

Research Report

INELASTIC PREFERENCE FOR ETHANOL IN RATS: An Analysis of Ethanol's Reinforcing Effects

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Abstract—*This experiment evaluated the relationship between availability of ethanol and preference for ethanol in rats. One dipper served a mixture of 10% ethanol and 10% sucrose, and a second dipper served 10% sucrose. In the first condition, access to each dipper was governed by a variable-interval 5-s schedule. In subsequent conditions, the interval requirement for the ethanol mixture was increased to 30 s. However, increases in the interval requirement did not decrease preference for ethanol. Instead, preference increased somewhat or remained about the same. In contrast, when both dippers served sucrose, increases in the interval requirement at one dipper systematically shifted preference to the other dipper. Analysis showed that preference for ethanol was correlated with amount of ethanol consumed, whereas preference for sucrose was correlated with changes in the reinforcement contingencies. Ethanol's food value, as measured by calories, did not predict preference. Rather, the results were most simply explained by the theory that ethanol's pharmacological consequences maintained responding.*

For more than five decades, laboratory rats have been plied with ethanol in the hope of developing a convenient animal model of alcoholism. A frequently cited experiment by Meisch and Thompson (1973) is representative of the earlier literature. Responses on one lever were reinforced with an 8% ethanol solution, and responses on a second lever were reinforced with water. When the rats were food deprived, they consumed about 2.0 g/kg of ethanol in the first hour of the session. This figure is well above the rate at which a rat metabolizes ethanol, about 0.3 g/kg/hr (Wallgren & Barry, 1970), and thus is likely to have produced pharmacological effects. However, when the rats were subsequently put on free-feed, ethanol consumption declined to about 0.3 g/kg for the first

hour of the session, the clearance rate. It is likely that the decline was in large part due to ethanol's sensory effects. Anosmic rats drank more ethanol than did normal rats (Kahn & Stellar, 1960), and rats with identical drinking histories consumed about two to six times more ethanol when oral ingestion was bypassed (Amit & Stern, 1969; Deutsch & Eisner, 1977). Thus, it seems likely that in Meisch and Thompson's study, ethanol consumption was a joint function of positive caloric consequences and negative sensory properties. When the rats were food deprived, the caloric effects prevailed; when they were food sated, taste and smell prevailed. Other studies obtained similar findings in monkeys (Myers, Stoltman, & Martin, 1972) and rats (Roehrs & Samson, 1982), and, consequently, reviewers concluded that a promising animal model of human ethanol consumption had yet to be developed (Cicero, 1979; Dole, 1986; Lester & Freed, 1973).

However, there are findings, mostly recent, which suggest that under certain conditions ethanol's pharmacological effects are reinforcing in rats. First, in studies which used intragastric (Deutsch & Cannis, 1980) and intravenous (Numan, 1981) self-administration, free-feeding rats consumed 8 to 12 g/kg/day of ethanol. Moreover, the rats defended intake levels; self-administration increased when there was either a decrease in ethanol concentration (Deutsch & Cannis, 1980) or an increase in the response requirement (Numan, 1981). Second, selective breeding techniques produced strains of rats that drank pharmacologically active amounts of ethanol under free-feeding conditions (Li, 1990). Third, Samson and his colleagues (Samson, 1986; Samson, Pfeffer, & Tolliver, 1988) developed procedures which induced free-feeding rats to consume ethanol at rates well above the clearance rate. One of their methods was to gradually substitute ethanol for sucrose. They suggested that this technique may have attenuated

the rats' initial aversion to ethanol's taste (Tolliver, Sadeghi, & Samson, 1988). These results, in contrast to earlier findings, show that food deprivation is not a necessary condition for ethanol consumption in rats.

Although ethanol consumption in free-feeding rats is consistent with the hypothesis that ethanol's pharmacological effects are reinforcing, other aspects of the data suggest a different interpretation. In a study which combined selective breeding with the sucrose-fading procedure, free-feeding, alcohol-preferring (P) rats were induced to self-administer pharmacologically significant amounts of a 10% ethanol solution orally (Schwarz-Stevens, Samson, Tolliver, Lumeng, & Li, 1991). When water was the alternative reinforcer, the rats strongly preferred ethanol. However, when water was replaced by 1% and 5% sucrose solutions, preference for ethanol decreased to 50% and 12%, respectively, and consumption of ethanol decreased by about 12% and 75%. Since a 1% sucrose solution is a weak reinforcer, even in food-deprived rats (Heyman & Monaghan, 1991), ethanol must not have been a potent reinforcer, and since sucrose consumption replaced ethanol consumption, ethanol's calories rather than pharmacology may have maintained responding. That is, if ethanol's pharmacological effects were reinforcing, the rats should not have shifted to sucrose, all else being equal. Consequently, the interpretation of the recent free-feeding data is unclear: Rats that had free access to laboratory chow consumed pharmacologically significant amounts of ethanol, yet when weak sucrose solutions were available, they switched from ethanol to sucrose.

In the experiment described in this paper, ethanol was mixed with sucrose in order to attenuate its aversive effects, and a 10% sucrose solution was available in order to determine whether sucrose substituted for ethanol as a reinforcer. In one set of conditions, access to ethanol

was restricted. If the reinforcing effects of the two substances were similar, the rats should have switched to the more readily available sucrose solution.

