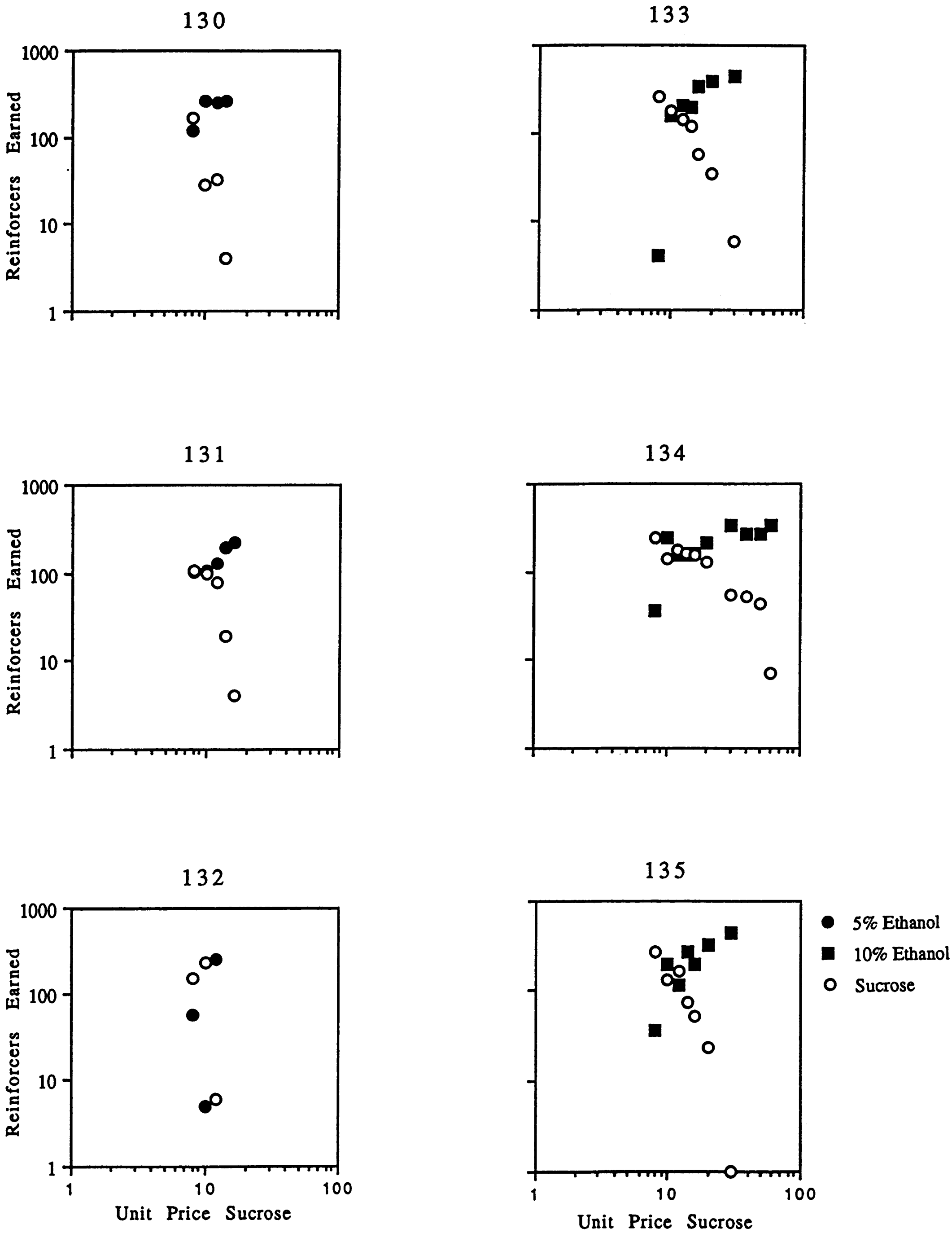

Fig. 4. Consumption of ethanol mix and sucrose as a function of unit price of the sucrose. See Figure 2 for further details.

Table 2

Own-price elasticity of sucrose and cross-price elasticity of ethanol mix in Experiment 2.

	Rat 130		Rat 131		Rat 132		Rat 133		Rat 134		Rat 135	
VR	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price
10	−7.87	3.38	*−0.56*	0.21	*1.78*	−10.98	−1.70	16.30	−2.47	8.58	−3.11	7.64
12	−3.92	1.78	*−0.88*	0.64	−8.04	3.69	−1.49	9.65	*−0.84*	3.55	−1.15	2.84
14	−6.62	1.41	−3.14	1.16			−1.37	6.97	*−0.75*	2.64	−2.28	3.59
16			−4.78	1.10			−2.14	6.38	*−0.71*	2.19	−2.37	2.47
20							−2.20	5.00	*−0.71*	1.97	−2.68	2.40
30							−2.84	3.56	−1.16	1.68	−4.23	1.91
40									*−0.98*	1.24		
50									*−0.96*	1.10		
60									−1.77	1.10		

junction with the attenuation in sucrose-reinforced responding, ethanol-mix-maintained responding increased markedly. Responding was exclusively on the ethanol lever by VR 12 to VR 16 for rats responding for 5% ethanol. In those responding for 10% ethanol, responding for sucrose continued to decline, but more gradually. Sucrose requirements increased to VR 30 to VR 60 before responding was primarily for ethanol.

The amount of ethanol consumed in each condition is shown in Appendix A. As the sucrose response requirement was raised, ethanol consumption increased. The largest augmentation of ethanol consumption occurred when the sucrose VR changed only slightly, from VR 8 to VR 10. Rats that consumed only small amounts of ethanol in baseline (e.g., 0.05 to 0.70 g/kg) consumed pharmacologically significant amounts (1.8 to 2.9 g/kg) when the response requirement for the alternative reinforcer increased slightly.

Table 2 shows own-price elasticity values for sucrose and cross-price elasticities for ethanol mix. With the exception of Rat 134, virtually all the values indicate that demand for sucrose was elastic. This table also indicates that ethanol mix served as a substitute for sucrose. As the price of sucrose increased, ethanol mix served as a substitute in 27 of the 30 possible comparisons. Figure 4 shows the number of reinforcers earned as a function of unit price for sucrose, and illustrates the elasticity of demand for sucrose and the substitution of ethanol mix for sucrose. It is important to note that these data demonstrate that decreases in the availability of a nondrug reinforcer resulted in a substantial increase in drug seeking and in drug consumption. This result is consistent with that found by other researchers. For example, Samson et al. (1982, 1983) found that increases in the FR requirement for a 3% to 5% sucrose solution resulted in increases in responding for a 5% ethanol reinforcer.

EXPERIMENT 3: CONCURRENT SUCROSE-SUCROSE: INCREASING VR REQUIREMENTS ON THE PREFERRED SIDE

When the same reinforcer is available on equivalent VR requirements at two levers, responding is exclusive on one lever (e.g., Herrnstein & Loveland, 1975). No advantage is gained by switching between the two levers. When the response requirement for the preferred lever is increased, responding switches to the other lever. The increase in VR necessary to induce the switch may result from a side bias or from an inability to detect the change.

These rats did not show a great degree of side bias, but they did demonstrate sensitivity to alterations in response requirements. The sides at which the two reinforcers were available were switched approximately once every 3 months. The correlations between responding at the two sides were .92 for ethanol mix and .89 for sucrose, which were similar to daily alterations in responding. Changes in response rates were noted even with very minimal changes in VRs in the previous experiments. Experiment 3 further examined the sensitivity of the rats to changes in response requirements. Sucrose was available at both levers, and the response requirement at the preferred lever was gradually raised until preference switched.

Method

After completing Experiment 2, rats were presented with 10% sucrose solution available at both levers on concurrent VR 8 VR 8 schedules of reinforcement. After responding had stabilized, the requirement for the preferred side was systematically increased to VR 10, VR 12, and VR 14, while the requirement on the nonpreferred side remained at VR 8. Each requirement was kept in place until responding had stabilized. When responding occurred predominantly on the previously nonpreferred lever, the rat continued to the next experiment.

Results and Discussion

Figure 5 shows responding on the originally preferred and originally nonpreferred levers across conditions for the 6 rats. As expected, when the response requirements and reinforcers were equivalent, responding occurred almost exclusively on one lever. When the response requirement on this lever was raised to 10, 12, and 14, the subjects switched to exclusive responding on the previously nonpreferred lever.

