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Concurrent Chains Schedules as a Method to Study Choice Between Alcohol Associated Conditioned Reinforcers

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CONCURRENT-CHAINS SCHEDULES AS A METHOD TO STUDY CHOICE BETWEEN ALCOHOL-ASSOCIATED CONDITIONED REINFORCERS

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An extensive body of research using concurrent-chains schedules of reinforcement has shown that choice for one of two differentially valued food-associated stimuli is dependent upon the overall temporal context in which those stimuli are embedded. The present experiments examined whether the concurrent chains procedure was useful for the study of behavior maintained by alcohol and alcohol-associated stimuli. In Experiment 1, rats responded on concurrent-chains schedules with equal variable-interval (VI) 10-s schedules in the initial links. Across conditions, fixed-interval schedules in the terminal links were varied to yield 1:1, 9:1, and 1:9 ratios of alcohol delivery. Initial-link response rates reflected changes in terminal-link schedules, with greater relative responding in the rich terminal link. In Experiment 2, terminal-link schedules remained constant with a 9:1 ratio of alcohol delivery rates while the length of two equal duration initial-link schedules was varied. Preference for the rich terminal link was less extreme when initial links were longer (i.e., the initial-link effect), as has been previously reported with food reinforcers. This result suggests that the conditioned reinforcing value of an alcohol-associated stimulus depends on the temporal context in which it is embedded. The concurrent-chains procedure and quantitative models of concurrent chains performance may provide a useful framework within which to study how contextual variables modulate preference for drug-associated conditioned reinforcers.

Key words: conditioned reinforcement, concurrent chains, choice, drug cues, alcohol, ethanol, drug self-administration, nose-poke, rats

The generalized matching law accounts for the relative allocation of behavior among response alternatives as a function of the relative rate of reinforcement delivered by each alternative (Baum, 1974). Several studies have shown that the matching law adequately captures the relation between relative response rates and relative rates of drug reinforcement (cocaine, opiates, and barbiturates) in monkeys (e.g., Anderson, Velkey, & Woolverton, 2002; Anderson & Woolverton, 2000; Meisch & Spiga, 1998; Spiga, Maxwell, Meisch, & Grabowski, 2005; Woolverton, 1996; Woolverton & Alling, 1999; Woolverton & Anderson, 2006). More recently, Jimenez-Gomez and Shahan (2008) showed the matching law also accurately described free-operant behavior maintained by alcohol reinforcement in rats. Specifically, rats were trained to respond on concurrent variable-interval (VI) VI schedules for the delivery of an oral alcohol solution. Across conditions, the relative rate of alcohol delivery was varied from 1:1 (VI 60 s–VI 60 s) to 3:1 (VI 40 s–VI 120 s), 9:1 (VI 33.33 s–VI 300 s), 1:3 (VI 120 s–VI 40 s), and 1:9 (VI 300 s–VI 33.33 s). The relative allocation of responding to the two alternatives across conditions was described well by the generalized matching law.

It is important to note, however, that choice behavior is not only controlled by the relative rate or magnitude of reinforcement, but also is mediated by environmental variables such as the presence of stimuli signaling reinforcer availability (see Davison & McCarthy, 1988, for review). Stimuli that accompany the delivery of drugs can acquire reinforcing value through Pavlovian associations and become conditioned reinforcers (e.g., Schuster & Woods, 1968; see also Di Chiara, 1999; Everitt & Robbins, 2005). Current theories of drug addiction highlight the role of drug-associated conditioned reinforcers in the maintenance

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and persistence of drug-taking behavior (e.g., Robinson & Berridge, 1993, 2000), as well as craving, and relapse (e.g., Stewart, de Wit, & Eikelboom, 1984, for research with animals; Marissen et al., 2006, for research with humans; see also Carter & Tiffany, 1999). Thus, incorporating the role of drug-associated conditioned reinforcers in the study of choice behavior maintained by drug reinforcers is relevant both to exploring the generality of quantitative models of choice behavior and to further understanding the variables controlling choice for drug reinforcers.

Several choice models have been developed to account for behavior maintained by both primary and conditioned reinforcers (e.g., delay-reduction theory, Squires & Fantino, 1971; contextual choice model, Grace, 1994; hyperbolic value addition model, Mazur, 2001). These models differ in how they incorporate the role of conditioned reinforcement. For instance, according to delay-reduction theory (DRT), a stimulus functions as a conditioned reinforcer because it signals a reduction in time to primary reinforcement relative to the average time to reinforcement in the absence of differential stimuli (Fantino, 1969; Squires & Fantino, 1971). However, all models make similar basic predictions regarding performance in concurrent chains schedules (e.g., effects of relative rate of primary reinforcement, initial-link effect). In a concurrent-chains schedule, subjects choose between two concurrently available alternatives (i.e., initial links) to obtain access to one of two mutually exclusive stimulus contexts associated with some schedule of primary reinforcement (i.e., terminal links; Herrnstein, 1964; Autor, 1969). The relative allocation of behavior during the initial links reflects preference for the terminal-link stimuli, which typically are considered to function as conditioned reinforcers (e.g., Moore, 1985; Dunn, Williams, & Royalty, 1987; see Williams, 1994, for review).

