



Published in final edited form as:

*J Exp Anal Behav.* 2016 May ; 105(3): 375–392. doi:10.1002/jeab.207.

## Behavioral Momentum Theory Fails to Account for the Effects of Reinforcement Rate on Resurgence

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### Abstract

The behavioral-momentum model of resurgence predicts reinforcer rates within a resurgence preparation should have three effects on target behavior. First, higher reinforcer rates in baseline (Phase 1) produce more persistent target behavior during extinction plus alternative reinforcement. Second, higher rate alternative reinforcement during Phase 2 generates greater disruption of target responding during extinction. Finally, higher rates of either reinforcement source should produce greater responding when alternative reinforcement is suspended in Phase 3. Recent empirical reports have produced mixed results in terms of these predictions. Thus, the present experiment further examined reinforcer-rate effects on persistence and resurgence. Rats pressed target levers for high-rate or low-rate variable-interval food during Phase 1. In Phase 2, target-lever pressing was extinguished, an alternative nose-poke became available, and nose-poking produced either high-rate variable-interval, low-rate variable-interval, or no (an extinction control) alternative reinforcement. Alternative reinforcement was suspended in Phase 3. For groups that received no alternative reinforcement, target-lever pressing was less persistent following high-rate than low-rate Phase-1 reinforcement. Target behavior was more persistent with low-rate alternative reinforcement than with high-rate alternative reinforcement or extinction alone. Finally, no differences in Phase-3 responding were observed for groups that received either high-rate or low-rate alternative reinforcement, and resurgence occurred only following high-rate alternative reinforcement. These findings are inconsistent with the momentum-based model of resurgence. We conclude this model mischaracterizes the effects of reinforcer rates on persistence and resurgence of operant behavior.

### Keywords

resurgence; relapse; behavioral momentum; reinforcement rate; extinction; operant behavior

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Behavior that is extinguished in the presence of an alternative source of reinforcement often recurs once alternative reinforcement is discontinued. This form of relapse is termed *resurgence* (Epstein, 1983; 1985). Under some circumstances, resurgence is thought to lead to adaptive problem-solving by generating behavior that produced reinforcement in the past (Epstein, 2015; Kestner, Redner, Watkins, & Poling, 2015; Lattal & Wacker, 2015; Lieving & Lattal, 2003; Shahan & Chase, 2002). Conversely, resurgence might be considered

detrimental if the target response has maladaptive consequences, as is often the case in clinical settings. Indeed, extinction of target behavior plus provision of an alternative source of reinforcement is a common intervention strategy for elimination of problem behavior in application (e.g., see Petscher & Bailey, 2008; Petscher, Rey, & Bailey, 2009), and resurgence often occurs when these treatments are suspended (see Lattal & St. Peter Pipkin, 2009; Volkert, Lerman, Call, & Trosclair-Lasserre, 2009). Thus, isolating factors that affect resurgence could inform strategies for promoting recurrence of extinguished behavior when it is desirable and deterring recurrence when it is undesirable.

Laboratory investigations of resurgence typically use a three-phase preparation (Leitenberg, Rawson, & Bath, 1970; Leitenberg, Rawson, & Mulick, 1975). In Phase 1, target responding produces reinforcement. Next, during Phase 2, reinforcement for target responding is discontinued while an alternative source of reinforcement is made available, usually contingently on an alternative response. Finally, all reinforcement is suspended to test for resurgence in Phase 3. Resurgence is said to occur if target responding increases in frequency relative to terminal Phase-2 levels of responding.

One parameter of the standard resurgence preparation detailed above that has received considerable empirical attention is the rate at which responding produces reinforcement. For example, Leitenberg, Rawson, and Mulick (1975, Experiment 3) examined effects of high-rate (variable-interval [VI] 30-s), low-rate (VI 240-s), and no (an extinction control) alternative reinforcement on persistence and resurgence of pigeons' key pecking previously maintained by VI 120-s reinforcement. Varying rates of alternative reinforcement had two effects on target responding. First, in Phase 2, high-rate alternative reinforcement produced faster decreases in responding than low-rate alternative reinforcement or extinction alone. Further, though target responding decreased at statistically comparable rates in the groups that experienced low-rate alternative reinforcement and extinction alone, responding in the low-rate group was visibly lower than responding in the extinction group early in Phase 2. Second, when alternative reinforcement was suspended, resurgence occurred for the high-rate alternative-reinforcement group while slight, but not statistically significant, increases in target responding occurred for the low-rate group (for similar findings in rats and humans, see Bouton & Trask, 2015; Cançado, Abreu-Rodrigues, & Aló, 2015; Pritchard, Hoerger, Mace, Penney, & Harris, 2014).

Some findings suggest that reinforcer rates in Phase 1 also impact target-response persistence during Phase 2 and resurgence during Phase 3. Podlesnik and Shahan (2009), for example, trained pigeons to peck keys in a two-component multiple schedule where one component was associated with high-rate (VI 120-s + variable-time [VT] 20-s) reinforcement and the other was associated with low-rate (VI 120-s) reinforcement. In Phase 2, all previous sources of reinforcement (VI and VT) were suspended, and pecking a second key produced VI 30-s alternative reinforcement in both components. Finally, alternative reinforcement was suspended in Phase 3 to test for resurgence. Target responding in the component associated with high-rate Phase-1 reinforcement was more persistent in the face of extinction plus alternative reinforcement and resurged to a greater degree in Phase 3 (see also Kuroda, Cançado, & Podlesnik, 2016; Podlesnik & Shahan, 2010). Based on the findings reviewed above, reinforcer rates for target and alternative behavior have opposing

effects on target-response persistence in Phase 2. That is, higher target-reinforcer rates produce greater target-response persistence, and higher alternative-reinforcer rates produce less persistence. Both target- and alternative-reinforcer rates, however, have the same effect on the magnitude of resurgence observed in Phase 3: Higher rates produce more resurgence than lower rates.