Table 3 shows own-price elasticities of the sucrose obtained from the originally preferred lever, as well as cross-price elasticities of the sucrose obtained from the other lever. Although demand for the preferred-lever sucrose was inelastic in half of the rats with the initial change in VR from 8 to 10, by the final condition all rats showed very elastic demand for the preferred-lever sucrose, with large negative slopes ranging from −5.8 to −25. In all cases in which demand for the preferred-lever sucrose was elastic, the non-preferred-lever sucrose served as a substitute, with large positive slopes. These relations are illustrated in Figure 6, which shows reinforcers earned plotted as a function of unit price for the preferred-lever sucrose.

This experiment demonstrates that the rats were highly sensitive to changes in response requirements. Some responding was consistent with sensitivity to very minimal changes (VR 8 to VR 10) in response requirements, and all rats changed lever preference when the schedules differed by a factor of 1.75. Sensitivity to these alterations in response requirements was noted regardless of any possible concomitant side biases.

Despite the sensitivity of the rats to these schedule changes, all rats demonstrated changes in response rates for both alternatives when the changes in response requirements were small (VR 8 to VR 10) in the previous two experiments. One interpretation of these differential results is that the rats were less biased toward one side when two different reinforcers (ethanol mix vs. sucrose) were concurrently available than when the same reinforcer was available at both sides. Alternatively, these results may suggest that changes in response requirements were harder to detect when rats were accustomed to responding exclusively at one side, and were thus less likely to sample the other side.

EXPERIMENT 4: CONCURRENT ETHANOL SOLUTIONS: INCREASING THE VR REQUIREMENT FOR 5% ETHANOL

This experiment examined the effects of altering the VR requirement on one lever when two different doses (5% and 10% ethanol) of the same drug reinforcer were available. If two different doses of the same drug reinforcer are perfectly substitutable, then increases in the response requirement for 5% ethanol mix should result in decreased responding for the 5% ethanol mix, with increased responding for the 10% ethanol mix.

Method

One lever provided 5% ethanol/10% sucrose, and the other provided 10% ethanol/10% sucrose. Both solutions were available on VR 8 schedules of reinforcement. The response requirements for the 5% ethanol solution were increased systematically to 10, 12, 14, 16, 20, 30, 40, 50, and 60, while the response requirement for the 10% ethanol remained at VR 8. Each condition was in effect until responding had stabilized at that schedule.

Results and Discussion

Figure 7 shows the response rates for the two solutions at each condition. Four of the rats responded almost exclusively for 5% eth-

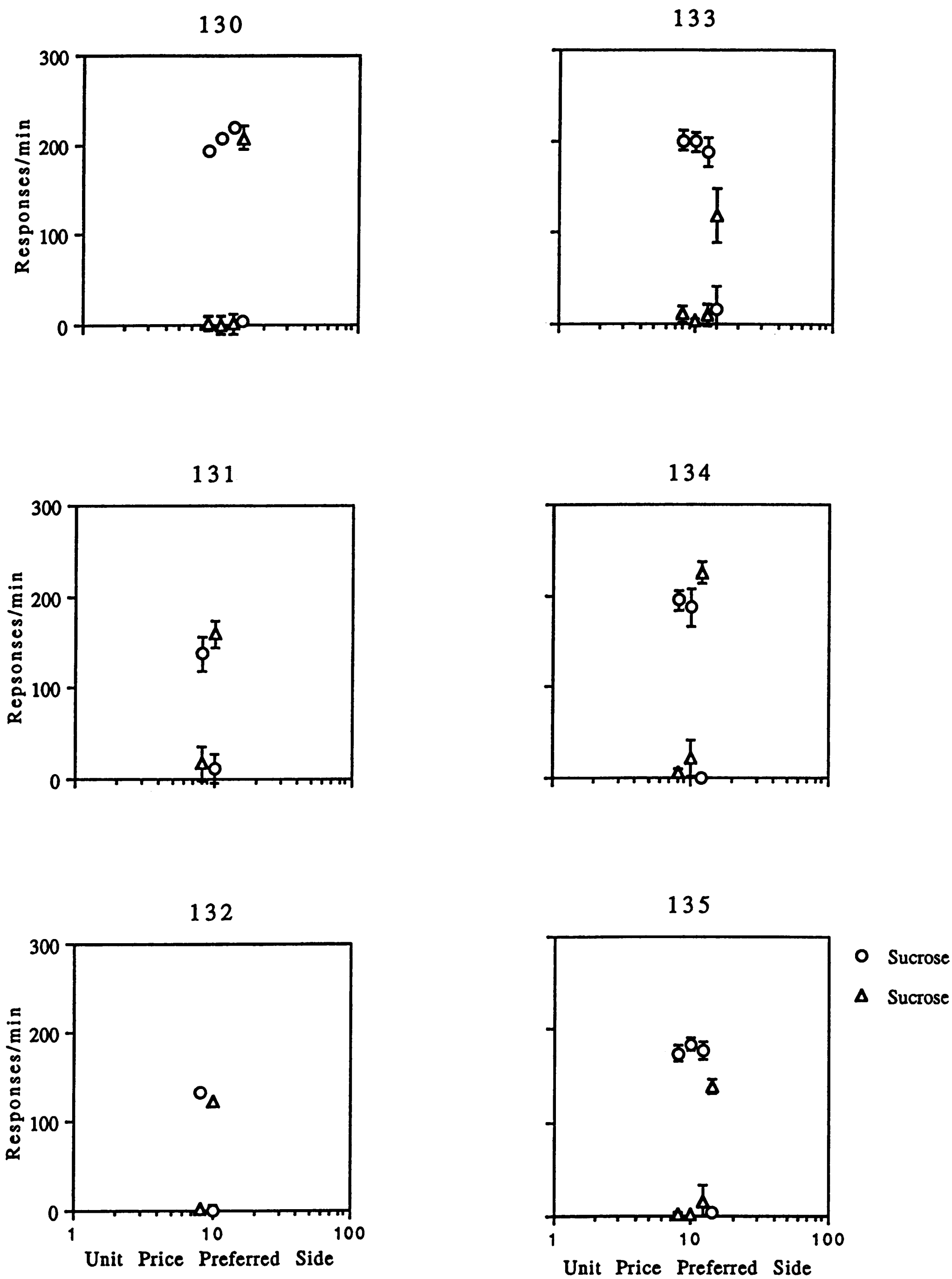

Fig. 5. Response rates for sucrose from the originally preferred lever and for sucrose from the originally non-preferred lever across increasing VR requirements for the initially preferred lever. See Figure 1 for further details.

Table 3

Own-price elasticity of sucrose on preferred lever and cross-price elasticity of sucrose on non-preferred lever in Experiment 3.

	Rat 130		Rat 131		Rat 132		Rat 133		Rat 134		Rat 135	
VR	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price
10	*−0.24*	−0.64	−12.25	9.43	−22.98	17.50	*−0.11*	−3.30	−9.39	15.54	*−0.30*	−0.51
12	−1.67	0.26					*−0.39*	0.92	−25.02	9.13	*−0.56*	4.90
14	−7.78	9.23					−5.88	4.95			−7.36	7.33

anol when the response requirements were equal for both reinforcers. By the time the requirement for the 5% solution had been increased to between 30 and 40 responses, however, all rats had switched predominantly to the lever that provided 10% ethanol. Two of the rats that had responded for 10% ethanol mix in Experiments 1 and 2 responded predominantly for the 10% mix in the baseline condition. Increases in 5% ethanol response requirements did not greatly or systematically affect responding for either alternative in these subjects, except that there were slight decreases in 5% ethanol responding at higher VRs.

The average number of both 5% and 10% ethanol-mix reinforcers obtained across the different conditions is shown in Appendix A. For Rats 130, 131, 132, and 134, the amount of ethanol consumed in the VR 8 VR 8 condition, when they responded almost entirely for 5% ethanol mix, is remarkably similar to the amount consumed in the final conditions of Experiment 2, when they also responded almost entirely for 5% (or 10%, Rat 134) ethanol mix. Rats 133 and 135 consumed slightly less ethanol per session in this experiment than in the final condition of Experiment 2. For all rats, the total amount of ethanol consumed across the conditions did not change in any systematic way with the changes in response requirements.

Table 4 shows own-price elasticities of 5% ethanol mix and cross-price elasticities of 10% ethanol mix across conditions. The 5% ethanol mix acted as both an elastic and inelastic commodity, although it tended to be more inelastic in rats that normally consumed 5% ethanol. The 10% ethanol mix generally served as a substitute for the 5% ethanol mix in Rats 130, 131, and 132. In the 2 rats that preferred 10% ethanol mix in baseline, 10% ethanol-mix consumption was independent of 5% ethanol-mix consumption.