DRT has been used widely to account for the effects of contextual variables (e.g., delay to reinforcement) on concurrent-chains performance. The quantitative expression of DRT states,

$$\frac{B_1}{B_2} = \left(\frac{R_1}{R_2}\right)\left(\frac{T_{total} - T_{t1}}{T_{total} - T_{t2}}\right), \qquad (1)$$

where B represents initial-link responses per min, R represents overall rates of primary reinforcement, the subscripts refer to the response alternatives, T_{total} is the mean time to primary reinforcement from the beginning of the initial links, and T_{t1} and T_{t2} are the mean times to primary reinforcement from the onset of the terminal links (Squires & Fantino, 1971).

One basic prediction of all models of concurrent-chains performance (e.g., DRT, contextual choice model) is that preference in the initial links will change with changes in the relative delay to primary reinforcement delivery in the terminal links (see Mazur, 2006). By increasing the delay to primary reinforcement in a terminal link, the value of the terminal-link conditioned reinforcer is decreased (Squires & Fantino, 1971). Another well-established prediction of all models of concurrent-chains performance, termed the initial-link effect, occurs when, given unequal terminal-link schedules, preference for the terminal link with a shorter delay to primary reinforcement is made less extreme by increasing the length of the initial-link schedules (Fantino, 1969; Jimenez-Gomez, Podlesnik, & Shahan, 2009; see Davison & McCarthy, 1988, for review). According to DRT, when the initial-link schedules are increased, entering the preferred terminal link will signal a relatively smaller reduction in overall time to reinforcement compared to the other terminal link than when the initial-link schedules are shorter. As a result, preference for the preferred terminal link should decrease. Thus, the initial-link effect can be interpreted as a decrease in the relative value of the conditioned reinforcers (Squires & Fantino, 1971). Both the effects of changes in relative reinforcement delay and the initial-link effect emphasize the role of contextual variables in modulating the value of conditioned reinforcers (see Fantino, 2001).

To the best of our knowledge, application of concurrent-chains procedure and quantitative models of concurrent-chains performance to the study of drug-associated conditioned reinforcers has not been pursued previously. Iglauer and Woods (1974) used the concurrent-chains procedure with a drug reinforcer, but the use of this procedure was mainly to diminish the disruptive effects of cocaine on choice behavior, not for an analysis of choice

between drug-associated conditioned reinforcers. The purpose of the present experiments was to extend the concurrent-chains procedure to the study of choice between stimuli associated with different delays to delivery of alcohol reinforcement (Experiment 1) and assess whether choice was sensitive to the temporal context by changing the duration of the initial links (Experiment 2).

EXPERIMENT 1

The purpose of this experiment was to assess the usefulness of the concurrent-chains procedure for studying choice between two stimuli associated with different delays to delivery of alcohol. In addition, this experiment examined whether preference for alcohol-associated stimuli in the initial links depends upon the relative delays to alcohol reinforcement signaled by the terminal link stimuli.

Method

Subjects

Five male Long-Evans rats approximately 7 months old and with prior experience with alcohol self-administration in a choice procedure (Jimenez-Gomez & Shahan, 2008) were used. The rats were maintained at 80% of their adult free-feeding weights (~350 g) by supplementary feeding of 12–15 g of rat chow after the daily sessions. Water was freely available in the home cage. The rats were housed individually in a temperature-controlled colony with a 12:12 hr light/dark cycle (lights on at 7:00 a.m.). Experimental sessions were conducted 7 days per week during the light periods at approximately the same time every day. Animal care and housing was conducted in accordance to the standards set by the Guide for the Care and Use of Laboratory Animals (National Research Council, 1996).

Apparatus

Four Med Associates® (St. Albans, Vermont, USA) operant conditioning chambers and equipment were used. Each chamber was approximately 30 cm long, 24 cm wide, and 21 cm high, and housed in a sound-attenuating cubicle. The back panel of each chamber was equipped with five nose-poke holes. Only the three center nose-poke holes were used in this experiment. Each nose-poke hole was 2.5 cm square and 2.2 cm deep. An infrared detector was located across each nose-poke hole unit 1.0 cm from the front to detect and record entries. A yellow 6.4 mm diameter stimulus light was mounted flush behind the back wall of each nose-poke hole. Each chamber contained a 28-V DC houselight at the top center of the front panel, which also held a Sonalert (2900 ± 500 Hz, 75–85 dB) and a solenoid-operated dipper that delivered the liquid solutions. Extraneous noise was masked by a chamber ventilation fan and white noise, both located on the back of the sound-attenuating cubicle. Control of experimental events and data recording was conducted using Med Associates® interfacing and programming. Solutions were prepared with distilled water, table sugar, and 95% stock ethanol.

Procedure

Preliminary training was not necessary because rats had prior experience self-administering alcohol on a concurrent variable-interval (VI) VI schedule of reinforcement (Jimenez-Gomez & Shahan, 2008). As in previous studies of alcohol-associated cues conducted in our laboratory (Shahan, 2002, 2003; Shahan & Jimenez-Gomez, 2006), a 2% sucrose (w/v) 10% alcohol (v/v) solution was used as reinforcer in the present experiment.