In light of these findings, Shahan and Sweeney (2011) proposed a quantitative model of resurgence based on the description of extinction performance offered by behavioral momentum theory (see Craig, Nevin, & Odum, 2014; Nevin & Shahan, 2011, for reviews). Momentum theory asserts that response rate and resistance to change are two separable aspects of operant behavior. On the one hand, response rate is governed by the relation between responding and the delivery of reinforcers made contingent on the response. Resistance to change, on the other hand, is governed by the Pavlovian relation between reinforcers and the discriminative stimuli in the presence of which they are delivered. Higher reinforcer rates produce stronger Pavlovian stimulus–reinforcer relations than lower rates, thus producing behavior that is relatively more persistent in the face of disruption (a finding that has been empirically supported; for review, see Nevin, 1992; 2002). Importantly for present purposes, the theory states the source of reinforcement does not matter in terms of Pavlovian determination of resistance to change—as long as reinforcers are delivered in the presence of discriminative stimuli, they may contribute to response persistence. Nevin, Tota, Torquato, and Shull (1990) found that adding alternative reinforcement into a discriminative context, either response- independently or contingently on an alternative response, increased persistence of pigeons' target-key pecking, providing support for this assertion.

The behavioral-momentum based description of extinction performance is as follows (see Nevin & Grace, 2000; see also Nevin & Shahan, 2011):

$$\log \left( \frac{B_t}{B_0} \right) = \frac{-t(c+d\Delta r)}{r^b} \quad (1)$$

The left side of Equation 1 is log-transformed proportion-of-baseline response rates at time  $t$  in extinction. The right side of the equation represents those factors that contribute to extinction performance and can be broken into two more general terms. First, the numerator represents those factors that produce decreases in responding during extinction. Here,  $t$  is time in extinction measured in sessions,  $c$  is the impact on responding of suspending the response–reinforcer contingency, and  $d\Delta r$  represents generalization decrement (where  $\Delta r$  is the change in reinforcers delivered per hr between baseline and extinction and  $d$  scales the impact of this disruptor). The denominator is meant to capture a masslike quality of behavior (metaphorically “behavioral mass”) that is engendered by the Pavlovian stimulus–reinforcer relation and that promotes persistence of responding during extinction. Here,  $r$  is baseline reinforcer rates (in reinforcers delivered per hr), and  $b$  is a sensitivity parameter.

Shahan and Sweeney (2011) incorporated rates of alternative reinforcement into Equation 1 as follows:

$$\log\left(\frac{B_t}{B_0}\right) = \frac{-t(kR_a + c + d\Delta r)}{(r + R_a)^b} \quad (2)$$

Thus, in the numerator, alternative reinforcement adds to disruption of target behavior produced by extinction in a manner proportional to the rate of its delivery ( $R_a$ , multiplied by a scaling parameter,  $k$ ). Because alternative reinforcers are delivered in the same discriminative-stimulus situation as reinforcers for target responding, the model asserts alternative reinforcers also contribute to behavioral mass in the denominator. When alternative reinforcement is suspended in Phase 3, its disruptive impact on target behavior in the numerator is removed, but its historical contribution to behavioral mass is maintained. The model thus asserts that resurgence occurs because target behavior is released from the disruptive impact of alternative reinforcement.

Using free parameter values typically reported when Equation 2 is fitted to obtained resurgence data (i.e.,  $c = 1$ ,  $d = 0.001$ ,  $b = 0.5$ , and  $k = 0.05$ ; see Shahan & Sweeney, 2011), Equation 2 predicts the effects of target ( $r$ ) and alternative ( $R_a$ ) reinforcer rates on target-response persistence and resurgence summarized above in the following manner. Increasing  $r$  produces greater behavioral mass, thus producing behavior that is more persistent in the face of Phase-2 disruption and more susceptible to resurgence during Phase 3 (e.g., Kuroda et al., 2016; Podlesnik & Shahan, 2009; 2010). Higher  $R_a$  produces greater disruption (and hence faster target-response elimination) than lower  $R_a$  during Phase 2 (e.g., Leitenberg et al., 1975). Since  $R_a$  also contributes to behavioral mass, increasing  $R_a$ , like increasing  $r$ , produces behavior that is more susceptible to resurgence (e.g., Bouton & Trask, 2015; Cançado, et al., 2015; Leitenberg et al., 1975; Pritchard et al., 2014).

Though Equation 2 provides accurate descriptions of data from the resurgence studies reviewed thus far, several recent findings challenge Shahan and Sweeney's (2011) characterization of reinforcer-rate effects on target-response persistence and resurgence. For example, Cançado and Lattal (2013) and Fujimaki, Lattal, and Sakagami (2015) reported no systematic relation between alternative-reinforcer rates and resurgence in a series of experiments with pigeon subjects. Further, Sweeney and Shahan (2013b) found that low rates of alternative reinforcement during Phase 2 (VI 100-s, relative to VI 45-s reinforcement for target responding during Phase 1) produced target-lever pressing in rats that was *more* persistent than extinction of target-lever pressing alone. This finding is problematic because Equation 2 asserts that any alternative reinforcement should add to the disruptive impact of extinction on target behavior. Winterbauer and Bouton (2010) conducted a series of experiments that were similarly problematic for Shahan and Sweeney's interpretation. Groups of rats pressed target levers for food pellets that were delivered either at a high (VI 10-s) or low (VI 30-s) rate during Phase 1. During Phase 2, target-lever pressing was extinguished and a second lever became available for all subjects. For both high-rate and low-rate target-reinforcement groups, three subgroups received high-rate (VI 10-s), low-rate (VI 30-s), or no alternative reinforcement for pressing the second lever. Relative to Phase-2 target-lever persistence in the extinction-alone groups, low-rate alternative reinforcement either produced no difference in persistence (for rats that experienced low-rate Phase-1

reinforcement) or greater persistence (for rats that experienced high-rate Phase-1 reinforcement, similar to Sweeney & Shahan, 2013b). As detailed above, Equation 2 predicts neither of these findings.