The log-log plot of reinforcers earned across the unit price of the 5% ethanol mix is shown in Figure 8. In this graph, unit price for the ethanol mix was defined as one unit for each 5% ethanol reinforcer consumed and as two units for each 10% ethanol reinforcer consumed. Consumption of ethanol mix was relatively inelastic with initial changes in VR for rats that had preferred 5% ethanol mix in baseline. As response requirements continued to rise, 5% ethanol consumption dropped precipitously. In general, the number of 10% ethanol-mix reinforcers earned rose as the cost of the 5% ethanol mix increased. In the 2 rats that preferred the stronger ethanol solution, increases in VR requirements for the 5% mix did not affect 10% ethanol-mix consumption, but did decrease 5% ethanol-mix consumption.

This experiment demonstrates that demand for 5% ethanol was relatively inelastic at lower prices; as price initially increased, responding increased and consumption remained stable, especially in those rats that preferred 5% to 10% ethanol mix. However, at greater increases in price, demand for 5% ethanol mix became elastic, and responding for it declined. The 5% ethanol mix may have been a relatively inelastic commodity because ethanol, in concentrations above 5%, can taste aversive to rats (Amit & Stern, 1969; Deutsch & Eisner, 1977; Kahn & Stellar, 1960).

This experiment also shows that the relationship between these reinforcers varied as a function of price. The 10% ethanol mix tended to be an independent commodity when 5% ethanol mix was inelastic. As the price of 5% ethanol rose, the stronger etha-

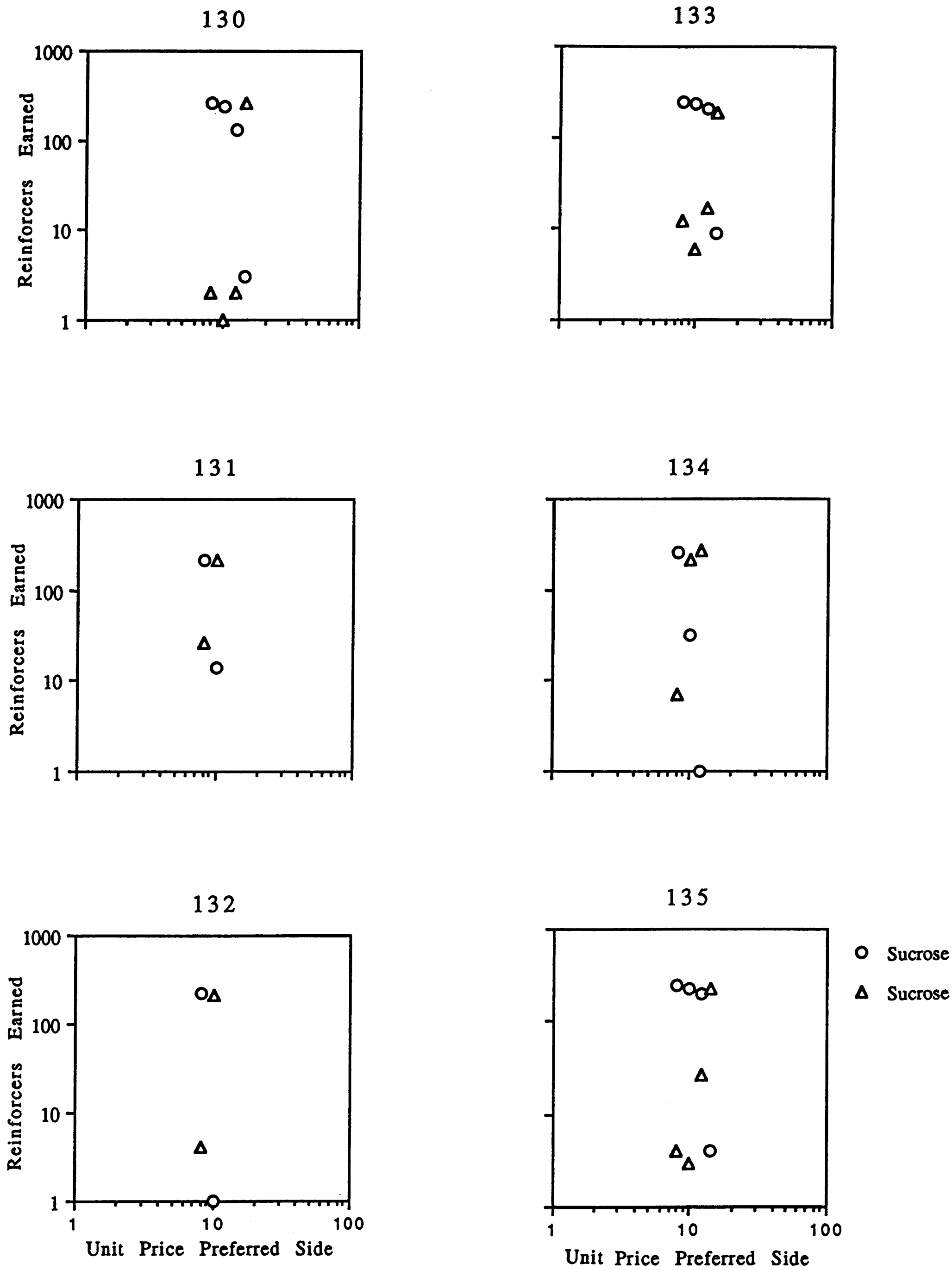

Fig. 6. Consumption of sucrose via the originally preferred lever and sucrose via the originally nonpreferred lever across increasing VR requirements for the preferred lever. See Figure 2 for further details.

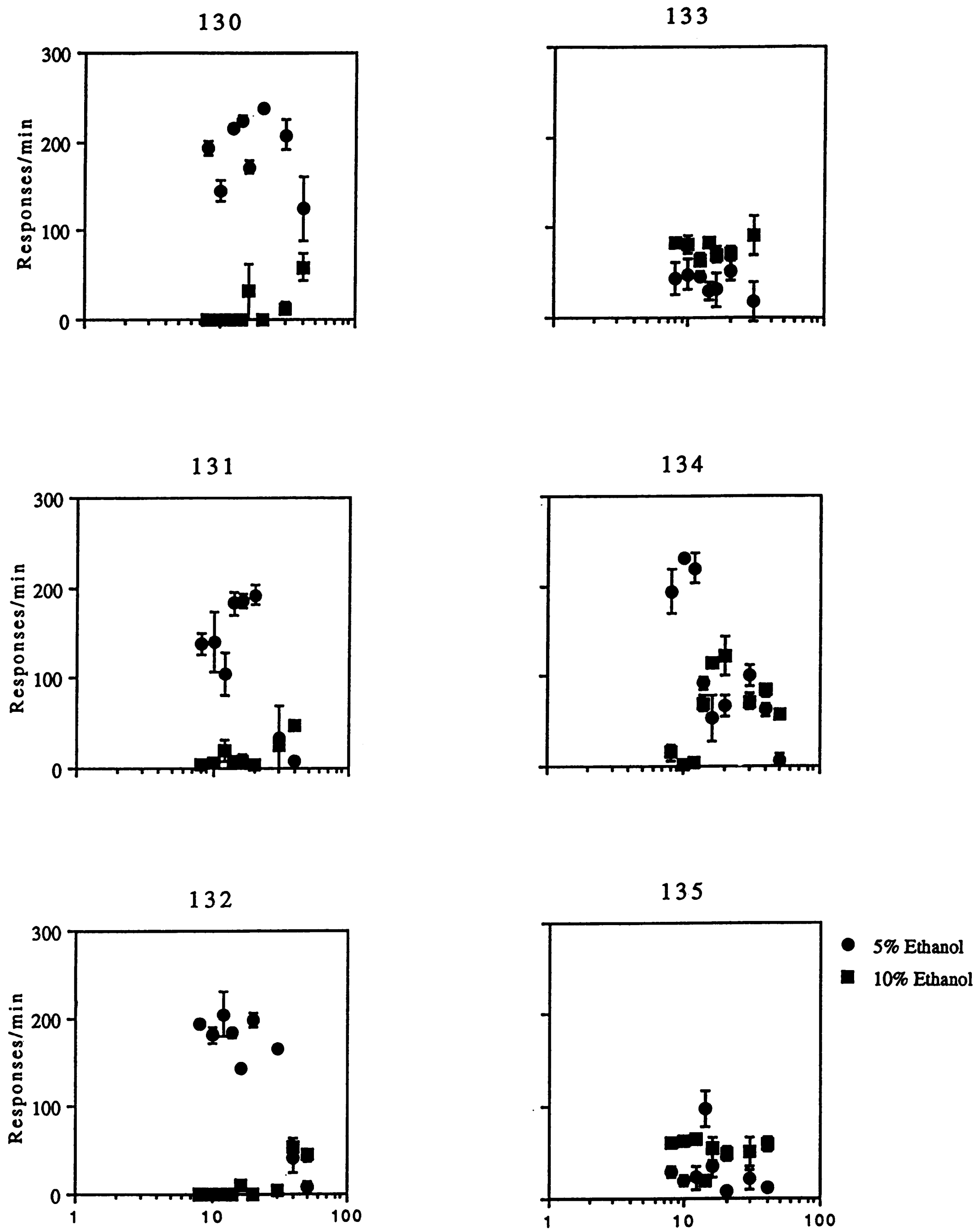

Fig. 7. Response rates for 5% ethanol mix and 10% ethanol mix across increasing VR requirements for the 5% ethanol mix. See Figure 1 for further details.