During the initial links, the two side nose-poke holes were lit. A response on a side nose-poke hole initiated the timers for the initial-link schedules. After an initial-link schedule had timed out, a response on the corresponding side nose-poke hole extinguished the side nose-poke hole lights and lit the center nose-poke hole. The two terminal links were differentially signaled by a pulsing tone (0.5 s on, 0.5 s off) or steady tone. Assignment of these stimulus conditions was counterbalanced across rats. The houselight was lit during the entire session, except during alcohol deliveries. During the 3-sec alcohol deliveries, all lights were extinguished and the light inside the dipper trough was lit. After an alcohol dipper (0.1 ml) was delivered in a terminal link, the initial-link stimuli were reinstated. This cycle was repeated 30 times per session. If rats did not complete all 30 cycles, the session ended after 60 min. This limit on session duration was needed for rat N92 during the

Table 1

Individual subjects' average g/kg of alcohol delivered in the last 5 sessions of each condition.

		g/kg alcohol				
Exp	Condition	N86	N87	N90	N91	N92
1	1:1	0.66	0.75	0.73	0.69	0.72
	9:1	0.67	0.75	0.73	0.68	0.71
	1:9	0.66	0.77	0.73	0.69	0.71
	Mean	0.66	0.76	0.73	0.69	0.72
	SD	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*
2	VI 60 IL	0.66	0.76	0.72	0.69	0.71
	VI 10 IL	0.67	0.76	0.73	0.69	0.72
	VI 60 IL	0.66	0.76	0.72	0.68	0.69
	Mean	0.66	0.76	0.72	0.69	0.71
	SD	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*

first few sessions of Experiment 2 and for all rats during the vehicle control condition.

Initially, concurrent VI 10 s VI 10 s schedules were arranged in the initial links and a fixed-ratio 1 was arranged in the terminal links. Each initial link was timed independently, according to a 10-interval list (Fleshler & Hoffman, 1962). A 0.5-s changeover delay (COD) was imposed for switching from one response to the other in the initial links and was timed from the first response on the changed-to alternative. The schedule of reinforcement for the terminal links was gradually increased across approximately 20 sessions to fixed-interval (FI) 5 s.

The overall rate of alcohol deliveries remained constant across conditions, but the relative delay to alcohol deliveries in the two terminal links varied as follows: 1:1 (FI 5 s FI 5 s), 9:1 (FI 1 s FI 9 s), and 1:9 (FI 9 s FI 1 s). Hereafter, the FI 1-s schedule will be referred to as the rich terminal link and the FI 9-s schedule will be referred to as the lean terminal link. The order in which rats were exposed to the 1:9 and 9:1 conditions was counterbalanced. All conditions lasted 15 sessions.

Data Analysis

Preference during the initial links was calculated as the logarithmic (log) ratio of absolute responses on the left-to-right nose poke. Individual-subject log preference ratios were calculated for each session and the average of the last five sessions of each condition were used for statistical analysis. Repeated-measures analysis of variance (ANOVA) with condition as within-subject variable was used to assess whether the log preference ratios significantly differed across conditions. Statistical significance was determined when p values were smaller than 0.05.

Results and Discussion

Table 1 presents individual subjects' average g/kg of alcohol delivered during the last five sessions of each condition, which remained relatively constant. This was supported by one-way repeated-measures ANOVA comparing the last five sessions of each condition for all subjects [$F(2, 8) = 2.545$, *ns*]. This finding was expected because each terminal link entry ended with the delivery of an alcohol dipper and the same number of cycles occurred in each session. The amount of alcohol delivered was comparable to previous studies of oral alcohol self-administration in rats (e.g., Jimenez-Gomez & Shahan, 2008).

Figure 1 shows individual rats' preference across each condition of Experiment 1 (see Appendix for absolute response rates). As the terminal link schedules changed across conditions, the allocation of behavior in the initial links changed to reflect preference for the rich terminal link, consistent with previous findings with food-maintained behavior (e.g., Herrnstein, 1964). During the 1:9 condition, all rats preferred the right terminal link, as indicated by the left bar falling below zero on the y-axis, the indifference point. The middle bar in Figure 1 close to the zero line reflects indifference between the terminal link alternatives in the 1:1 condition. During the 9:1 conditions all rats preferred the left terminal link, as indicated by the right bar falling above the indifference point. The