Winterbauer and Bouton (2010) also observed only modest differences in target-lever pressing between alternative-reinforcement groups during resurgence testing. It should be noted that Equation 2 predicts these modest differences in resurgence between these groups in Winterbauer and Bouton's (2010) study for at least three reasons. First, in this study, only four sessions of Phase 2 were conducted prior to testing for resurgence (a duration of treatment that is shorter than in most resurgence experiments). Shahan and Sweeney's (2011) model predicts a positive relation between Phase-2 duration and relative differences in resurgence between groups that experienced different rates of Phase-2 reinforcement because the disruptive terms in the numerator of the model grow multiplicatively with time in extinction ( $t$ ). If Phase 2 is sufficiently short, not much disruption from suspending the response–reinforcer contingency ( $c$ ) or generalization decrement ( $d\Delta r$ ) is present during resurgence testing, thus masking the differential behavioral mass ( $[r + R_a]^b$ ) produced by differential alternative-reinforcer rates. Second, both reinforcer rates used in this study (VI 10 s and VI 30 s) were relatively high. Because Equation 2 asserts resurgence is directly related to behavioral mass, the model predicts diminished differential resurgence with higher absolute values of  $r + R_a$ . Finally, these reinforcer rates differed by a factor of three. Because differential persistence in resistance-to-change research most often is observed using reinforcer rates that differ by at least a factor of four, the relatively small differences in reinforcer rates used by Winterbauer and Bouton (2010) could have been insufficient to show differential resurgence.

As the above review suggests, the specific effects of reinforcer rates for target and alternative behavior on target-response persistence and resurgence are unclear. Thus, it is equally unclear at present if Equation 2 offers a reasonable description of target-response elimination and resurgence. The present experiment aimed to provide a more rigorous test of the prediction of Equation 2 with respect to effects of Phase-1 and Phase-2 reinforcer rates on persistence and resurgence of rats' lever pressing. The procedures systematically replicated those used by Winterbauer and Bouton (2010). Rats pressed target levers for either high-rate or low-rate reinforcement during Phase 1. In Phase 2, target-lever pressing was extinguished and an alternative nose-poke response produced either high-rate, low-rate, or no alternative reinforcement. Finally, during Phase 3, alternative reinforcement was suspended to test for resurgence. For the reasons noted above, reinforcer rates generally were lower than those used in Winterbauer and Bouton's (2010) study, and the high and low reinforcer rates used here differed by a factor of four instead of a factor of three. Further, phase durations were extended. Equation 2 was fitted to obtained data to provide a quantitative test of the model.

## Method

### Subjects

Thirty-four experimentally naïve male Long Evans rats (Charles River, Portage, MI), approximately 90–100 days of age at the beginning of the study, served. Rats were housed

individually in a temperature-controlled colony room with a 12:12 hr light/dark cycle (lights on at 07:00). Rats had free access to water in their home cages and were maintained at 80% of their free-feeding body weights by the use of supplementary postsession feedings as necessary. Sessions were conducted daily at the same time during the rats' light cycle. Animal care and housing, and all procedures detailed below, were conducted in accordance with Utah State University's Institutional Animal Care and Use Committee.

## Apparatus

Ten identical modular operant chambers for rats (Med Associates, St. Albans, VT), each housed in individual sound-attenuating cubicles, were used. Each chamber was constructed of clear Plexiglas and brushed aluminum with aluminum work panels on the front and back walls. On the back wall of the chamber was an array of five small, horizontally arranged and equally spaced nose-poke apertures. Only the left-most aperture was used during this study and was internally illuminated, when specified below, by a yellow LED. On the front wall, retractable response levers with stimulus lights situated above them were located left and right of center. A feeder aperture with a 28 Vdc feeder light into which 45 mg grain-based food pellets (Bio Serv, Flemington, NJ) could be delivered was located in the center of this panel. A 28-Vdc house light partially encased in an aluminum covering was positioned at the top center of the front panel and provided general illumination at all times except during reinforcer deliveries and magazine training. Reinforcement consisted of delivery of a single food pellet into the illuminated food aperture and a 3-s timeout from sessions. White noise generated by fans mounted on the sound-attenuating cubicles was present at all times to mask extraneous sounds. Sessions were controlled by Med-PC (Med Associates) software run on a PC computer in an adjoining room.

## Procedure

**Magazine training**—Each rat first was trained to retrieve food pellets from the illuminated feeder aperture in three daily sessions. During magazine training, the chamber was dark and the levers were retracted. Food was delivered according to a VT (response-independent) 60-s schedule. The VT schedule and all VI (response-dependent) schedules mentioned below were constructed of 10 intervals derived from the constant-probability algorithm provided by Fleshler and Hoffman (1962). Magazine training sessions, and sessions for the remainder of the experiment, lasted 30 min, excluding time for reinforcer deliveries.

**Phase 1**—Sessions of Phase 1 began with insertion of both response levers into the chamber and illumination of the stimulus light positioned above one of the levers (either left or right, counterbalanced across rats). Pressing this target lever produced food as detailed below. Presses to the other inactive lever were recorded but had no consequences.