Table 4

Own-price elasticity of 5% ethanol mix and cross-price elasticity of 10% ethanol mix in Experiment 4.

	Rat 130		Rat 131		Rat 132		Rat 133		Rat 134		Rat 135	
VR	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price	Own price	Cross price
10	−1.79	10.32	*−0.52*	1.13	*−0.50*	−5.40	*−0.19*	−0.03	*0.14*	−10.32	−2.34	0.42
12	*−0.28*	0.00	−1.13	4.17	*−0.34*	−0.88	*−0.37*	−0.29	*−0.16*	−3.42	−1.36	0.30
14	*−0.30*	0.00	*−0.25*	0.96	*−0.48*	0.47	−1.32	0.18	−1.74	3.22	1.28	−1.78
16	*−0.77*	9.21	*−0.30*	1.00	*−0.76*	4.39	−1.15	0.01	−2.50	3.21	*−0.53*	−0.04
20	*−0.35*	2.51	*−0.33*	0.15	*−0.28*	−2.51	*−0.57*	0.01	−1.89	2.46	−2.18	0.01
30	*−0.53*	4.26	−1.68	1.76	*−0.62*	1.88	−1.41	0.16	−1.16	1.47	−1.04	−0.01
40	−1.01	4.41	−2.49	1.77	−1.59	3.01			−1.42	1.31	−1.42	0.09
50					−2.27	2.59			−2.62	1.06		

nol solution substituted for the weaker one. Regardless of concentration of the ethanol mix consumed, the rats maintained constant levels of ethanol intake.

EXPERIMENT 5: SIMULTANEOUS INCREASES IN VR REQUIREMENTS FOR BOTH ETHANOL MIX AND SUCROSE

This experiment examined the effects of equivalent increases in VR requirements for both commodities. Responding for the reinforcer that is more inelastic should persist, and responding for the more elastic reinforcer should decrease. Because demand for sucrose was more elastic than was demand for ethanol mix in the previous experiments, ethanol-mix-reinforced responding was expected to persist at high rates across more conditions than sucrose-maintained responding. Sucrose-reinforced responding, on the other hand, was expected to decrease systematically. A new group of animals served as subjects in this experiment in order to generalize the applicability of this procedure and these findings. Moreover, female rats, which are known to consume more ethanol per gram of body weight than males, were used to extend the basic findings to both sexes.

Method

Rats were trained as described in the General Method section. After several months of high ethanol intake, the requirement for both solutions was systematically raised from VR 8 to 10, 12, 14, 16, 20, 30, 40, 50, 60, 80, 100, and 120. Again, responses and number of reinforcers on each lever were recorded. Results are presented from the last three sessions of each condition, and each condition was kept in effect for a minimum of five sessions and until responding had stabilized.

Figure 9 shows response rates for both ethanol mix and sucrose in each rat across conditions. Small increases in response requirements generally resulted in increases in responding for one or both reinforcers. However, when the response requirements had increased five-fold, 7 of the 8 rats responded almost exclusively for the ethanol mix. Appendix B shows the number of ethanol-mix and sucrose reinforcers consumed across the different response requirements. Rats in this experiment consumed slightly more ethanol-mix reinforcers than rats in the previous experiments did. Moreover, these female rats weighed an average of 292 g, whereas the male rats weighed an average of 346 g. Thus, these female rats consumed an ethanol dose of approximately 2.2 g/kg on average. The high rates of responding demonstrated in Figure 9 indicate that the rats defended baseline levels of intake during initial changes in response requirements. However, as the price continued to increase, consumption of both reinforcers declined. By VR 50, consumption was almost exclusive for the ethanol mix in all but 1 subject.

Table 5 shows own-price elasticities of both reinforcers as the prices of both were increased. At virtually every change in VR requirement, demand for ethanol mix was inelastic for 7 of the 8 rats. Demand for sucrose was more likely to be elastic. These relations

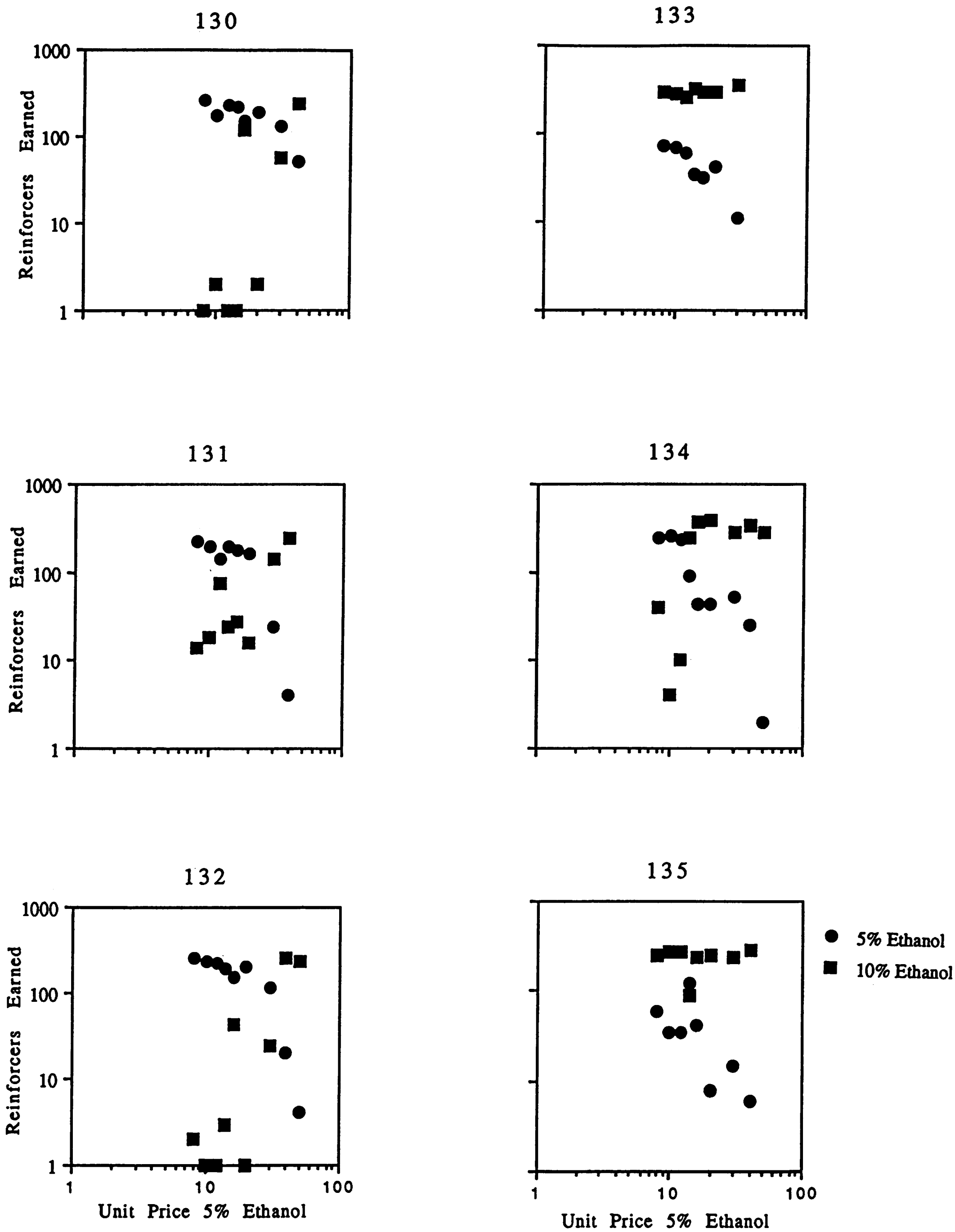

Fig. 8. Consumption of 5% ethanol mix and 10% ethanol mix across increasing VR requirements for the 5% ethanol mix. See Figure 2 for further details.