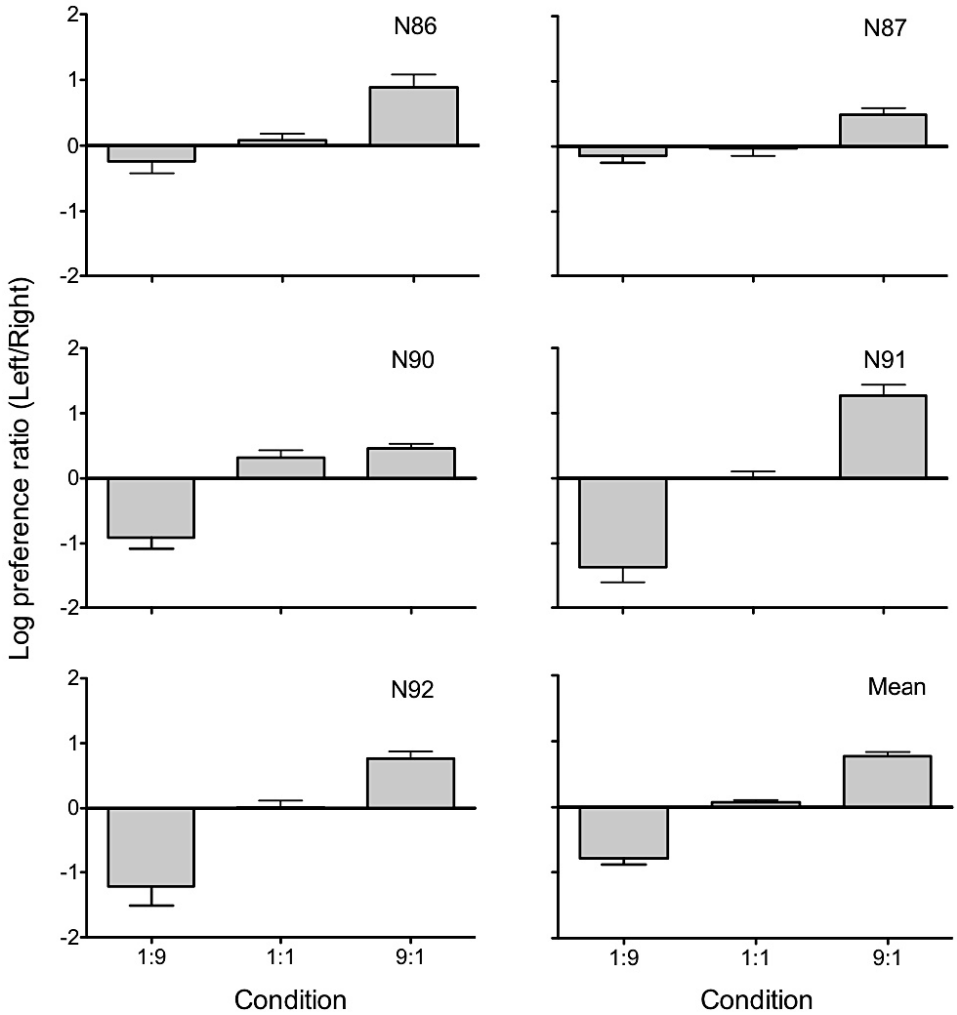

Fig. 1. Individual subjects' left-to-right log preference ratio for each condition of Experiment 1. Each bar represents the average of the last five sessions of each condition. Error bars represent *SD* (*SEM* for Mean data).

change in the log preference ratio across conditions was statistically significant, F (2, 8) = 16.13, p = .002. These findings are consistent with previous studies of concurrent-chains performance of food-maintained responding, in which subjects show preference for the initial link leading to the terminal link with the shorter delay to delivery of primary reinforcement (Herrnstein, 1964; see Davison & McCarthy, 1988; Williams, 1988, for reviews).

Obtained preference values were similar, although somewhat less extreme than those predicted by models of concurrent-chains performance (e.g., DRT, Squires & Fantino, 1971). According to DRT (i.e., Equation 1), the predicted rich-to-lean preference ratios during the 1:9 and 9:1 conditions are 0.06 (log ratio = −1.19) and 15.55 (log ratio = 1.19), respectively. The mean obtained preference ratios were 0.30 (log ratio = −0.77) and 7.44 (log ratio = 0.77) for the 1:9 and 9:1 conditions, respectively. Thus, variations in the relative delay to alcohol reinforcement signaled by the terminal-link stimuli in a concurrent-chains procedure produced shifts in preference for those stimuli in a manner consistent with the predictions of DRT. These findings suggest that the concurrent-chains procedure and models of concurrent-chains performance may be useful tools for the study of alcohol-associated stimulus contexts.

EXPERIMENT 2

The findings of Experiment 1 extended the concurrent-chains procedure to alcohol reinforcement and showed that the relative allocation of responding in the initial links is sensitive to manipulations of the relative delay to alcohol (i.e., terminal link duration) as predicted by models of concurrent-chains performance. Another prediction of models of concurrent-chains performance is the initial-link effect, which refers to a decrease in preference in the initial links as the overall duration of the initial-links increases (Fantino, 1969; Jimenez-Gomez, Podlesnik, & Shahan, 2009). According to DRT, this decrease in preference reflects a change in the relative value of the terminal-link conditioned reinforcers. The purpose of Experiment 2 was to examine whether the initial-link effect was obtained with rats responding for alcohol reinforcers in a concurrent-chains procedure. A demonstration of the initial-link effect with alcohol-maintained responding would suggest that the value of drug-associated stimuli (i.e., conditioned reinforcement) is modulated by contextual variables such as overall delay to primary reinforcement.

Method

Subjects and Apparatus

The same rats and equipment as described for Experiment 1 were used.

Procedure

Initial-link effect. This experiment began immediately after completing Experiment 1, in which rats responded for an alcohol solution on a concurrent-chains procedure with equal initial-link schedules and a nine-fold difference in relative delays to alcohol deliveries across two terminal links. The duration of the two equal-valued initial-link VI schedules was varied across phases to assess whether preference for the rich terminal link would decrease with longer initial links (i.e., initial-link effect). The first condition arranged VI 60 s initial links and FI 1 s versus FI 9 s terminal links. Rats N86, N87, and N91 had the FI 1 s and FI 9 s assigned to the right and left terminal links, respectively. Rats N90 and N92 had the opposite assignment. After 15 sessions of the initial condition, both initial-link schedules were decreased to VI 10 s. Finally, initial-link schedules were returned to VI 60 s. As in Experiment 1, all conditions lasted 15 sessions.

Vehicle control condition. Immediately after completing the second VI 60-s initial-link condition, the 10% alcohol 2% sucrose solution was replaced by a 2% sucrose solution. The purpose of this condition was to demonstrate that responding during the previous conditions was maintained by alcohol and not the 2% sucrose in the solution. This condition lasted 30 sessions.