Half of the rats received food pellets for target-lever pressing according to a VI 15-s schedule. The other half received food for lever pressing according to a VI 60-s schedule. In the first session of Phase 1, the first press a rat made to the target lever produced food to facilitate acquisition, after which the appropriate VI schedule commenced. Phase 1 lasted for 30 sessions.



**Phase 2**—Prior to Phase 2, rats that received high-rate (VI 15-s) food during Phase 1 were divided into three groups such that mean rates of target-lever pressing during the last five sessions of Phase 1 did not differ between groups. Rats that received low-rate (VI 60-s) food during Phase 1 likewise were divided into three groups. These groups received either high-rate (VI 15-s), low-rate (VI 60-s), or no (an extinction control) alternative reinforcement during Phase 2, thus producing six distinct groups: High High (meaning they experienced high-rate reinforcement during both Phases 1 and 2), High Low, High EXT, Low High, Low Low, and Low EXT. See Table 1 for a summary of reinforcement conditions these groups experienced across phases of the experiment. All groups, except High EXT and Low EXT, contained six rats. One rat was excluded from each EXT group because of equipment malfunctions during Phase 1, so these groups contained five rats each.

Sessions of Phase 2 began the same way as sessions of Phase 1 (i.e., insertion of both retractable levers and illumination of the stimulus light above the target lever). In addition, the left-most nose-poke aperture on the back chamber wall was illuminated. For all rats, reinforcement for target-lever pressing was suspended. For groups that received alternative reinforcement, the first nose poke into the illuminated nose-poke aperture during the first session of Phase 2 produced food to facilitate acquisition of nose poking—pokes thereafter produced food according to the reinforcement schedules detailed in Table 1. Nose pokes were recorded but had no consequences for extinction control groups. Phase 2 lasted for 20 sessions.

**Phase 3**—The Phase-3 stimulus situation was identical to that of Phase 2 (i.e., levers were inserted into the chamber, the stimulus light above the target lever was illuminated, and the left-most nose-poke aperture was illuminated for all rats). Any alternative reinforcement, however, was suspended. Phase 3 lasted for five sessions.

**Statistical analyses**—All statistical tests reported below were deemed significant at an  $\alpha$  level of .05. Greenhouse-Geisser corrections to degrees of freedom were used when the assumption of sphericity in analyses of variance (ANOVA; tested using Mauchly's method) were violated.

## Results

### Phase 1

Mean (plus standard error of the mean [*SEM*]) target-lever response and reinforcer rates from the last five sessions of Phase 1 for each group may be found in Table 2. Response rates did not differ between groups that responded for food according to the same reinforcement schedules. Responding occurred at a higher rate, however, in groups that received VI 15-s reinforcement than in groups that received VI 60-s reinforcement. A one-way ANOVA conducted on these data supported these observations,  $F(5, 28) = 3.56$ . Rates of responding to the inactive lever and the darkened nose-poke aperture were near zero for each group (see Table 2).

## Phase 2

The top panels of Figure 1 show mean rates of lever pressing during the last five sessions of Phase 1 and all sessions of Phase 2 for each group. These data, logarithmically (base 10) transformed are found in the bottom panel of the figure to aid with visual inspection of relevant between-group differences. In general, target responding in groups that experienced low-rate alternative reinforcement tended to persist to a greater degree during Phase 2 than responding in the other groups. Further, target responding for the High High group was visually elevated across sessions of Phase 2 relative to the High EXT group, but responding was lower in the Low High group than in the Low EXT group. These group differences also were evident on the level of individual-subject comparisons (see Appendix A).

A  $2 \times 3 \times 20$  (Target-Reinforcer Rate  $\times$  Alternative-Reinforcer Rate  $\times$  Session) mixed-model ANOVA was conducted on responses per min across sessions of Phase 2 to examine the statistical reliability of the group differences detailed above. The main effects of Session,  $F(1.64, 45.9) = 58.36$ , and Alternative-Reinforcer Rate,  $F(2, 28) = 4.2$ , were significant, as was the Session  $\times$  Target-Reinforcer Rate interaction,  $F(1.64, 45.9) = 14.9$ . No other terms were significant. Fisher's LSD post-hoc tests for the main effect of Alternative-Reinforcer Rate revealed significant differences in extinction performance between groups that received low-rate alternative reinforcement and groups that received either high-rate alternative reinforcement or extinction alone. Responding in these latter groups, however, did not differ. A  $2 \times 3$  - (Target-Reinforcer Rate  $\times$  Alternative-Reinforcer Rate) ANOVA was conducted on response rates during the final session of Phase 2. Even after 20 sessions, terminal Phase-2 response rates differed significantly between groups,  $F(5, 28) = 3.42$ , and these differences were the product only of alternative-reinforcer rates,  $F(2, 28) = 7.73$  (the main effect of Target-Reinforcer Rate was not significant, nor was the interaction term). Fisher's LSD post-hoc comparisons showed terminal Phase-2 response rates were significantly higher in groups that received low-rate alternative reinforcement than groups that received either high-rate alternative reinforcement or extinction alone. Thus, consistent with the findings of Winterbauer and Bouton (2010) and Sweeney and Shahan (2013b), Phase-2 target responding for low-rate alternative-reinforcement groups was elevated relative to high-rate alternative-reinforcement and extinction groups throughout the phase.

Mean alternative response rates across sessions of Phases 2 and 3 are shown in Figure 2. High-rate alternative reinforcement tended to produce higher nose-poke response rates than low-rate alternative reinforcement during Phase 2, and nose-poke response rates occurred at near-zero levels for rats that received no alternative reinforcement. Further, nose-poke response rates differed only with respect to alternative-reinforcer rates. A  $2 \times 3$  (Target-Reinforcer Rate  $\times$  Alternative-Reinforcer Rate) mixed-model ANOVA conducted on mean nose-poke rates from the final five sessions of Phase 2 (see Table 3) revealed a significant effect of Alternative-Reinforcer Rate,  $F(2, 28) = 14.23$ , while no other terms were significant. Fisher's LSD post-hoc comparisons revealed that alternative nose-poke response rates were significantly higher in groups that received high-rate alternative reinforcement than all other groups. Further, groups that received low-rate alternative reinforcement nose poked more frequently than groups that experienced extinction alone. Inactive-lever responding occurred at near-zero levels during these sessions (see Table 3).