METHOD

Subjects

Four male, experimentally naive, Wistar rats (Charles River breeders, Wilmington, MA) served as subjects. At the start of the ethanol-induction phase of this study, the rats were approximately 2 months old and had free-feeding weights of about 280 to 300 g. They were housed singly, and the colony room was illuminated 12 hr a day (lights on at 7:00 a.m.). Their diet consisted of mixtures of ethanol and sucrose, consumed during the experimental sessions, and laboratory chow (Purina), consumed after the sessions. The amount of chow (about 8 g/day) was adjusted so that the rats remained at approximately 80% of their free-feeding weight. In the home cage, there was also free access to water.

Apparatus

The experiments were conducted in two standard operant chambers (MED Associates: 28 cm, 20.5 cm, 26 cm). Two 5-cm-wide levers were inserted into the front wall, 7 cm above the floor and 1 cm from each side. The levers were operated with a force of about 0.25 N. Just below each lever (2 cm) was an opening into which a 0.1-ml dipper could be raised. The dippers, when not raised, sat in a trough that held approximately 170 ml of liquid. The trough that held ethanol had an aluminum cover in order to reduce evaporation. Experimental events were arranged and recorded with an IBM-compatible personal computer that used MED-PC software and interface (Tatham & Zurn, 1989).

Procedure

Preexperimental induction of ethanol consumption

Prior to the experiments reported here, the subjects were induced to drink ethanol. One dipper served water, and the other dipper served ethanol mixed with 10% sucrose solution (w/v). Ethanol

concentration was varied from 5% to 30% (v/v). Access to each dipper was governed by an independent variable-interval (VI) 5-s schedule. Each concentration was kept in effect until response rates were stable. The criterion was the absence of an increasing or decreasing trend for three consecutive sessions. Response rates maintained by the ethanol mixture changed as a function of ethanol concentration. Upon introduction of a higher concentration, response rates decreased and then, in a few sessions, recovered to levels somewhat below the level for the previous concentration. New, higher concentrations often left the rats markedly ataxic. Ethanol consumption varied between about 2.71 and 8.15 g/kg as a function of concentration. The amount consumed was calculated from the amount of liquid left in the troughs at the end of the session. (This amount was about 84% of the nominal amount, as calculated from the number of reinforcers.) Following the 30% condition, the ethanol concentration was reduced to 25%, and a sucrose solution was substituted for water in the second dipper. The concentration of sucrose was varied from 0.5% to 32%. The results from these two phases of the study are described elsewhere (Oldfather, 1990). The next phase, described in this report, began 102 sessions after the initial introduction of ethanol.

Experiment 1: The effect of interval requirement on preference for ethanol relative to sucrose

One dipper served a mixture of 10% ethanol (v/v) and 10% sucrose (w/v); the other served 10% sucrose. The dippers were operated by lever presses according to independent VI schedules and remained accessible for 3 s during reinforcement. In the first condition, the average interval duration was 5 s for both dippers. Subsequently, the mean interval for the ethanol-sucrose mixture was increased to 7.5, 10, 15, and 30 s. The mean interval for the sucrose solution remained at 5 s throughout. The distribution of intervals was approximately Poisson and was generated by the algorithm described by Fleshler and Hoffman (1962). Each pair of VI schedules was kept in effect for five sessions and until relative response frequencies appeared

stable. The criterion for stability was three consecutive sessions in which relative response frequencies showed neither an increasing nor a decreasing trend. Experimental sessions were 30 min long and occurred 5 or 6 days a week. The alcohol (200 proof, Quantum Laboratories) mixtures were prepared biweekly.

Experiment 2: The effect of decreased access on preference for sucrose relative to sucrose

The purpose of this study was to determine elasticity of preference when both reinforcers were identical sucrose solutions. The same subjects and apparatus were used, and the procedure was identical to the one used in Experiment 1 except that both dippers served 10% sucrose. In the initial condition, the VI requirement for both dippers was set at 5 s. In subsequent conditions, the interval requirement for the dipper that had served ethanol in Experiment 1 was increased. The schedule values and sequence of increases were the same as in Experiment 1.

Elasticity of preference

In Experiments 1 and 2, changes in preference were plotted as a function of changes in the availability of reinforcement. Economists have taken a similar approach to preference. In economics, changes in consumption of a commodity are displayed as a function of changes in its price. This is called a demand curve, and the degree to which price affects demand is called price elasticity of demand. By analogy, in this experiment, the schedule elasticity of preference for ethanol was evaluated.

Equation 1, which is based on the generalized matching law (Baum, 1974; Herrnstein, 1970; Williams, 1988), was used to quantify the relationship between changes in the VI requirement for ethanol and preference for ethanol:

$$\frac{B_1}{B_2} = a \left(\frac{VI_2}{VI_1} \right)^b \quad (1)$$

On the left side, B_1/B_2 stands for the ratio of responses or time spent responding at the two levers. This ratio was used to index preference. On the right side are

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two fitted constants, *a* and *b*, discussed below, and the programmed reinforcement ratio, VI_2/VI_1 . For example, if VI_1 is 30 s and VI_2 is 5 s, then the scheduled reinforcement rates are 2/min and 12/min, respectively, and the programmed reinforcement ratio is 1/6. Thus, Equation 1 expresses preference as a power function of the ratio of the two programmed reinforcement rates.¹

The parameter *b* reflects the relationship between change in schedule values and change in preference. For example, if *b* is equal to 1, changes in VI values produce proportional changes in preference ($B_1/B_2 = a(VI_2/VI_1)$, when $b = 1$). Consequently, $b = 1$ will be referred to as *unit elasticity*. However, if *b* is equal to 0, preference remains fixed and independent of changes in the schedule values ($B_1/B_2 = a$, when $b = 0$). Thus, preference becomes increasingly inelastic as *b* approaches 0. In previous experiments, *b* varied as a function of the degree of similarity between the alternative reinforcers. For instance, when the alternative reinforcers were identical, *b* ranged from about 0.80 to 1.0 (Baum, 1979), but when the alternative reinforcers were food and water, *b* was negative (Hursh, 1978). (Negative values occurred because the subjects responded so as to maintain an approximately constant ratio between water and food consumption.) Thus, if the reinforcing effects of ethanol and food are similar, *b* should approach 1.