Data Analysis

Preference during the initial links was calculated as the log ratio of absolute responses on the initial link leading to the rich terminal link (FI 1 s) relative to responses on the initial link leading to the lean terminal link (FI 9 s). An individual subject's log preference ratios were calculated for each session and the average of the last five sessions of each condition was used for statistical analysis. Repeated-measures ANOVA with condition as within-subject factor was used to assess whether the initial-link log preference ratio significantly differed across conditions in which the initial link durations were varied. Separate two-way repeated-measures ANOVAs with condition (alcohol vs. vehicle) and response alternative (rich vs. lean) as within-subject factors were used to examine the effects of removal of alcohol from the reinforcer solution on response rates and number of dipper deliveries. Statistical significance was determined when p values were smaller than 0.05.

Results and Discussion

As in Experiment 1, the average g/kg of alcohol delivered per session across conditions remained constant (see Table 1). This was supported by one-way repeated-measures ANOVA comparing the last 5 sessions of each condition for all subjects [$F(2, 48) = 1.332$, *ns*].

Figure 2 shows individual rats' average rich-to-lean log preference ratios across the conditions of Experiment 2. Preference for the rich terminal link was less extreme for all rats during the two VI 60-s conditions (side gray bars in Figure 2) than during the VI 10-s condition (middle black bar). The change in the log preference ratio across conditions was statistically significant, $F(2, 8) = 19.76$, $p = .001$. According to DRT, the predicted rich-to-lean preference ratio during the VI 60-s and VI 10-s conditions are 1.49 (log ratio = 0.17) and

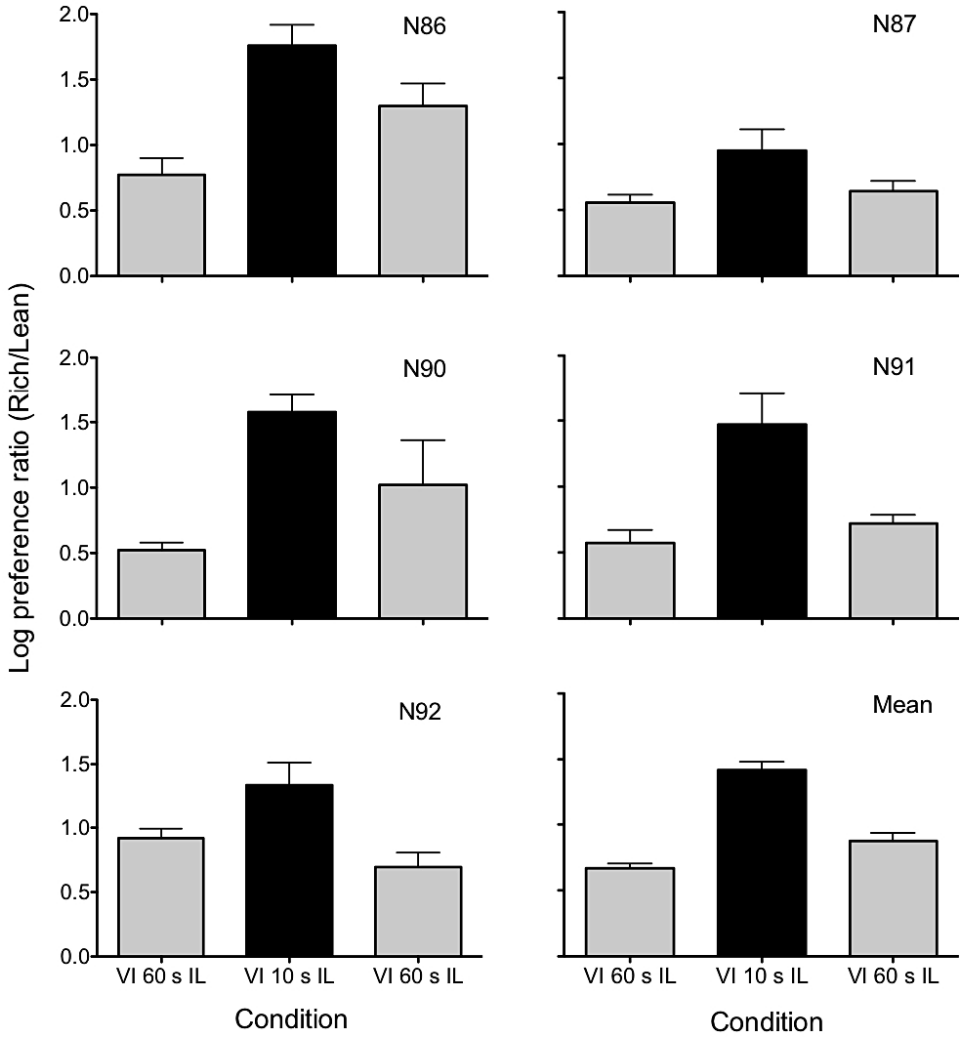

Fig. 2. Individual subjects' rich-to-lean log preference ratio for each condition of Experiment 2. Each bar represents the average of the last five sessions of each condition. Error bars represent *SD* (*SEM* for Mean data).

15.55 (log ratio = 1.19), respectively. The obtained preference values were consistent, although more extreme, than those predicted. The mean obtained preference ratios were 6.43 (log ratio = 0.81) and 35.99 (log ratio = 1.56) for the VI 60-s and VI 10-s conditions, respectively.