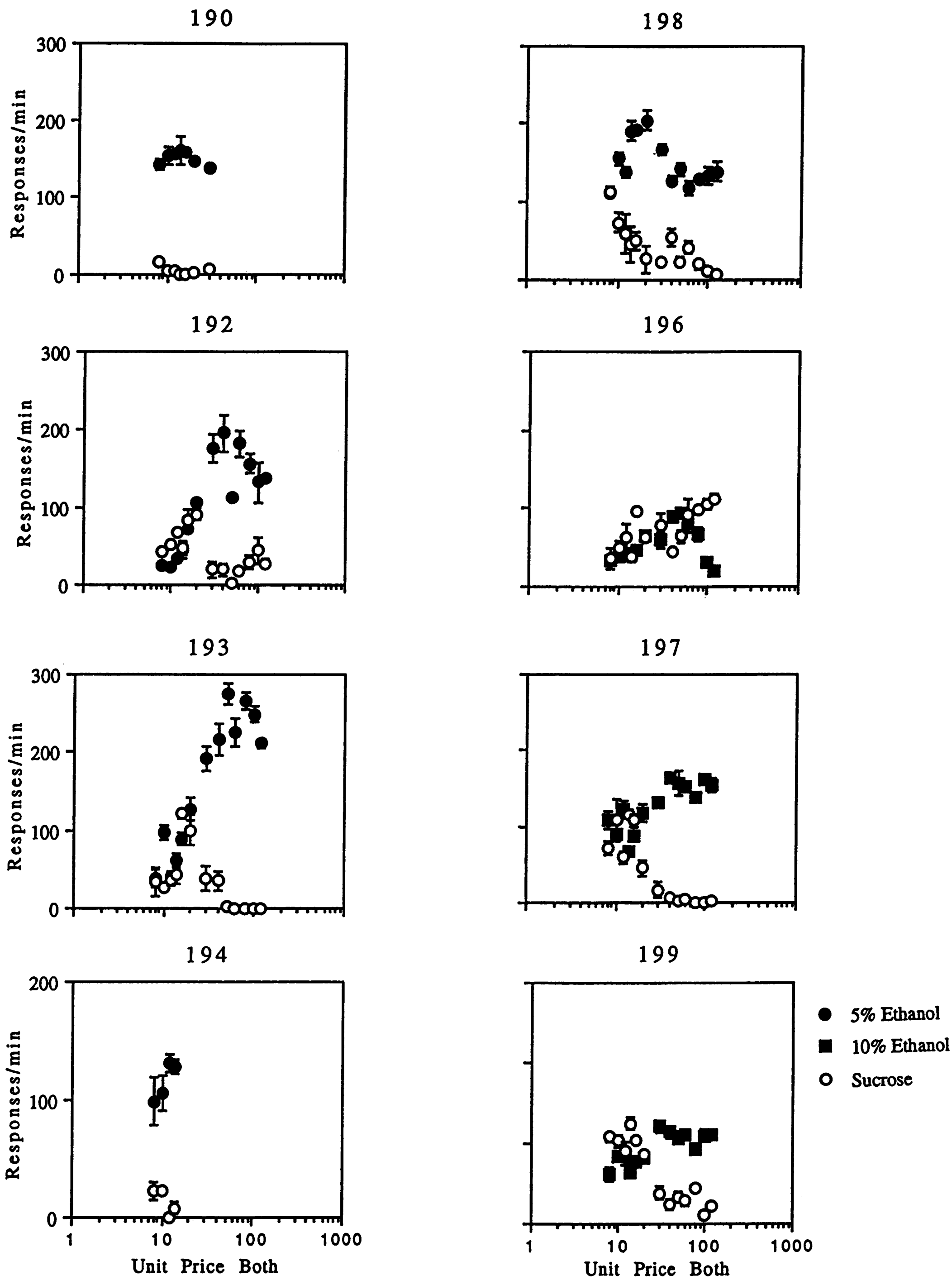

Fig. 9. Response rates for ethanol mix and sucrose across increasing VR requirements for both reinforcers. See Figure 1 for further details.

Table 5

Own-price elasticities of ethanol mix and sucrose in Experiment 5.

	Rat 190		Rat 192		Rat 193		Rat 194	
VR	Ethanol price	Sucrose price	Ethanol price	Sucrose price	Ethanol price	Sucrose price	Ethanol price	Sucrose price
10	*−0.21*	−2.51	*−1.00*	*0.00*	2.45	−2.31	*−0.30*	*−0.58*
12	*−0.31*	−1.38	*−0.19*	*0.15*	*−0.64*	*−0.49*	*0.11*	−26.20
14	*−0.34*	−2.24	*0.03*	*0.14*	*−0.24*	*0.44*	*−0.22*	*−0.68*
16	*−0.39*	−2.81	*0.52*	*−0.14*	*−0.07*	*0.66*		
20	*−0.50*	*−0.92*	*0.56*	*−0.24*	*0.17*	*0.13*		
30	*−0.59*	*−0.42*	*0.58*	−1.47	*0.24*	*−0.83*		
40			*0.40*	−1.36	*0.14*	*−0.86*		
50			*0.02*	−2.50	*0.15*	−2.33		
60			*0.14*	−1.24	*0.00*	−5.55		
80			*−0.04*	−1.04	*−0.04*	−4.86		
100			*−0.18*	*−0.87*	*−0.13*	−4.43		
120			*−0.21*	−1.03	*−0.23*	−4.13		

are illustrated in Figure 10, which shows the plot of reinforcers earned versus unit price.

GENERAL DISCUSSION

In order to facilitate comparison of elasticity coefficients across the different experiments, Figures 11 and 12 show the group median own-price and cross-price elasticity values for the different conditions in all five experiments. Median values were calculated only for those conditions in which at least 3 subjects participated. Figure 11 shows that demand for ethanol mix was more likely to be inelastic than was demand for sucrose. In fact, in every experiment in which the price of ethanol mix was varied, demand for it was inelastic in at least three conditions. The median own-price elasticity values for sucrose were always below −1.0 in Experiments 2 and 3. In Experiment 5, demand for sucrose was inelastic at initial price increases. However, although demand for ethanol mix continued to be inelastic throughout the conditions, demand for sucrose became elastic at VR 30.

Figure 12 displays median cross-price elasticities of ethanol mix and sucrose. Sucrose was a substitute for sucrose in Experiment 3, but throughout Experiment 1 sucrose consumption was independent of ethanol-mix consumption. In Experiment 4, 10% ethanol mix was independent of 5% ethanol mix with initial changes in the price of 5% ethanol mix. At higher prices, 10% ethanol mix substituted for 5% ethanol mix. Interestingly, in Experiment 2, ethanol mix always served as a substitute for sucrose, and the largest median cross-price elasticity value occurred with the smallest change in sucrose price.

Four major findings emerged from these experiments. First, ethanol consumption in these animals seems to be related to the pharmacological effects of ethanol, and the rats regulated their daily intake. Second, demand for ethanol mix was relatively inelastic; increases in price, especially at lower prices, resulted in enhanced responding to maintain baseline levels of ethanol-mix intake. Third, demand for sucrose was relatively elastic; increases in its price resulted in systematic decreases in consumption. Fourth, ethanol served as a substitute for sucrose, but sucrose consumption was independent of ethanol-mix price.