Baum (1974) defined *a* as bias, or the degree to which one reinforcer is favored over the other. For example, if the two VI schedules were the same, but preference nevertheless differed, *a* would differ from 1. In experiments, *a* of the generalized matching law equation approached 1 when the reinforcers were

1. Equation 1 uses the programmed reinforcement ratios, whereas the practice in the matching law literature is to use the obtained reinforcement ratios. The two measures are usually about the same. However, since this study asks whether preference changes as a function of the arranged reinforcement contingency, the schedule values are a more appropriate independent variable. In addition, the schedule values provide a fixed independent variable or point of reference, whereas the obtained reinforcement rates vary somewhat as a function of preference.

identical (Baum, 1974) and systematically differed from 1 when the reinforcers differed in magnitude (Keller & Golub, 1977) or kind (Miller, 1976). Note, though, that the value of *a* is constant and does not affect the relationship between changes in the schedule values and changes in choice. For example, in an experiment in which the two reinforcers were brain stimulation and food (Hollard & Davison, 1971), there was a bias in favor of food, but preference was nevertheless elastic: Increases in the interval requirement for food shifted preference to brain stimulation, and vice versa. Thus, preference for ethanol relative to sucrose may be perfectly elastic, even though the two reinforcers differ in a variety of ways.

Equation 2 shows that the logarithm of the preference ratio is a linear function, with *b* equal to the slope:

$$\log\left(\frac{B_1}{B_2}\right) = \log a + b \log\left(\frac{VI_2}{VI_1}\right). \quad (2)$$

This is convenient because linear regression techniques can be used to estimate *b* and to test whether *b* differs significantly from important reference points, such as 0 and 1. Thus, the slope of the line relating log choice ratios to log schedule values quantifies the degree of elasticity. For example, a slope of 0 means that preference was independent of the schedule values, whereas a slope of 1 means that choice ratios changed in proportion to schedule ratios.

Finally, although the logarithmic transformation of Equation 1 provides a convenient method for determining and displaying elasticity of preference for ethanol, log ratios are not as interpretable or as familiar as simple proportions. Consequently, data will be presented as simple proportions whenever the precise magnitude of the elasticity index is not in question.

RESULTS

As shown in Figure 1, when the ethanol mixture and sucrose solution were available equally often, VI 5-s schedule for each, one subject (Rat 26) preferred the 10% ethanol mixture and the other three preferred the 10% sucrose solu-

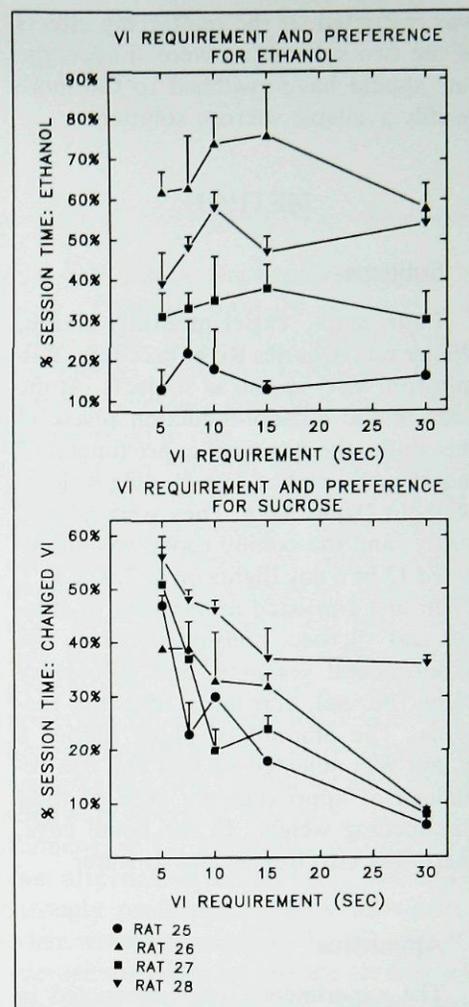


Fig. 1. Individual subject choice proportions as a function of the interval requirement. The top panel shows the relationship between preference and schedule requirement when one dipper served ethanol and the other served sucrose; the bottom panel shows this relationship when both dippers served sucrose. In the ethanol phase, the interval requirement for sucrose was 5 s throughout. In the sucrose phase, the interval requirement for the lever that had served ethanol was varied, and the requirement for the other lever was set at 5 s. The data were averaged from the last three sessions of each condition. Error bars show between-session standard deviations.

tion, with preference defined by either the percentage of responses or the percentage of time spent responding. (The data points were calculated from the last three sessions of each condition; the error bar indicates one standard deviation of the mean). However, when the VI requirement for the ethanol mixture was increased, preference did not shift to su-