Figure 3 presents individual rats' initial-link and terminal-link response rates as an average of the last five sessions with alcohol in the solution and during the vehicle control condition. Initial-link response rates decreased significantly when a 2% sucrose solution was substituted for the 10% alcohol 2% sucrose solution [$F(1, 4) = 18.12$, $p < .05$] and initial-link response rates were significantly lower on the response alternative leading to the lean terminal link [$F(1, 4) = 16.64$, $p < .05$]. There was a significant condition by response alternative interaction [$F(1, 4) = 13.91$, $p < .05$], suggesting that responding on the nose-poke hole leading to the lean terminal link decreased to a greater extent than responding on the one leading to the rich terminal link. Terminal-link response rates decreased significantly during the vehicle control condition [$F(1, 4) = 69.98$, $p < .01$], but they were not significantly different between the two

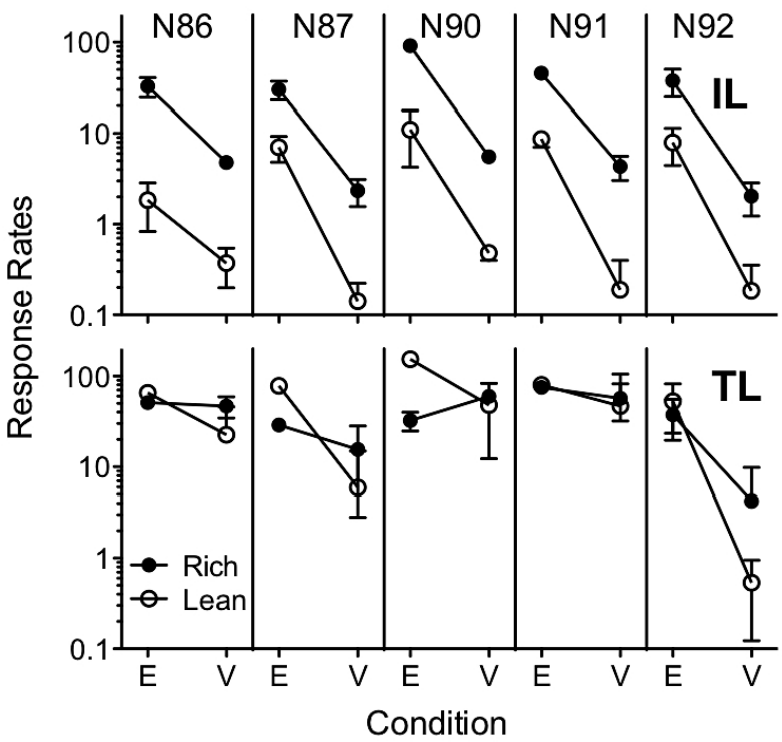

Fig. 3. Individual subjects' average (± *SD*) initial-link (IL; top) and terminal-link (TL; bottom) response rates for the Rich and Lean alternatives during the last five sessions of Experiment 2 (E) and the last five sessions of the vehicle control condition (V).

response alternatives [F (1, 4) = 1.57, *ns*]. The condition by response alternative interaction was not statistically significant [F (1, 4) = 6.01, *ns*], suggesting that responding during the rich and lean terminal links decreased to the same degree (but see analysis below). The number of dippers delivered per session significantly decreased during the vehicle control condition [F (1, 4) = 9.3, $p < .05$; see Appendix]. As expected, the number of dippers delivered in the rich and lean terminal links was significantly different and matched the scheduled reinforcement rate of 9:1 or 1:9 [F (1, 4) = 60.17, $p < .001$; see Appendix]. Taken together, these results suggest that the alcohol in the solution contributed to the maintenance of behavior during Experiments 1 and 2.

Given that response rates decreased significantly with the removal of alcohol from the solution, this manipulation can be conceptualized as a disruptor of responding. Within the framework of behavioral momentum theory, preference in the initial links of a concurrent chains schedule and resistance to change are indices of the underlying strength of behavior (Nevin & Grace, 2000). Resistance to change is assessed by the change in rates of responding during a period of disruption (e.g., extinction, satiation) relative to the preceding baseline and depends on the rate or magnitude of reinforcement delivered in a stimulus context (i.e., stimulus–reinforcer relation; Nevin, Tota, Torquato, & Shull, 1990). Table 2 shows the log proportion of baseline responding in the rich and lean terminal links and the difference measure (rich–lean) for the vehicle control condition. The log proportion of baseline was calculated by dividing response rates during vehicle control condition sessions by the average response rate of the last five sessions of the preceding condition, followed by a log transformation. The difference measure is calculated by subtracting the log proportion of baseline of the lean terminal link from the log proportion of baseline of the rich terminal link. Difference measure values greater than zero correspond to greater resistance to

Table 2

Log proportion of baseline (BL) of responding in the rich and lean terminal links and difference measure (rich-lean) for the vehicle control condition.

	log prop BL		
Subject	Rich	Lean	Difference R-L
N86	−0.04	−0.46	0.42
N87	−0.27	−1.12	0.85
N90	0.27	−0.51	0.77
N91	−0.12	−0.23	0.11
N92	−0.95	−1.99	1.04
Mean	−0.22	−0.86	0.64

disruption in the rich terminal link, whereas values lower than zero correspond to greater resistance in the lean terminal link. Responding in the present study was more resistant to disruption in the rich terminal link. It is important to note that this relative difference in responding between the rich and lean terminal links was not apparent when the data were analyzed
as response rates (see above) and was only revealed with the behavioral momentum analysis, which also has been the case in previous studies (e.g., Podlesnik, Jimenez-Gomez, Ward, & Shahan, 2009). The finding of the present study that responding in a rich terminal link is more resistant to change is consistent with behavioral momentum theory and previous findings (e.g., Grace & Nevin, 2000). In addition, this behavioral momentum analysis is consistent with the initial-link preference results of this study (i.e., preference for rich alternative), providing support for the proposal that resistance to change and preference serve as measures of response strength.