### Phase 3

Mean target-lever response rates from the last session of Phase 2 and all sessions of Phase 3 for each group are shown in Figure 3. Increases in responding between phases (i.e., resurgence) occurred only for the high-rate Phase-2 alternative-reinforcement groups.<sup>1</sup> Responding in these groups tended to increase to levels of responding in the low-rate alternative-reinforcement groups (consistent with the modest differences in Phase-3 target responding reported by Winterbauer & Bouton, 2010), after which responding for all groups that experienced alternative reinforcement decreased at comparable rates across sessions of Phase 3. Again, the patterning of target-lever responding across sessions of Phase 3 observed at the group level also was evident at the level of individual-subject comparisons (see Appendix B).

A  $2 \times 3 \times 2$  (Target-Reinforcer Rate  $\times$  Alternative-Reinforcer Rate  $\times$  Phase) mixed-model ANOVA conducted on response rates from the last session of Phase 2 and the first session of Phase 3 revealed target-lever response rates differed between phases,  $F(1, 28) = 7.46$ , and that levels of responding depended on alternative-reinforcer rates,  $F(2, 28) = 7.24$ . The Phase  $\times$  Alternative-Reinforcer Rate interaction also was significant,  $F(2, 28) = 11.7$ , suggesting that response rates changed between phases in a manner that depended on alternative reinforcer rates. No other terms were significant. To determine the source of the significant interaction, follow-up  $2 \times 2 \times 2$  (Target-Reinforcer Rate  $\times$  Alternative-Reinforcer Rate  $\times$  Phase) mixed-model ANOVA were conducted for each pairwise comparison between alternative-reinforcer rates. The Phase  $\times$  Alternative-Reinforcer Rate interaction was present when groups that experienced high-rate alternative reinforcement were compared to groups that experienced low-rate alternative reinforcement,  $F(1, 20) = 15.08$ , and extinction alone,  $F(1, 20) = 15.78$ . No interaction was present, however, when groups that experienced low-rate alternative reinforcement were compared to groups that experienced extinction alone. Further, increases in responding between phases were specific to the target lever: Inactive-lever response rates did not increase significantly between phases (evidenced by a nonsignificant main effect of Phase in a  $2 \times 3 \times 2$  [Target-Reinforcer Rate  $\times$  Alternative-Reinforcer Rate  $\times$  Phase] mixed-model ANOVA conducted on inactive-lever response rates).

A  $2 \times 3 \times 5$  (Target-Reinforcer Rate  $\times$  Alternative-Reinforcer Rate  $\times$  Session) mixed-model ANOVA was conducted on target-lever response rates across all sessions of Phase 3 to determine if reinforcer rates significantly impacted rates of change in responding. Significant decreases in response rate were confirmed by a significant main effect of Session,  $F(2.2, 61.65) = 23.2$ . Further, the Session  $\times$  Alternative-Reinforcer Rate interaction was significant,  $F(4.4, 61.65) = 4.08$ . To determine the source of this interaction, follow-up  $2 \times 2 \times 5$  (Target-Reinforcer Rate  $\times$  Alternative-Reinforcer Rate  $\times$  Session) mixed-model ANOVA were conducted for each pairwise comparison between alternative-reinforcer rates. The interaction was significant when groups that experienced high-rate alternative reinforcement,  $F(1.96, 35.31) = 9.03$ , and groups that experienced low-rate alternative

<sup>1</sup>It is worth noting that resurgence occurred for at least two rats that experienced low-rate alternative reinforcement (see Appendix B). This finding notwithstanding, responding either decreased or remained the same between the final session of Phase 2 and the first Session of Phase 3 for the majority of these rats. Thus, it is reasonable to assert resurgence did not occur for low-rate Phase-2 reinforcement groups.

reinforcement,  $F(2.36, 42.42) = 6.48$ , were compared to groups that experienced extinction alone. Changes in responding during Phase 3 did not differ significantly between alternative-reinforcement rate groups.

Finally, rates of alternative nose poking decreased across sessions of Phase 3 for groups that experienced alternative reinforcement during Phase 2, and decreases tended to occur more quickly in groups that experienced high-rate alternative reinforcement (see Fig. 2). A  $2 \times 2 \times 5$  (Target-Reinforcer Rate  $\times$  Alternative-Reinforcer Rate  $\times$  Session) mixed-model ANOVA confirmed this observation. Only the main effect of Session,  $F(1.53, 30.6) = 56.64$ , and the Session  $\times$  Phase-2 Rein-forcer Rate interaction,  $F(1.53, 30.6) = 5.15$ , were significant.

### Model fits

Equation 2 was fitted to the logarithms (base 10) of proportion-of-baseline target-response rates, aggregated by group, across sessions of Phases 2 and 3 using Microsoft Excel<sup>®</sup> Solver. Proportion-of-baseline response rates were calculated by dividing mean target-lever response rates for a group during each session of Phases 2 and 3 by the mean rate of target-lever pressing for those groups from the final five sessions of Phase 1. The parameters  $k$ ,  $c$ ,  $d$ , and  $b$  were allowed to vary and were set at initial values of 0.05, 1, 0.001, and 0.5, respectively. These values were selected based on model fits reported by Shahan and Sweeney (2011). Target ( $\Delta r$  in the numerator and  $r$  in the denominator) and alternative ( $R_a$ ) reinforcer-rate terms were set equal either to 240 or 60 reinforcers per hr, which correspond to reinforcer rates delivered by VI 15-s and VI 60-s schedules, respectively. Equation 2 was fitted to data from all groups simultaneously. The resulting model fits may be found in Figure 4, and the free-parameter values derived from these fits are in Table 4.