Regarding the first finding, the male and female rats averaged 1.24 g/kg/day and 2.2 g/kg/day of ethanol consumption, respectively. Blood ethanol levels of from 50 to 150 mg/dl (Heyman, 1994; Heyman & Gendel, unpublished findings) have been ascertained in other rats in this laboratory that participated in similar experiments and consumed equivalent daily amounts of ethanol. These blood ethanol levels have been shown to lead to cognitive impairments, such as decreased habituation in a spontaneous alternation task (Petry, 1994a). Biopsies of rats from this laboratory demonstrated multifocal hepatic necrosis, liver inflammation and hemorrhages, and biliary duct hyplasia (Heyman, unpublished findings). Thus, rats trained in the

Table 5

(*Extended*)

	Rat 198		Rat 196		Rat 197		Rat 199	
VR	Ethanol price	Sucrose price	Ethanol price	Sucrose price	Ethanol price	Sucrose price	Ethanol price	Sucrose price
10	1.09	−2.38	*−0.62*	*0.58*	−1.46	1.14	*0.74*	*−0.92*
12	*0.36*	−1.86	*−0.57*	*0.40*	*−0.13*	*−0.88*	*0.26*	*−0.92*
14	*0.52*	−2.14	*−0.51*	*0.23*	−1.30	*0.40*	*−0.45*	*−0.31*
16	*0.32*	−1.66	*−0.57*	*0.46*	*−0.81*	*0.07*	*−0.19*	*−0.58*
20	*0.22*	−2.09	*−0.18*	*−0.23*	*−0.35*	*−0.92*	*−0.19*	*−0.74*
30	*−0.13*	−1.67	*−0.42*	*−0.23*	*−0.34*	−1.60	*−0.02*	−1.33
40	*−0.40*	*−0.94*	*−0.23*	*−0.67*	*−0.30*	−2.18	*−0.17*	−1.46
50	*−0.37*	−1.37	*−0.28*	*−0.51*	*−0.37*	−2.13	*−0.28*	−1.21
60	*−0.51*	*−0.95*	*−0.44*	*−0.29*	*−0.43*	−1.94	*−0.32*	−1.20
80	*−0.51*	−1.29	*−0.54*	*−0.39*	*−0.52*	−5.00	*−0.46*	−1.02
100	*−0.52*	−1.51	*−0.90*	*−0.40*	*−0.50*	−2.30	*−0.43*	−1.57
120	*−0.53*	−1.81	−1.01	*−0.41*	*−0.54*	−1.83	*−0.45*	−1.27

manner described in this report drink pharmacologically significant amounts of ethanol. These data demonstrate that ethanol consumption was fairly constant between and within studies. For example, the total amount of ethanol consumed in the last condition of Experiment 2 was very similar to the total amount of ethanol consumed in most conditions of Experiment 4. This consistency of intake suggests that some pharmacological property of ethanol may be mediating its consumption (see also Petry, 1994b, in press).

The second major finding was that demand for ethanol mix was relatively inelastic, as shown in Experiments 1, 4, and 5. Increases in the price of ethanol mix were associated with enhanced responding and, to a limited extent, increases in consumption. One interpretation of this result is that the pharmacological properties of ethanol mediated its consumption. The reinforcement gained from the ethanol mix may have been unique in comparison to other reinforcers that were available to the rats, and the animals, therefore, may have been more likely to defend intake levels despite increasing costs. Another, although not mutually exclusive, interpretation of the inelasticity of demand for the ethanol mix is related to the additional calories that the ethanol mix provided. Because the rats were food deprived, demand for the reinforcer providing the richer source of calories may have been more inelastic. However, Experiment 4 demonstrated that 5% ethanol mix, although less caloric, was preferred to 10% ethanol mix, and demand for the 5% ethanol was relatively inelastic. Despite altering costs, similar total amounts of ethanol were consumed in this experiment, again suggesting a pharmacological component to the reinforcement of ethanol mix that may be unrelated to calories.

In contrast to the relatively inelastic demand for the ethanol mix, demand for sucrose was elastic. Demand for sucrose was elastic regardless of whether ethanol or sucrose was the alternative reinforcer. In fact, comparing Figures 4 and 6, demand for sucrose was more elastic when it was paired with ethanol mix than with itself. As prices of both reinforcers increased in Experiment 5, consumption of sucrose dropped sooner than consumption of ethanol did. Figure 11 further demonstrates that, with the exception of initial price increases in Experiment 5, demand for sucrose was elastic in all three experiments in which its price was manipulated.

These results may be due in part to the economies in which the two reinforcers were available. Within this concurrent access paradigm, sucrose consumption seems to be highly related to pre- and postsession food consumption, but ethanol-mix responding is not. Heyman (1993) and Petry (unpublished findings) found that sucrose-maintained responding decreased when rats were given chow immediately prior to the session or when postsession feedings increased in magnitude. However, ethanol consumption either increased or remained unchanged with these same alterations. In the present experiments, then, the two reinforcers may have been avail-

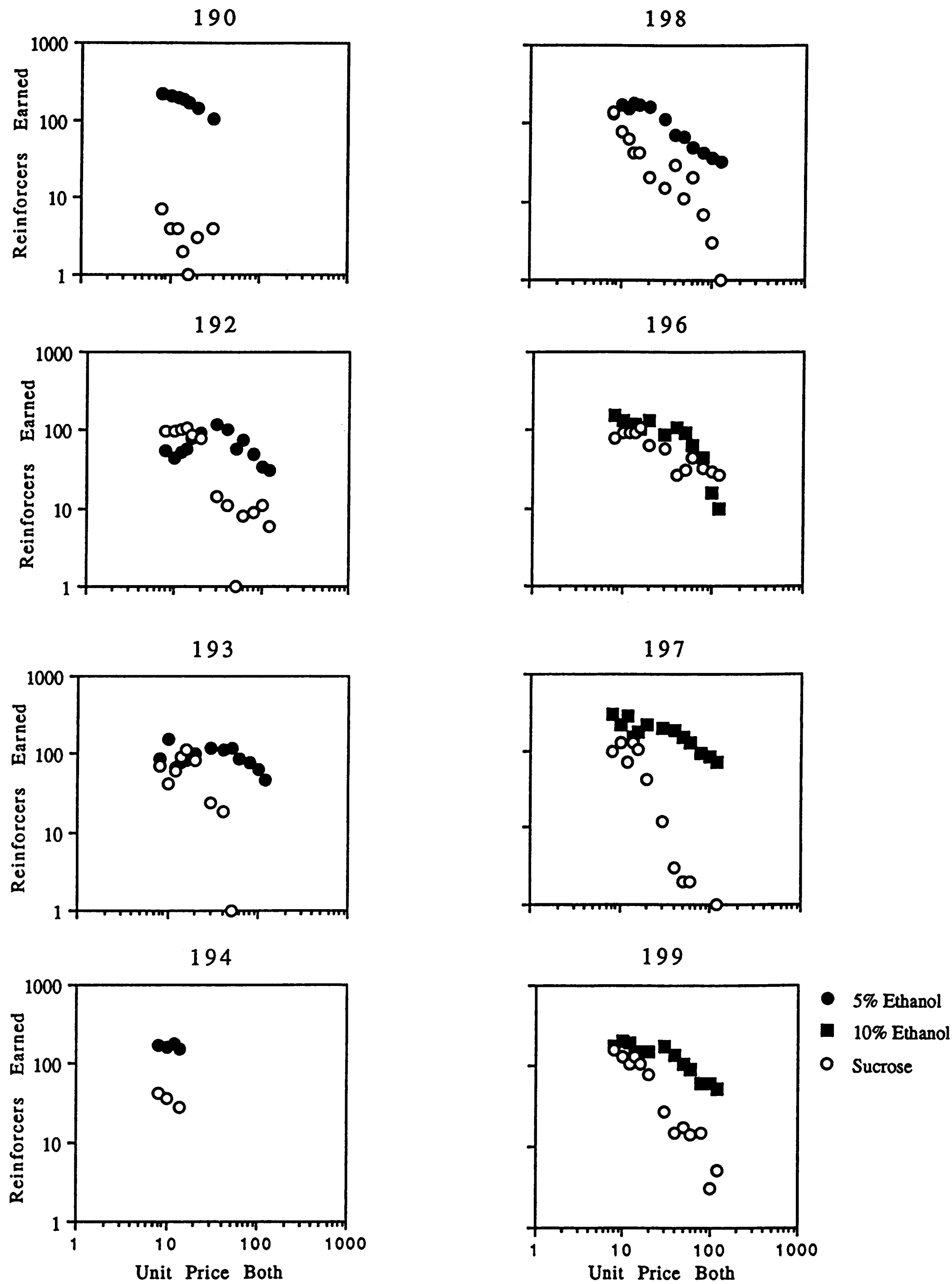

Fig. 10. Consumption of ethanol mix and sucrose as a function of unit price (VR requirements) of both reinforcers. See Figure 2 for further details.