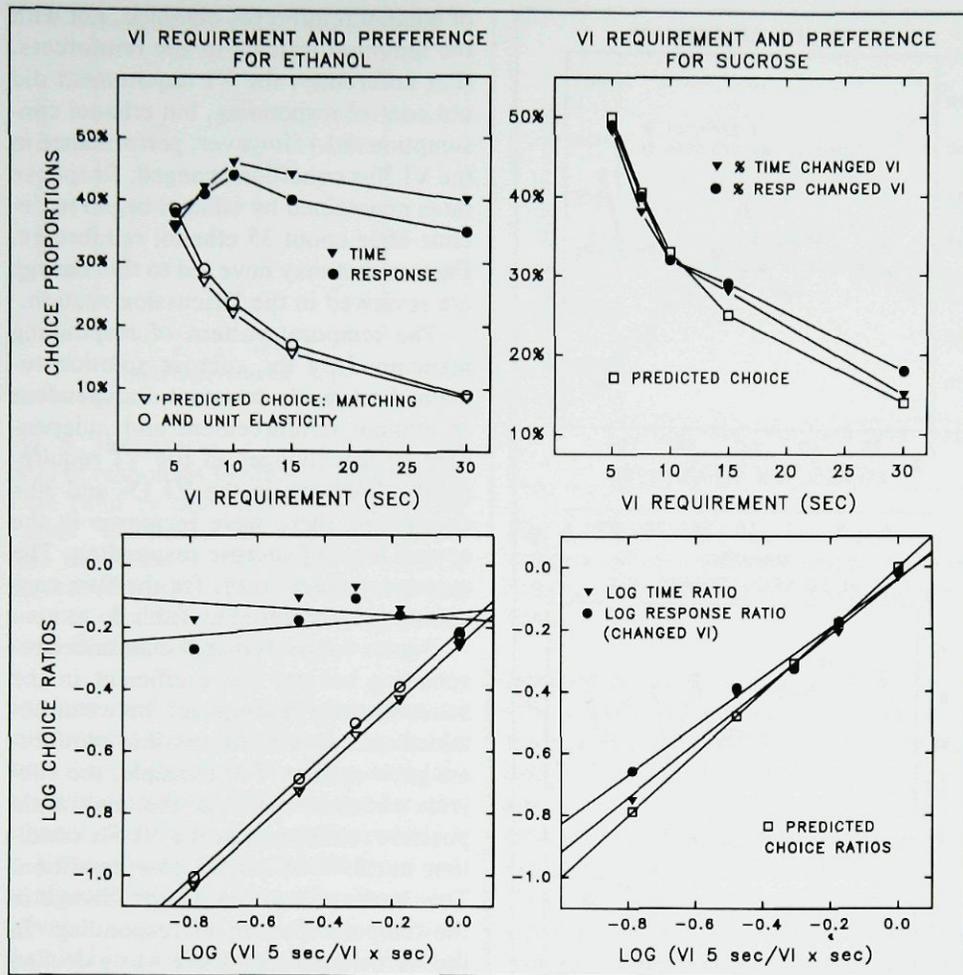


Fig. 2. Average choice proportions and choice ratios. The open symbols show predicted preferences for the assumption that choice proportions perfectly matched the scheduled reinforcement proportions (matching and unit elasticity). When both dippers served sucrose, the predictions closely approximated performance. In contrast, preference for ethanol, shown in the two left panels, was inelastic.

crose. Instead, preference for ethanol stayed about the same or increased slightly. All subjects showed about the same degree of inelasticity, even though their preferences differed when ethanol was available as often as sucrose.

The bottom panel of Figure 1 shows that preference was relatively elastic when both dippers served 10% sucrose. An increase in the VI interval at one dipper shifted responding to the other, more frequently available dipper. Three of the subjects showed similar degrees of elasticity, and the one subject that did not show a marked shift in preference (Rat 28) nevertheless was more influenced by the reinforcement contingency in this phase of the study than when ethanol was available.

Figure 2 shows average choice proportions, log choice ratios, and the predicted preferences given the assump-

tions of unit elasticity and matching. The averages were calculated from the results displayed in Figure 1. The predictions for choice ratios in the bottom panels were calculated from Equation 1 with b , the elasticity index, set to 1. The predictions for choice proportions in the top panels were calculated from the algebraic equivalent of Equation 1 for proportions. When b is 1, this is simply

$$\frac{B_1}{(B_1 + B_2)} = \frac{(a/VI_1)}{(a/VI_1) + (1/VI_2)} \quad (3)$$

Thus, the graphs compare the obtained preferences with those which would have occurred had elasticity of preference been equal to exactly 1.

When ethanol was available, the line fitted to the relationship between prefer-

ence and schedule values had a slope of -0.06 when preference was measured as time allocation and a slope of $+0.09$ when preference was measured as response allocation. According to a t test (Hays & Winkler, 1970), neither slope was different from 0 ($p > .25$). Thus, over the range of schedule values used, choice proportions maintained by ethanol were independent of changes in the schedule contingency. However, this panel also suggests that preference might have become more elastic if VI values greater than 30 s had been used.

The slopes of the lines fitted to the choice ratios when both dippers served sucrose were 0.88 for time allocation and 0.79 for response allocation. The 95% confidence interval for the line fitted to the time ratios (± 0.18) included a slope of 1, unit elasticity, but the 95% confidence interval for the line fitted to the response ratios (± 0.18) did not. Thus, when both dippers served sucrose, predictions based on the assumption of unit elasticity approximated time allocation and to a lesser degree response allocation.

The predicted preferences for the sucrose condition (open squares in the right panels) approximated the obtained preferences. These predictions were based on a single premise: Choice proportions approximated the arranged reinforcement proportions. Thus, the predictions were calculated from Equations 2 and 3, with a and b set to 1, implying no bias and unit elasticity.