Several features of these model fits are noteworthy. First, free-parameter estimates were substantially different from those Shahan and Sweeney (2011) prescribe for describing target-response persistence and resurgence (see Table 4): Values of  $c$  and  $k$  were lower, and the value of  $d$  was higher, than those values by several orders of magnitude. Obtained Phase-2 persistence data systematically deviated from the predictions generated by Equation 2. Though response persistence was significantly higher in low-rate alternative-reinforcement groups than in the other groups, the best fitting parameters generated little differential Phase-2 persistence. In the case of groups that experienced high-rate reinforcement for target-lever pressing, the model systematically over-predicted response persistence early in Phase 2 and under-predicted persistence later in Phase 2 for both groups that experienced alternative reinforcement. Further, the model severely over-predicted persistence for the group that experienced extinction alone. In the case of groups that experienced low-rate target reinforcement, the model systematically over-predicted response persistence in the group that experienced high-rate alternative reinforcement. Early in Phase 2, the model over-predicted persistence for the low-rate alternative-reinforcement group and under-predicted persistence for this group later in Phase 2. Further, it is clear on semi-log coordinates that responding decreased substantially more quickly in the High EXT group than in the Low EXT group. Equation 2, however, predicted only small differences in persistence between these groups.<sup>2</sup> Finally, the characteristics of the predicted and obtained response functions differed. While the model predicted linear decreases in log-transformed

proportion-of-baseline response rates, the obtained log proportion-of-baseline response-rate functions deviated substantially from linearity. More specifically, responding generally tended to decrease most quickly early in Phase 2 and to decrease more slowly later in Phase 2.

As is clear in Figure 4 (see also the bottom panels in Fig. 1), resistance to extinction was lower for the High EXT group than for the Low EXT group. With the best fitting parameter values, Equation 2 predicted this ordinal difference in resistance to extinction, but the model predicted much greater persistence in the High EXT group than was observed. To further clarify how the model of extinction offered by behavioral momentum theory would describe the negative relation between baseline reinforcer rates and resistance to extinction in the present study, Equation 1 was fitted to persistence data from these groups alone. These fits were carried out as detailed above and are displayed in Figure 5. Though Equation 1 was able to describe these data tolerably well ( $R^2 = 0.64$ ) and captured the negative relation between baseline reinforcer rates and resistance to extinction for these groups, values of  $c$  (0.039) and  $b$  (0.26) were substantially lower than those typically reported in extinction research using multiple schedules of reinforcement ( $d = 0.0018$  in these fits, however, which is consistent with values from previous reports).

In terms of the resurgence data, the model predicted resurgence for all groups that experienced alternative reinforcement. As noted above, however, resurgence occurred only for groups that experienced high-rate alternative reinforcement. Further, the predicted levels of Phase-3 responding systematically deviated from obtained levels of Phase-3 responding for most groups. The model under-predicted response levels for the High High and High Low groups and over-predicted Phase-3 levels of responding in the Low-High group.

## Discussion

The present experiment aimed to test predications of Shahan and Sweeney's (2011) quantitative model of resurgence. Specifically, effects of Phase-1 and -2 reinforcer rates on target-response suppression and resurgence were examined. In the sections that follow, we first will describe discrepancies between the present findings and the predictions of Equation 2. We then will review several other empirical findings that pose challenges for the model. Finally, we will discuss our findings in relation to Bouton and colleagues' (Bouton, Winterbauer, & Todd, 2012; Winterbauer & Bouton, 2010; 2011) contextual theory of resurgence.

### Equation 2 Accounts Poorly for Reinforcer-Rate Effects

As reviewed in the Introduction, Equation 2, when using free-parameter values typically reported when the model is fitted to obtained resurgence data, makes three core predictions related to reinforcer rates. First, relatively higher rates of reinforcement for target behavior during Phase 1 should produce target responding that is more persistent during Phase 2 than

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<sup>2</sup>The lack of predicted differences in Phase-2 responding in the present model fit owed to the best fitting parameter values of the regression. Though the exact patterning of predicted results in Figure 4 resulted from the interaction between all fixed (i.e.,  $t$ ,  $r$  and  $R_d$ ) and free ( $k$ ,  $c$ ,  $d$ , and  $b$ ) parameters, the best-fitting value of  $k$  was about 10-fold smaller than the value prescribed by Shahan and Sweeney (2011). Thus, alternative-reinforcer rate had little impact on predicted Phase-2 target-response disruption.

relatively lower rates of Phase-1 reinforcement. Second, high-rate alternative Phase-2 reinforcement should disrupt target responding during Phase 2 more than low-rate alternative reinforcement. Relatedly, alternative reinforcement plus extinction of target behavior during Phase 2 should produce faster decreases of target responding than extinction alone. Finally, resurgence of target responding during Phase 3 should be positively related to both Phase-1 and Phase-2 reinforcer rates.