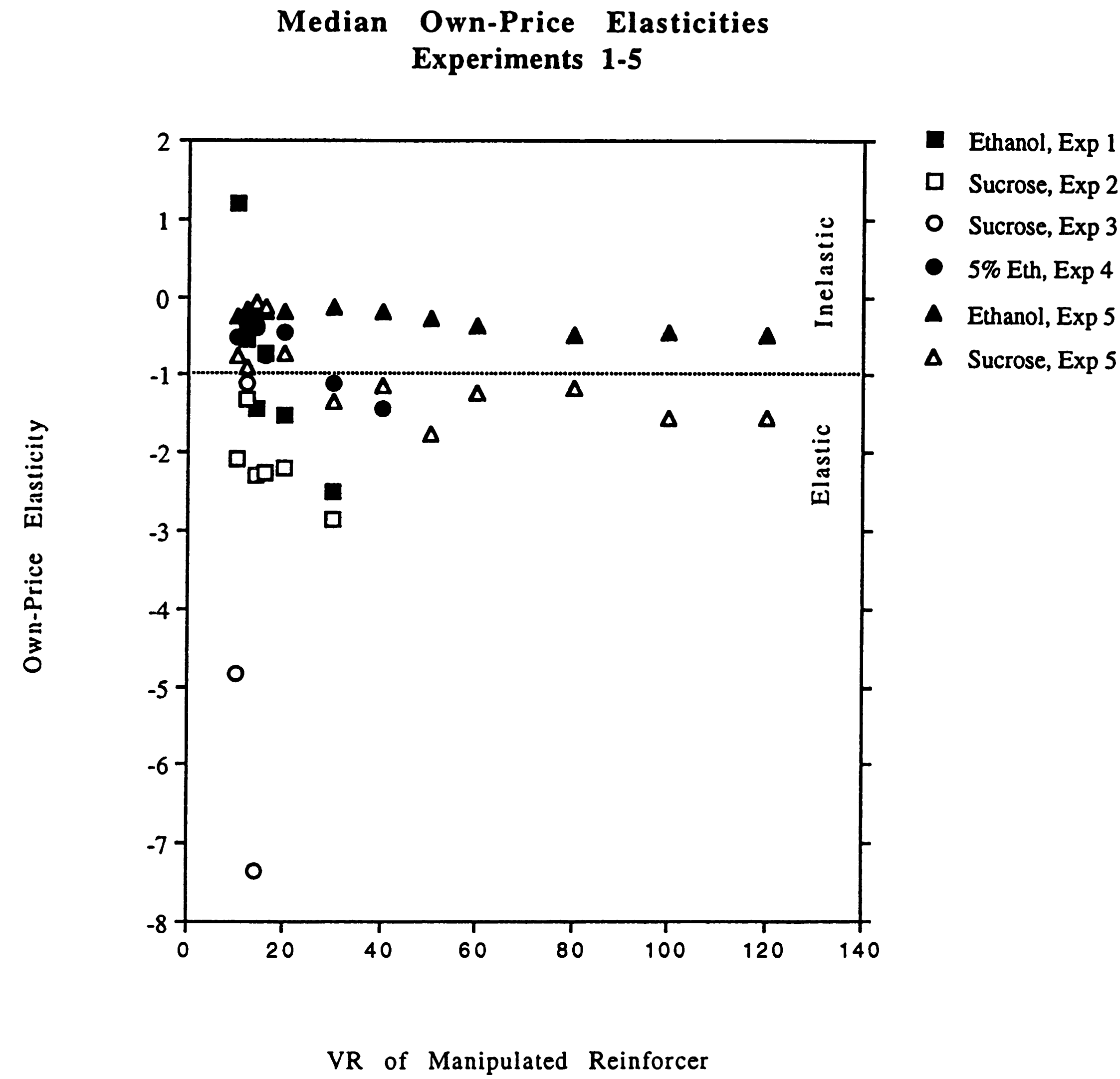

Fig. 11. Median own-price elasticity values for ethanol mix and sucrose across VR requirements in Experiments 1 through 5. See text for further details.

able in different types of economies: food and sucrose in an open economy, but ethanol mix in a closed economy. The elasticity of demand for a reinforcer seems to depend on the type of economy in which it is available. Hursh (1980), for example, demonstrated that demand for food can be elastic in an open economy but inelastic in a closed economy. The inelasticity of the demand for ethanol mix found in the present experiments may have resulted because the drug was available only during the experimental sessions, whereas food was available after the session. Regardless of the nature of the type of economy in which the reinforcers were available, the differential elasticities of demand for the two reinforcers further support the interpretation that the reinforcing properties of the ethanol mix and sucrose were qualitatively distinct (see also Heyman, 1993, in press-a, in press-b; Heyman & Oldfather, 1992; Petry, 1994b, in press).

The inelastic demand for ethanol is surprising when compared to previous reports. Numerous reviews of the literature (e.g., Cicero, 1979; Dole, 1986; Lester & Freed, 1973)

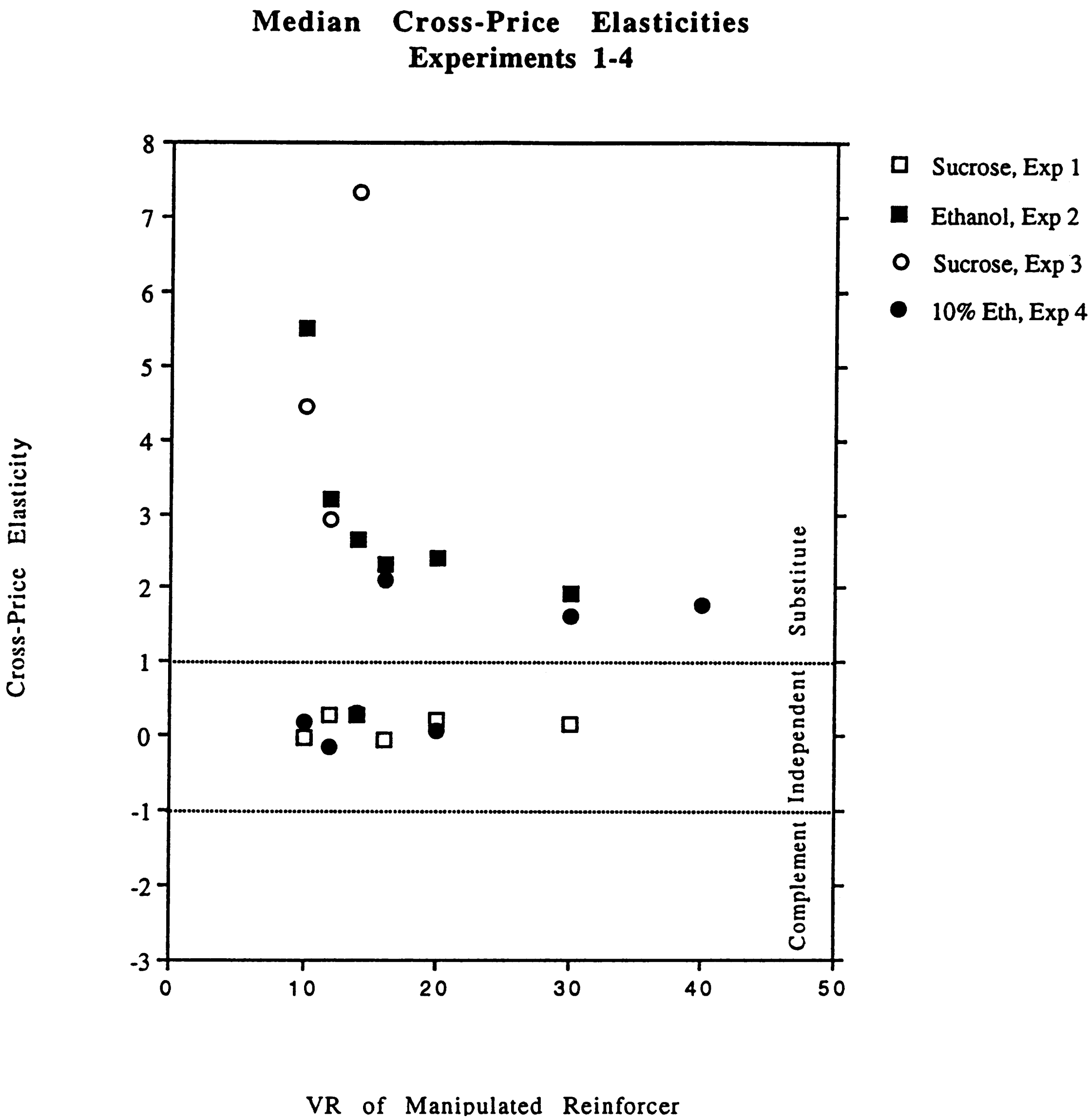

Fig. 12. Median cross-price elasticity values for ethanol mix and sucrose across variable-ratio requirements in Experiments 1 through 4. See text for further details.

and a multitude of experiments (e.g., Meisch & Thompson, 1973; Roehrs & Samson, 1982; Samson, 1986; Samson, Pfeffer, & Tolliver, 1988; Schwarz-Stevens, Samson, Tolliver, Lumeng, & Li, 1991) have demonstrated the difficulty in establishing oral self-administration of ethanol in rats. Most studies that have been able to induce substantial amounts of ethanol consumption have found that intake is related to caloric properties and rapidly dissipates with the introduction of an alternative food source (e.g., Meisch & Thompson, 1973; Schwarz-Stevens et al., 1991). In one experiment, however, Roehrs and Samson (1981) found demand for ethanol to be inelastic when it was concurrently available with water. Ethanol fixed ratios were raised from 8 to 50, yet animals maintained relatively similar response rates for ethanol. Using a modification of Samson's procedures, we have demonstrated in this and a previous report (Heyman & Oldfather, 1992) that demand for ethanol mix can be inelastic and that the reinforcing effects of ethanol and sucrose are different. A few other studies have also indicated that demand for drug reinforcers may be more inelastic than that for nondrug reinforcers. DeGrandpre et al. (1994) showed that elasticity coefficients were greater (more negative) for money than for cigarettes, and Carroll (1993) found that phencyclidine consumption was less sensitive to income reductions than was saccharin consumption.