Figure 3 shows absolute response rates as a function of ethanol consumption and session time. The data were collected in 15 consecutive 2-min bins. Displayed are the response rates averaged across subjects from the last sessions of the VI 5-s, 10-s, 15-s, and 30-s conditions.

Ethanol maintained response rate was correlated with ethanol consumption. In the VI 5-s condition, ethanol response rate held constant at about 30 responses/min for about the first 85 to 90 ethanol reinforcers, and then declined steadily, stabilizing at about 4 responses/min. The data for the VI 10-s condition show a similar pattern. But in the VI 15-s condition, ethanol responding remained stable throughout the session, because the subjects did not obtain more than 85 ethanol reinforcers. (One

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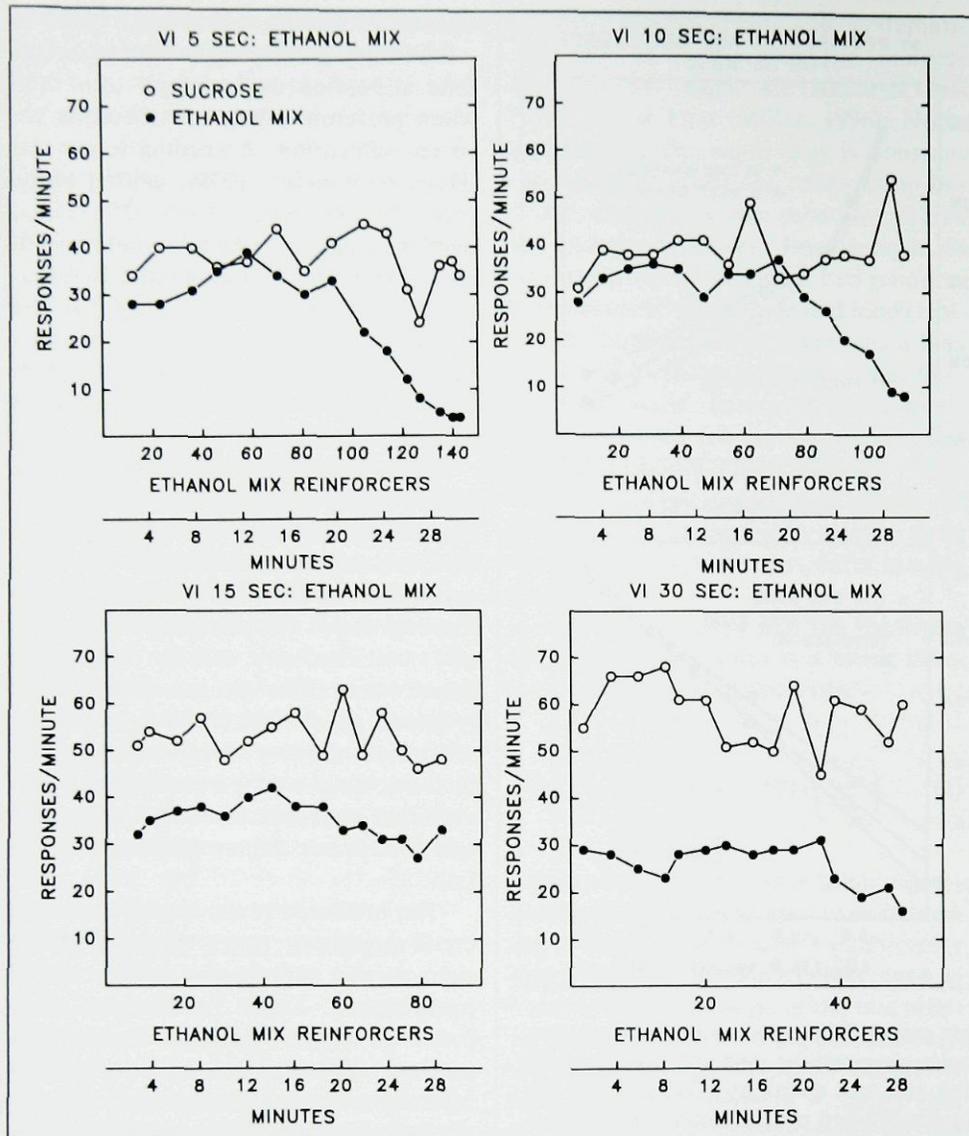


Fig. 3. Minute-by-minute response rates as a function of session time and cumulative ethanol reinforcers for four different interval requirements. The open symbols show response rate maintained by sucrose, and the closed symbols show response rate maintained by the ethanol mixture. The frequency of ethanol reinforcers decreased as a function of the increase in the schedule requirement. Sucrose was available on a VI 5-s schedule throughout the study. The graphs show that responding maintained by ethanol varied primarily as a function of the amount of ethanol consumed rather than the frequency of consumption. The data are from the last session of each condition.

hundred was the maximum possible; each took 3 s, and 15 s was the expected time to the next opportunity for reinforcement.) Consequently, only the first

limb of the VI 5-s pattern is evident. Thus, for interval requirements between 5 and 15 s, responding maintained by ethanol was correlated with the number

Table 1. Average response rates (responses/min) as a function of ethanol interval (VI) requirement

Dipper	VI requirement				
	5 s	7.5 s	10 s	15 s	30 s
Ethanol	22.5	24.8	28.8	32.9	24.3
Sucrose	39.3	39.6	40.3	50.0	55.9

of ethanol reinforcers obtained, not with the temporal spacing of the reinforcers. (Put differently, the VI requirement did not control responding, but ethanol consumption did.) However, performance in the VI 30-s condition changed. Response rates maintained by ethanol began to decline after about 35 ethanol reinforcers. Factors that may have led to this change are reviewed in the Discussion section.