Several findings from the current experiment were contrary to these basic predictions. As is clear in Figure 1, when no alternative source of reinforcement was available in Phase 2, target-response persistence during Phase 2 was *negatively* related to Phase-1 reinforcer rates. This finding is not only problematic for Shahan and Sweeney's (2011) model of resurgence, but it also challenges the conceptual underpinnings of the description of extinction offered by behavioral momentum theory (Eq. 1; for related discussions, see Craig, Nevin, & Odum, 2014; Nevin, 2012) because, without alternative reinforcement, Equation 2 reduces to Equation 1. Momentum theory predicts a positive relation between reinforcer rates in a discriminative-stimulus situation and resistance to extinction of behavior maintained in that situation. It is well established, however, that the opposite relation typically is observed when single schedules (like those in the present experiment) are used to study resistance to extinction (Cohen, 1998; Cohen, Riley, & Weigle, 1993; Lionello-Denolf & Dube, 2011; Shull & Grimes, 2006).

Fits of Equation 2 to the full dataset from the present experiment described the negative relation between Phase-1 reinforcer rates and target-lever persistence during Phase 2 for groups that received no alternative reinforcement (though, in the case of the High EXT group, the model predicted substantially more persistence than was observed). These fits were accomplished, however, by allowing free parameter values to assume values that differed by several orders of magnitude from those values typically reported. That is, according to the present model fits, suspending the response–reinforcer contingency ( $c$  in Eqs. 1 and 2) had a much smaller impact ( $c = 0.00064$ , relative to typical values of  $c = 1$ ), and generalization decrement ( $d\Delta r$ ) had a much larger impact ( $d = 0.012$ , relative to typical values of  $d = 0.001$ ), on target-response persistence (see Nevin & Grace, 2000; Shahan & Sweeney, 2011). The same was true when Equation 1 was fitted to data from the High EXT and Low EXT groups, alone (see Fig. 5); the model adequately described ordinal differences in extinction data from these groups, but free-parameter values were substantially different from those typically reported. As discussed by Craig and Shahan (2016), behavioral momentum theory is limited in that it does not describe why different training protocols (e.g., single vs. multiple schedules) should produce such large differences in the impact of reinforcement rate on resistance to extinction. The critical differences between single- and multiple-schedule training that produce differential dependencies of resistance to extinction on baseline reinforcer rates remain unclear (though, for potential interpretations, see Craig & Shahan; Gallistel, 2012; Nevin, 2012; Shull & Grimes, 2006), thus limiting generality of the fundamental principles of the theory.

The forms of the predicted and obtained log proportion-of-baseline response-rate functions in the current experiment also differed substantially. While Equations 1 and 2 predict proportion-of-baseline response rates during extinction to decrease in a linear manner on

semilog coordinates, obtained rates more closely approximated hyperbola-like functions. That is, responding decreased most dramatically early in Phase 2, but the rate of changes in responding was less later in Phase 2. It is possible that target-lever responding decreased during Phase 2 until ultimately reaching a low, operant level supported by the conditioning situation. Equations 1 and 2 fail to capture this facet of extinction.

In the present experiment, high-rate alternative reinforcement produced faster response suppression than low-rate alternative reinforcement, consistent with the predictions of Equation 2. The relation between persistence in these groups and in the groups that experienced extinction alone, however, is not consistent with Equation 2. More specifically, Equation 2 asserts that any source of alternative reinforcement should produce faster decreases in target behavior than extinction alone. This prediction was not upheld. Low-rate alternative reinforcement produced target-lever pressing that was more persistent in Phase 2 than target-lever pressing in rats that experienced extinction alone (cf. Sweeney & Shahan, 2013b; Winterbauer & Bouton, 2010). Further, though no statistical difference in Phase-2 target responding was detected between high-rate alternative-reinforcement groups and groups that experienced extinction alone, target responding was, if anything, more persistent for the High High group than for the High EXT group (see Figs. 1 and 4). Inspection of individual-subject data from these groups (Appendix A) provides further support for this observation. Thus, alternative reinforcement does not uniformly serve to disrupt target responding when it is experienced in conjunction with extinction, as Equation 2 asserts. Under some circumstances, alternative reinforcement actually increases persistence of target behavior relative to experience with extinction conditions alone.

Finally, Equation 2 inaccurately described differences in resurgence of target-lever pressing during Phase 3. Resurgence, defined as an increase in the frequency of extinguished target behavior following suspension of an alternative source of reinforcement, occurred only in groups that received high-rate alternative reinforcement during Phase 2. For groups that received low-rate alternative reinforcement, no significant change in levels of target-lever pressing occurred between the final session of Phase 2 and the first session of Phase 3 (see Fig. 3). Equation 2, when fitted to obtained data, predicted resurgence for all alternative-reinforcement groups. Further, the model predicted greater levels of Phase-3 responding for high-rate alternative-reinforcement groups than for low-rate groups. No difference, however, was observed (for similar findings see also Cançado & Lattal, 2013; Craig, Nall, Madden, & Shahan, 2016; Fujimaki et al., 2015; Winterbauer & Bouton, 2010). Thus, Equation 2 not only is limited in its ability to describe effects of alternative reinforcement on target-response suppression during Phase 2, but also the model fails to adequately describe the relation between these rates and levels of Phase-3 responding.

### **Other Conceptual and Practical Issues for the Model**

In addition to rates of Phase-1 and Phase-2 reinforcement, Shahan and Sweeney's (2011) resurgence model cannot account well for several other findings in the resurgence literature. For example, Equation 2 predicts that the magnitude of resurgence obtained during Phase 3 should be inversely related to the duration of Phase 2. Though data from some resurgence preparations support this assertion (Sweeney & Shahan, 2013a; Wacker et al., 2011) others

(e.g., Winterbauer, Lucke, & Bouton, 2013) have shown no relation between Phase-2 duration and magnitude of resurgence during Phase 3, calling into question the generality of this prediction. The model further asserts the source of alternative reinforcement should not matter in terms of its effects on response suppression and resurgence so long as rate of alternative reinforcement is held constant. Delivery of alternative reinforcers contingently on an alternative response, however, appears to more effectively suppress target behavior than delivery of alternative reinforcers response- independently (see, e.g., Sweeney et al., 2014). Further, as shown in Figure 4, Equation 2 predicts Phase-3 target-response rates should be highest in the first session following suspension of alternative reinforcement, after which rates should decrease monotonically across Phase-3 sessions. Often, however, target behavior during Phase 3 follows a bitonic function (i.e., rates increase during the first few Phase-3 sessions, after which they decrease; e.g., Cançado & Lattal, 2011; Podlesnik & Kelley, 2014; Podlesnik & Shahan, 2009; 2010). The reasons for these findings are unclear, but they challenge the fundamental architecture of the model.