GENERAL DISCUSSION

The concurrent-chains procedure has been used widely to study conditioned reinforcement (see Davison & McCarthy, 1988, for review). Most research using concurrent chains and testing the predictions of quantitative models of concurrent-chains performance has used pigeons responding for food reinforcement. In the present experiments, rats responded for access to two stimuli associated with different delays to alcohol delivery. All rats showed a preference for the stimulus associated with the delivery of alcohol after a shorter delay (Experiment 1) and preference decreased as a function of increases in initial-link schedules (Experiment 2). These findings are consistent with previous studies of concurrent-chains performance of food-maintained responding (Herrnstein, 1964; see Davison & McCarthy, 1988; Williams, 1988, for reviews).

Initial-link preference in Experiment 1 was somewhat less extreme than predicted by DRT (Equation 1). In Experiment 2 the obtained preference for the rich terminal link was more extreme than predicted. To further assess the adequacy of DRT in accounting for the present findings, the obtained left-to-right log preference ratios for both experiments were compared to those predicted from Equation 1. Figure 4 shows the obtained values as a function of predicted values for individual subjects (top panel) and residuals (bottom panel). Despite some individual variability, the obtained log preference ratios track those predicted by DRT with no systematic deviations, as indicated by the residuals. Thus, the present findings with alcohol as the reinforcer are consistent with the general predictions of a well-established quantitative model of choice maintained by primary and conditioned reinforcement (i.e., DRT, Squires & Fantino, 1971). Given that other extant models of concurrent-chains performance (e.g., contextual choice model, Grace, 1994; hyperbolic value addition model, Mazur, 2001) predict the same basic effects, the present findings suggest that the concurrent-chains procedure and associated quantitative models may be useful in the study of drug-associated conditioned reinforcement.

Given that concurrent-chains performance maintained by an alcohol reinforcer appears to share many similarities to such performance maintained by food reinforcement, basic findings from the procedure using food reinforcement might be used to guide future research on drug-associated conditioned reinforcement. For instance, the findings of Experiment 2 suggest that the concurrent-chains procedure lends itself to the analysis of both preference for and the persistence of behavior in the presence of a particular stimulus within the framework of behavioral momentum theory (Nevin & Grace, 2000). Preference in concurrent-chains schedules and the persistence of behavior under conditions of disruption (e.g., extinction, satiation) have been suggested to be indices of the underlying strength of behavior (e.g., Grace &

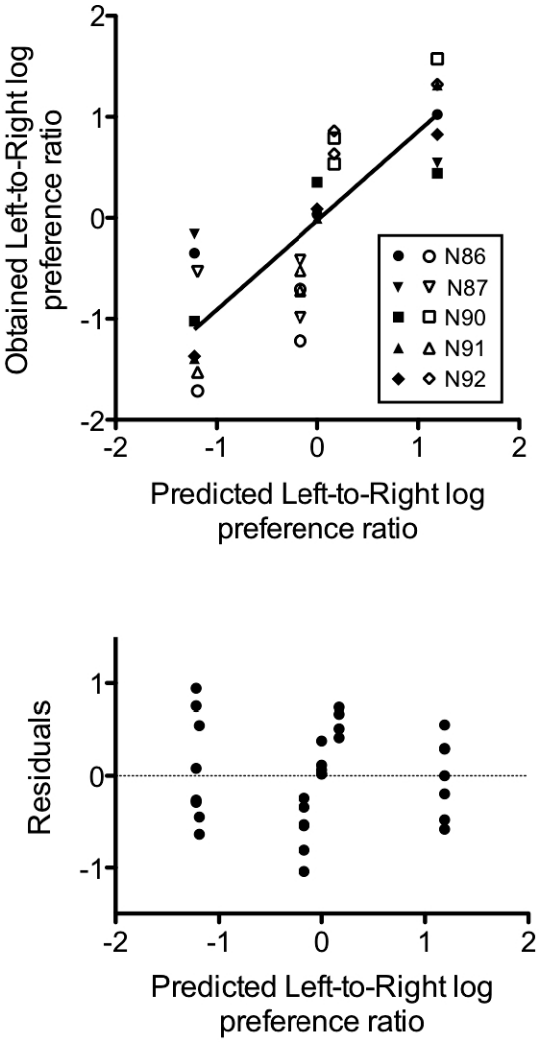

Fig. 4. Obtained left-to-right log preference ratio as a function of preference ratio predicted by DRT (top panel) and residuals (bottom panel). Symbols represent individual subjects. In the top panel, closed symbols denote values for Experiment 1 and open symbols denote values for Experiment 2. The straight line in the top panel represents the best-fit linear regression, calculated on GraphPad Prism.