The temporal pattern of responding maintained by the sucrose solution remained relatively constant, independent of ethanol reinforcement and independent of the changes in the VI requirement. However, in the VI 15- and 30-s conditions, there were increases in the overall level of sucrose responding. The average absolute rates for the five conditions are presented in Table 1.

Figure 4 shows ethanol maintained responding became more efficient in the sense that the discrepancy between obtained and maximum possible reinforcers grew smaller. For example, the subjects received 63% of the maximum possible reinforcers in the VI 5-s condition but 85% in the VI 15-s condition. This increase was due to the change in the temporal pattern of responding. In the VI 5-s condition, there was a decline in response rate in the final third of the session, whereas in the VI 15-s condition, no such decline occurred.

Figure 5 shows the relationship between preference, measured as time pro-

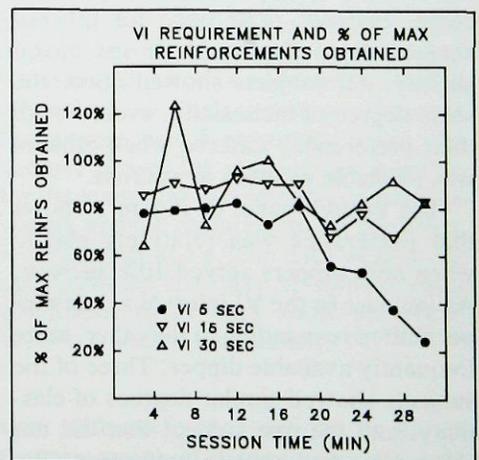


Fig. 4. The percentage of obtained ethanol reinforcers relative to the maximum possible number as a function of time for three different interval requirements. The graph shows that as the frequency of access to ethanol decreased, the rats became more efficient at obtaining ethanol.

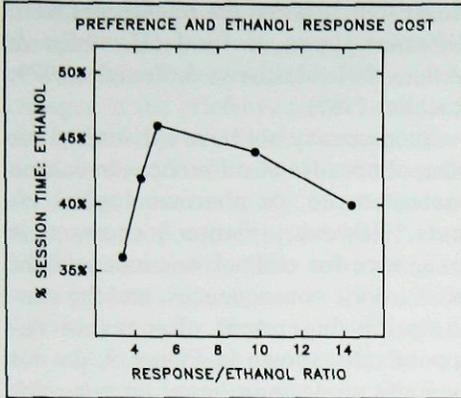


Fig. 5. Preference as a function of the ratio of responses to ethanol reinforcers. This ratio is often referred to as the "price" of a reinforcer. The graph shows that increases in the price of ethanol increased rather than decreased the amount of time spent responding at the lever that provided ethanol.

portions, and the ratio of responses to reinforcement on the lever associated with the ethanol mixture. For instance, when the interval requirement for the ethanol mixture was 5 s, approximately 1 in 3.4 responses at the ethanol lever was reinforced, whereas when the ethanol interval requirement was 30 s, approximately 1 in 14.4 responses at the ethanol lever was reinforced. This ratio is analogous to the price of a commodity, with responses as currency. However, in variable-interval schedule experiments, response cost is not a true independent variable since it varies as a function of the subject's behavior. For example, if preference had been perfectly elastic and declined as predicted by the matching law, responding would have decreased in proportion to the increase in schedule values so that the ratio of responses to ethanol servings would have remained approximately constant at 3.4:1. In other words, the graph shows that preference inelasticity increased the response cost of ethanol.

As noted earlier, rats consumed relatively little ethanol when they were not food deprived (Meisch & Thompson, 1973). This result was interpreted as indicating that ethanol's reinforcing effectiveness was due to its caloric value. Figure 6 tests whether this interpretation can explain the results of the current study. On the x-axis of the left panel is the relative number of calories provided by the ethanol mixture. This was calcu-

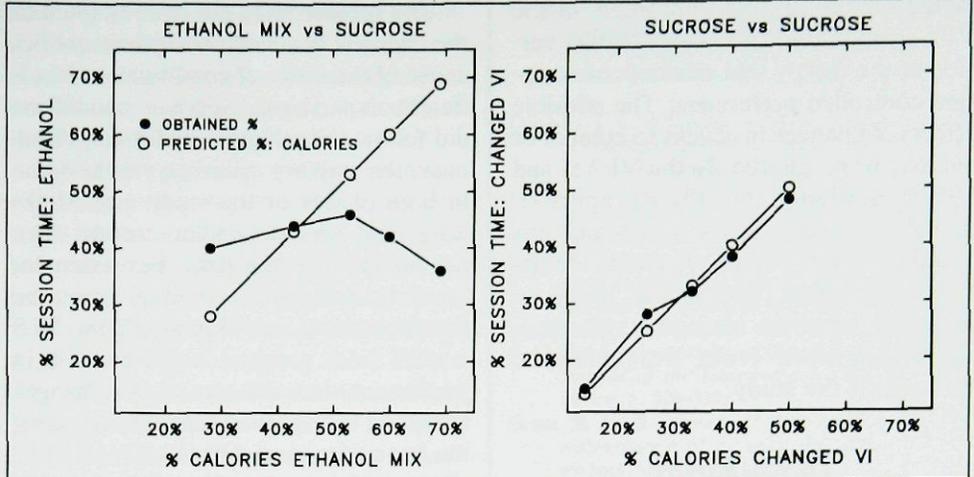


Fig. 6. Time allocation as a function of relative number of calories. Preference and relative calories were correlated when both dippers served sucrose, but were uncorrelated when one dipper served ethanol. Calories were calculated as described in the text.

lated on the basis of the ethanol's specific gravity, 0.79, and the caloric content of ethanol and sucrose, 7.1 kcal/g and 3.95 kcal/g, respectively. For example, a 0.1-ml serving of the ethanol mixture provided .096 kcal (.0561 from the ethanol and .0395 from the sucrose). Thus, when the two reinforcers were equally available, the ethanol mixture was a relatively richer source of calories, but when access to ethanol was reduced by more than a factor of three, the sucrose solution provided more calories.