The fourth major, and perhaps most important, finding dealt with the relationship between concurrently available reinforcers. Sucrose was generally an independent commodity when the price of ethanol mix varied. Thus, the price of the drug reinforcer had little effect on the consumption of the nondrug reinforcer. When the price of sucrose was manipulated, however, ethanol mix was a substitute for the sucrose. In other words, as the price of a nondrug alternative reinforcer increased, the consumption of a drug increased. Experiment 2 demonstrated a two- to 10-fold increase in drug consumption with increases in sucrose price.

Similar findings have been noted in previous studies of drug and nondrug interactions and may be relevant to the clinical understanding and treatment of drug abuse. For example, a number of laboratory experiments have demonstrated increased drug consumption in environments that contain few alternative reinforcers: food-deprived states, isolated housing and experimental conditions, and weak or nonexistent alternative, experimenter-arranged sources of reinforcement (e.g., Carroll, 1993; Carroll & Boe, 1982; Carroll & Lac, 1992; Carroll, Lac, & Nygaard, 1989; Meisch & Thompson, 1973). In the real world, those living in deprived environments have likewise demonstrated greater rates of drug addiction than those who engage in careers and family or social relationships that they find rewarding. Behavioral economic approaches may be useful in examining and quantifying the effects of alternative sources of reinforcement as precursors to drug abuse.

Figures 1 and 9 also demonstrated that increases in the cost of a drug reinforcer can produce increases in drug seeking. Other laboratory experiments have noted a similar relationship. For example, a decrease in dose or increase in price of cocaine or nicotine has resulted in enhanced responding for these drugs (e.g., Bickel, DeGrandpre, Higgins, Hughes, & Badger, in press; Bickel, DeGrandpre, Hughes, & Higgins, 1991; Goldberg, Hoffmeister, Schlichting, & Wuttke, 1971; Griffiths, Henningfield, & Bigelow, 1982). This escalation of drug seeking with increased costs may be relevant to current social issues. Proponents of drug legalization (e.g., Nadelmann, 1989) have argued that the increased sanctions placed on drug use (the "war against drugs") have not affected the demand for drugs, but instead have increased drug-associated crime. This increased crime, despite increased sanctions, may be analogous to the enhanced ethanol-lever pressing in the rats in Experiments 1 and 5—when the cost of drugs increased marginally, an increase in drug seeking was noted. However, these experiments also suggest that when the costs of drugs were extremely high in relation to the cost of an alternative reinforcer, drug seeking and consumption decreased. Thus, experiments similar to these, with different drug and nondrug reinforcers, are required to better elucidate this relationship between drug seeking and price or costs associated with drug use. Such experiments may provide input to drug policy (see also Hursh, 1991).

In addition, quantification of the interactions between reinforcers using behavioral economic concepts may lead to a better understanding of treatments for drug abuse. For example, many current treatment programs encourage patients to engage in activities that compete with drug use, such as attending Alcoholics Anonymous meetings or reestablishing ties with family and friends who do not use drugs (Higgins et al., 1991). Other therapies offer substitutes to drug use, such as methadone or psychotherapy (Higgins, Stitzer, Bigelow, & Liebson, 1986). Still others increase the costs associated with drug use by withholding alternative reinforcement (vouchers, buprenorphine, take-home doses of methadone) upon submission of drug-positive urines (Bickel et al., unpublished findings; Higgins, Bickel, & Hughes, 1994; Higgins, Budney, et al., 1994; Stitzer, Bickel, Bigelow, & Liebson, 1986; Stitzer, Iguchi, & Felch, 1992). Although still speculative, behavioral economic studies may prove to be useful in quantifying these relationships be-

tween drug and nondrug reinforcers and assessing their relationship to recovery and relapse.

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APPENDIX A

Mean reinforcers in the last 3 days at each condition in Experiments 1–4.

	Rat 130		Rat 131		Rat 132		Rat 133		Rat 134		Rat 135	
VR	Ethanol	Sucrose	Ethanol	Sucrose	Ethanol	Sucrose	Ethanol	Sucrose	Ethanol	Sucrose	Ethanol	Sucrose
Ethanol												
8	125	131	38	237	117	51	124	167	216	98	160	144
10	183	70	98	223	71	118	164	175	154	159	208	115
12	14	258	32	229	40	152	204	141	166	128	248	50
14	1	263	16	255	19	193	60	211	270	72	250	77
16			23	230	2	206	38	220	208	65	140	91
20			2	262			30	223	54	211	126	93
30							24	120	8	243	2	178
Sucrose												
8	120	162	102	110	58	156	4	256	36	250	36	268
10	255	28	107	97	5	232	152	175	244	144	198	134
12	247	33	132	77	259	6	200	140	152	178	114	168
14	264	4	195	19			198	119	158	164	268	75
16			219	4			332	58	164	153	200	52
20							392	34	218	131	326	23
30							440	6	330	54	450	1
40									264	52		
50									272	43		
60									332	7		
	Sucrose	Sucrose	Sucrose	Sucrose	Sucrose	Sucrose	Sucrose	Sucrose	Sucrose	Sucrose	Sucrose	Sucrose
Sucrose												
8	257	2	211	26	219	4	241	12	254	7	246	4
10	243	1	14	213	1	213	236	6	31	215	230	3
12	130	2					206	17	0	271	196	27
14	3	262					9	190			4	224
	10% ethanol	5% ethanol	10% ethanol	5% ethanol	10% ethanol	5% ethanol	10% ethanol	5% ethanol	10% ethanol	5% ethanol	10% ethanol	5% ethanol
5% ethanol												
8	0	258	14	221	2	257	288	71	40	244	244	59
10	2	173	18	197	1	230	286	68	4	252	268	35
12	0	230	76	140	1	224	256	61	10	229	276	34
14	0	218	24	192	3	196	318	34	242	92	90	121
16	118	151	28	180	42	152	290	32	370	43	238	41
20	2	188	16	164	0	199	290	42	380	43	246	8
30	56	128	144	24	24	114	354	11	280	53	240	15
40	242	51	242	4	254	20			330	25	280	6
50					230	4			280	2		

Note. 10% ethanol refers to twice the number of 10% ethanol reinforcers earned.

APPENDIX B

Mean reinforcers in the last three sessions at each condition in Experiment 5.

	Rat 190		Rat 192		Rat 193		Rat 194		Rat 198		Rat 196		Rat 197		Rat 199	
Sucrose VR	10% ethanol	Sucrose	10% ethanol	Sucrose	10% ethanol	Sucrose	10% ethanol	Sucrose	10% ethanol	Sucrose	10% ethanol	Sucrose	10% ethanol	Sucrose	10% ethanol	Sucrose
8	221	7	55	98	88	72	171	41	135	136	154	79	302	100	178	157
10	211	4	44	98	152	43	160	36	172	80	134	90	218	129	210	128
12	195	4	51	104	68	59	179	0	156	64	122	93	286	70	198	108
14	183	2	56	106	77	92	151	28	181	41	116	90	146	125	138	132
16	169	1	79	89	84	114			169	43	104	109	172	105	156	105
20	140	3	92	79	103	81			165	20	130	64	220	43	150	80
30	101	4	118	14	121	24			113	15	88	58	192	12	174	27
40			104	11	110	18			71	30	106	27	186	3	136	15
50			57	1	116	1			68	11	92	31	152	2	106	17
60			73	8	88	0			48	20	64	44	128	2	94	14
80			50	9	80	0			42	7	44	32	92	0	62	15
100			35	11	63	0			36	3	16	29	86	0	60	3
120			31	6	47	0			32	1	10	26	70	1	52	5

Note. 10% ethanol refers to twice the number of 10% ethanol reinforcers earned.