Nevin, 1997; see Nevin & Grace, 2000, for review). In humans, drug abuse and dependence are characterized by persistent patterns of drug-seeking and -taking behaviors (American Psychiatric Association, 1994). Research with animals has shown that the resistance to change or persistence of alcohol- (Jimenez-Gomez & Shahan, 2007; Pyszczynski & Shahan, 2011; Shahan & Burke, 2004) and cocaine-maintained (Quick & Shahan, 2009) behavior depends on the same contextual variables (e.g., rate of reinforcement in the context) as food-maintained behavior. Just as preference for a terminal-link stimulus can be interpreted as indicative of the value of the stimulus as a conditioned reinforcer, it can be used to predict how persistent behavior would be in the presence of that stimulus. In addition to providing a useful framework for the study of the value of drug-associated conditioned reinforcers, use of the concurrent-chains procedure allows for the assessment of the response-strengthening effects of drug reinforcers in the presence of those stimuli. Given that drug-associated conditioned reinforcers play a key role in triggering drug craving and relapse in humans (e.g., Carter & Tiffany, 1999; Marissen et al., 2006) and make drug seeking and taking more persistent, further study of the interaction between contextual variables and the persistence of drug taking is warranted.

Demonstration of the initial-link effect with alcohol-maintained responding in Experiment 2 suggests that the value of drug-associated conditioned reinforcement is modulated by contextual variables and is susceptible to change through environmental manipulations. Future research could further evaluate this by assessing the effect of access to stimuli associated with a nondrug reinforcer (e.g., food, sex). Because persons addicted to drugs increasingly lose contact with alternative nondrug sources of reinforcement as they spend more and more time seeking and taking drugs, increasing the magnitude or frequency of availability of nondrug conditioned reinforcers could decrease seeking drug-associated conditioned reinforcers and drug-taking behavior. Carroll and colleagues have shown that concurrent availability of nondrug reinforcers decreases self-administration of phencyclidine (Carroll, 1985), alcohol (Carroll, Rodefer, & Rawleigh, 1995), and cocaine (Comer, Hunt, & Carroll, 1994). Similarly, Nader and Woolverton (1991, 1992a, 1992b) have shown that variables such as the magnitude of the alternative nondrug reinforcers impact the degree to which drug self-administration is suppressed (see also, Campbell & Carroll, 2000). Thus, it is possible that concurrent availability of nondrug conditioned reinforcers also could decrease drug self-administration and the value of drug-associated conditioned reinforcers. As shown in the present experiments, the concurrent-chains procedure

provides a useful framework for the study of the variables that modulate preference for a drug-associated conditioned reinforcer and could be useful in the assessment of behavioral and pharmacological treatments aimed at decreasing drug taking, craving, and relapse.

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Appendix

Initial-link (IL) and terminal-link (TL) response rates as responses per min and dippers earned per session (dips) on the left (L) and right (R) nose-poke holes for each condition of Experiments 1 and 2.

			N86		N87		N90		N91		N92	
Exp	Condition		L	R	L	R	L	R	L	R	L	R
1	1:1	IL	14.7	12.0	29.4	30.8	40.5	19.9	28.9	28.3	30.0	30.4
		TL	74.2	82.1	95.5	85.9	101.2	110.0	91.2	92.3	99.5	92.2
		dips	17.4	12.6	14.0	16.0	18.2	11.8	15.0	15.0	16.0	14.0
	9:1	IL	66.4	8.4	54.0	17.3	89.1	30.7	98.0	5.6	95.2	16.8
		TL	53.1	101.6	39.9	83.5	41.6	184.5	71.9	81.0	136.0	46.5
		dips	20.2	9.8	18.6	11.4	9.0	21.0	25.0	5.0	7.6	22.4
	1:9	IL	21.8	39.3	28.7	39.6	8.7	69.4	5.5	112.4	6.5	104.2
		TL	107.8	49.7	96.0	31.6	153.0	30.9	108.2	76.7	42.2	111.6
		dips	13.0	17.0	13.8	16.2	17.2	12.8	3.0	27.0	18.4	11.6
2	VI 60 IL	IL	6.1	36.5	11.2	40.0	98.1	30.0	14.1	51.9	60.6	7.4
		TL	73.9	37.2	74.4	29.8	28.3	136.5	94.6	64.4	35.3	73.9
		dips	12.4	17.6	12.2	17.8	15.6	14.4	13.4	16.6	17.4	12.2
	VI 10 IL	IL	1.8	97.4	7.6	65.5	142.5	3.8	4.9	125.2	126.1	5.8
		TL	72.3	38.5	77.6	33.1	40.2	150.4	79.8	75.6	38.7	74.0
		dips	1.8	28.2	9.2	20.8	25.2	4.8	5.0	25.0	24.4	5.6
	VI 60 IL	IL	1.8	32.8	7.1	30.3	91.4	11.1	8.7	45.5	37.7	8.0
		TL	65.6	51.1	78.0	28.9	32.4	154.0	80.3	75.4	37.5	52.7
		dips	4.8	25.2	13.4	16.6	18.4	11.6	12.6	17.4	16.8	12.0
	vehicle	IL	0.4	4.8	0.1	2.3	5.6	0.5	0.2	4.3	2.0	0.2
		TL	22.6	46.7	5.9	15.5	59.7	47.8	46.8	57.0	4.2	0.5
		dips	2.0	27.8	0.8	12.4	26.8	3.2	1.8	22.2	9.2	2.0