Figure 6 shows that preference for ethanol was independent of its relative caloric content. During the course of the experiment, ethanol's relative caloric value decreased from about 70% to 28%, whereas over the same set of conditions, preference for ethanol either increased or remained the same. In contrast, when both dippers served sucrose, preference was elastic and changed as predicted by the matching law. Thus, time proportions matched reinforcement proportions, or, equivalently, as shown in Figure 6, time proportions matched the relative caloric value of the reinforcer.

Figure 7 shows predicted and obtained response proportions. The upright triangles show the predicted choices assuming matching and unit elasticity (Equation 3). The upside-down triangles show the predicted choices assuming strict ethanol regulation. These calculations were based on the assumption that the correlation between responding and ethanol consumption observed in the VI

5-s condition (see Fig. 3) remained fixed, independent of changes in the VI schedules and relative availability of sucrose. For instance, since the average number of ethanol reinforcers in the VI 15-s condition was 85, it was assumed that this performance mirrored the results ob-

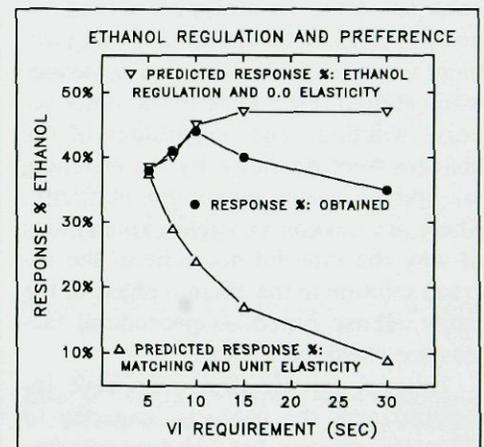


Fig. 7. Predicted and obtained response proportions. The matching law predictions were calculated as in Figure 2. It was assumed that the scheduled reinforcement proportions controlled behavior and that preference for ethanol was perfectly elastic ($b = 1$). Ethanol regulation predictions were based on three premises: that sucrose did not substitute for ethanol ($b = 0$), that changes in the VI requirement did not affect preference for ethanol, and that the relationship between preference and ethanol consumption in the VI 5-s condition remained fixed. This is the simplest version of the hypothesis that ethanol consumption regulated preference.

tained for the first 85 reinforcers in the VI 5-s condition. This is an extreme version of the theory that ethanol consumption controlled preference: The possible effects of changes in access to ethanol or sucrose were ignored. In the VI 7.5- and 10-s conditions, this theory approximated the results; in the VI 15- and 30-s conditions, there were systematic deviations. In contrast, predictions based on matching and unit elasticity systematically deviated from performance throughout the study.

DISCUSSION

The primary finding was that preference for the ethanol mixture was inelastic. For both time and response allocation, the parameter b of Equation 1, which quantified elasticity, was small and not significantly different from 0. This means that choice proportions maintained by ethanol showed little variation as a function of changes in the VI contingencies. Instead, as shown in Figures 3 and 7, choice proportions varied as a function of ethanol consumption. In contrast, when both dippers served sucrose, increases in the interval requirement for one sucrose solution systematically shifted responding to the other sucrose solution. The magnitudes of the changes were predicted by the matching law and the assumption of unit elasticity. There are several possible explanations of why the rats did not shift to the sucrose solution in the ethanol phase of the study. Those based on procedural factors are considered first.

Ethanol intoxication may have interfered with the subjects' capacity to adjust to changes in schedule requirements. For example, in the ethanol-induction phase of the study, the rats were often noticeably ataxic. However, there were no overt signs of intoxication during the phase of the experiment described in this report, and important aspects of the data are not explained by intoxication. For instance, response rates maintained by both ethanol and sucrose increased, and the temporal pattern of responding maintained by sucrose remained relatively constant, independent of ethanol consumption. If responding had been compromised, response rates should have decreased or become erratic.

The subjects may not have adapted to the changes in schedule requirement because of the order of conditions or insufficient experience. Sucrose conditions did follow the ethanol conditions. However, the stability criteria were the same in both phases of the study (see Methods), and time-dependent trends were not apparent in the data. For example, when both dippers served sucrose, the first increase in the VI requirement, VI 5 s to VI 7.5 s, resulted in a larger shift in preference than did any of the changes observed in the ethanol phase, including the last and largest shift (VI 15 s to VI 30 s). Also, if the order of conditions were a factor, then performance should have gradually approached the matching law predictions in the sucrose phase of the study. However, performance was as accurately described by the matching law in the first as in the last sucrose condition.

Baum (1974) suggested that b reflects the discriminability of the two reinforcement sources. For example, if discriminability is less than perfect, choice proportions should fall short of the nominal reinforcement proportions. In support of this theory, b tends to deviate toward values that are less than 1 even when the reinforcers are identical (Baum, 1979). Thus, Baum's account may explain why b was less than 1 in the sucrose phase of the study. However, there is no evidence that the two reinforcement sources were less discriminable from one another when one served ethanol. For example, Figure 3 shows that the temporal characteristics of responding at the two levers remained distinct throughout the study, and it is plausible that discriminability in this study was greater than in the standard matching law experiment because the reinforcers were qualitatively different.

The simplest account of why preference for ethanol was inelastic is that sucrose did not substitute for ethanol. At a behavioral level, this means that the reinforcing effects of sucrose and ethanol were different. At a biological level, this means that sucrose and ethanol consumption were regulated by different mechanisms. Other studies have also found that elasticity of preference depended on substitutability. The parameter b approached 1 when the reinforcers were identical (Baum, 1979), but was

closer to 0.50 when the reinforcers were different types of food (Hamblin & Miller, 1977; Matthews & Temple, 1979; Rachlin, 1989).

Sucrose may not have substituted for ethanol because of differences in caloric content, taste, or pharmacological effects. However, Figure 6 shows that preference for ethanol was independent of its caloric consequences, and the consumption-dependent changes in response rate, shown in Figure 3, do not easily fit an account based on taste differences. Direct evidence for the pharmacological interpretation is not presently possible since the pharmacological bases of ethanol's reinforcing effects are not known. However, preconditions for this interpretation were met in that there is strong evidence that the rats ingested pharmacologically significant amounts of ethanol and alternative hypotheses do not appear to fit the data.

Ethanol intake varied between 1.5 and 4.4 g/kg in half-hour sessions, depending on the VI schedule in effect. These values are well above the clearance rate, 0.3 g/kg/hr, and substantially exceed the maximum amounts consumed in studies that reported blood ethanol levels greater than 100 mg/dl (Grant & Samson, 1985; Samson, 1986). Indeed, we found only one study in which rats consumed amounts of ethanol that were comparable to those reported here. In an intragastric self-administration study (Amit & Stern, 1969), the average intake level was about 2.0 g/kg in 12-min sessions. In accordance with the high consumption levels reported here, the rats showed behavioral signs of pharmacological effects. In the ethanol-induction phase of this study, the rats were often ataxic at the end of the session, and throughout the study, responding maintained by ethanol showed minute-to-minute, consumption-dependent changes. Note that the consumption-dependent changes are not easily explained in terms of ethanol's food value. For example, Figure 3 shows that responding maintained by sucrose persisted independently of the decrease in ethanol maintained behavior. Thus, the pharmacological hypothesis provides the simplest account of both inelastic preference for ethanol and the moment-to-moment pattern of responding maintained by ethanol.

Calculations based on the assumption that preference was regulated by amount of ethanol consumed, independently of changes in the reinforcement contingencies (Fig. 7), predicted response proportions in the VI 7.5- and VI 10-s conditions, but systematically overestimated response proportions in the VI 15- and VI 30-s conditions. The overestimates were probably due to one or more of the following factors. First, as the VI schedule requirement was increased, the rats were forced to consume less ethanol. This may have led to a reduction in the reinforcing value of ethanol. Second, the forced decrease in ethanol consumption may have led to changes in the nature of ethanol's reinforcing efficacy such that sucrose became somewhat substitutable. In support of this explanation, responding maintained by sucrose increased in the VI 15- and 30-s schedules. Third, increases in the VI requirement reduced the "currency" value of time and responses (Fig. 5). For example, in terms of exchange for ethanol, time had lost about 83% of its value ($(1/30)/(1/5)$), and responses had lost about 76% of their value (Fig. 5) in the VI 30-s condition. The effect of cost (or income) on preference, independent of substitutability, could be evaluated in a study in which the schedule values were varied but their ratios kept constant.

In previous research, ethanol consumption decreased as food deprivation decreased (Meisch & Thompson, 1973). However, the data from this experiment suggest just the opposite relationship between ethanol preference and deprivation: If sucrose did not substitute for ethanol, then operations that reduce deprivation should, in the present procedure, increase preference for ethanol. This implication was tested in an experiment in which body weight and pre-session feeding were manipulated (Heyman, 1991).

As in this study, one dipper served a mixture of 10% ethanol plus 10% sucrose, and the other dipper served 10% sucrose. Access to each dipper was governed by a VI 5-s schedule. Increases in body weight from 85% to 115% increased preference for the ethanol mixture. Similarly, pre-session feeding with both chow and sucrose increased preference for ethanol. Moreover, preference changed so as to keep ethanol consumption constant at approximately 1.0 ml of pure eth-

anol per session. In other words, in conditions similar to those of the present study, ethanol consumption regulated preference and did so independently of the degree of food deprivation.

Although previous studies have not explicitly evaluated elasticity of preference for ethanol, the results presented here were anticipated by findings reported by Samson (1986). Rats had access to 10% ethanol and either water or sucrose solutions ranging from 1% to 5%. However, in contrast to the present study, access to the reinforcers was governed by ratio schedules. In ratio schedule choice procedures, preference is all-or-none if the reinforcers are identical (Herrnstein & Loveland, 1975), but graded if the reinforcers are not identical (Lea & Roper, 1977). For example, when the alternatives offer identical reinforcers, subjects exclusively choose the one with the lower ratio, but when the reinforcers are different, increases in ratio requirement may reduce preference without eliminating it (e.g., Lea & Roper, 1977). In Samson's ratio schedule choice experiment, sucrose reduced but did not eliminate ethanol consumption. This result, like those presented in this article, suggests that the reinforcing effects of sucrose and ethanol are different. The reasons for this difference have yet to be investigated. However, the data presented in this article are most simply explained by the assumption that ethanol's pharmacological effects controlled preference.

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