Other practical and conceptual issues arise with respect to the way Equation 2 characterizes the contributions of separate sources of reinforcement to behavioral mass (i.e., the term in the denominators of Eqs. 1 and 2). As reviewed above, behavioral mass is the construct within behavioral momentum theory that relates response persistence in the face of disruption, and resurgence, to previously experienced reinforcer rates. Equation 2 suggests both target- and alternative-reinforcer rates additively contribute to behavioral mass, yet this additive relation is counterintuitive under some circumstances. For example, for the High High and Low Low groups in the present experiment, no reinforcer-rate change occurred between Phases 1 and 2. The model, however, asserts that changing the source of reinforcement from a target lever press to an alternative nose poke between phases effectively doubled the Pavlovian stimulus-reinforcer relation for these groups. It is not intuitive to suppose that changing the source of reinforcement should increase behavioral mass in such a way. This assumption becomes yet more challenging when one considers situations where several alternative responses are trained and extinguished serially (e.g., Lambert, Bloom, Samaha, Dayton, & Rodewald, 2015; Reed & Morgan, 2006). If every discrete source of reinforcement combines additively in the denominator of Equation 2 (i.e.,  $r + R_{a1} + R_{a2} + \dots R_{an}$ ), behavioral mass could grow infinitely large if a large number of sources were made available. Since the limit of the right side of Equation 2 as  $(r + R_{a1} + R_{a2} + \dots R_{an}) \rightarrow \infty$  is 0, the model would predict no decreases in target responding, relative to baseline levels of responding, with a sufficiently large number of sequentially available alternative-reinforcement sources. This prediction seems unlikely.

### **An Alternative Account of Resurgence**

The findings detailed above challenge several fundamental, underlying assumptions of Shahan and Sweeney's (2011) quantitative theory of resurgence. Bouton and colleagues (e.g., Bouton, Winterbauer, & Todd, 2012; Winterbauer & Bouton, 2010; 2011) have posed similar criticisms of Equation 2 and have offered an alternative account of resurgence based on contextual control of extinguished behavior. According to this contextual theory, organisms learn to inhibit previously reinforced behavior during extinction in a manner that is context-specific (see Bouton & Todd, 2014, for discussion). If the context in which



extinction occurred is altered in some way, inhibitory learning that occurred in the first extinction context might fail to generalize to the new extinction context, thus producing relapse of extinguished behavior. Specifically in the case of resurgence, Phases 1, 2, and 3 of a standard resurgence preparation represent separate conditioning contexts that may be discriminated based on differences in reinforcer rate and source. Rate of target-response extinction during Phase 2 presumably is related to the degree of dissimilarity between Phase-1 and Phase-2 conditioning contexts, and magnitude of resurgence is related to the degree of dissimilarity between Phase-2 and Phase-3 conditioning contexts (see Bouton & Trask, 2015, for discussion).

Within this contextual account of resurgence, context is broadly defined, allowing the theory to describe a wide range of extinction and relapse phenomena (e.g., resurgence, reinstatement, renewal, spontaneous recovery) in a parsimonious manner. Notwithstanding this strength, Bouton and colleagues' theory has received several conceptual criticisms (for detailed discussion, see McConnell & Miller, 2014). For example, the theory is not quantitatively formalized and therefore is limited to making qualitative predictions. Further, the theory asserts the explanatory mechanism of behavior change is contextual change, and contextual change is inferred through behavior change (see Bouton & Trask, 2015; Winterbauer & Bouton, 2012). Thus, what constitutes changes in a conditioning context is usually defined in a post-hoc manner, limiting even qualitative predictions (for related discussion, see Podlesnik & Kelley, 2015).

The present experiment also poses empirical challenges for the contextual account of resurgence. For example, Phase-2 responding was more persistent in the Low Low group than in either the Low High or Low EXT groups. The theory might predict this pattern of behavior during Phase 2 by making the assumption that delivering the same rate of reinforcement during Phase 2 as during Phase 1 produced a less noticeable contextual change than delivering a different rate of Phase-2 reinforcement or suspending reinforcement altogether. Based on this conjecture, one would anticipate responding in the High High group to be more persistent during Phase 2 than responding in the High Low or High EXT groups. Responding in the High Low group, however, was higher than responding in either the High High or High EXT groups. A second finding from the present experiment that is potentially problematic for the context-based account of resurgence is that resurgence did not occur at all for rats that experienced low-rate alternative reinforcement. One interpretation of this finding is that the low-rate alternative-reinforcement context was insufficiently discriminable from the subsequent Phase-3 context to produce resurgence. Responding, however, actually *decreased* across sessions of Phase 3 for most rats in the High Low and Low Low groups, suggesting the change in reinforcer rate between phases was discriminable. From this perspective, it remains unclear why some alternative reinforcer-rate changes produce increases in target behavior (i.e., resurgence) while others produce decreases. Thus, when compared to Shahan and Sweeney's (2011) model, Bouton and colleague's contextual theory of resurgence appears equally incapable of describing behavior elimination under conditions of extinction plus alternative reinforcement and resurgence following removal of alternative reinforcement.

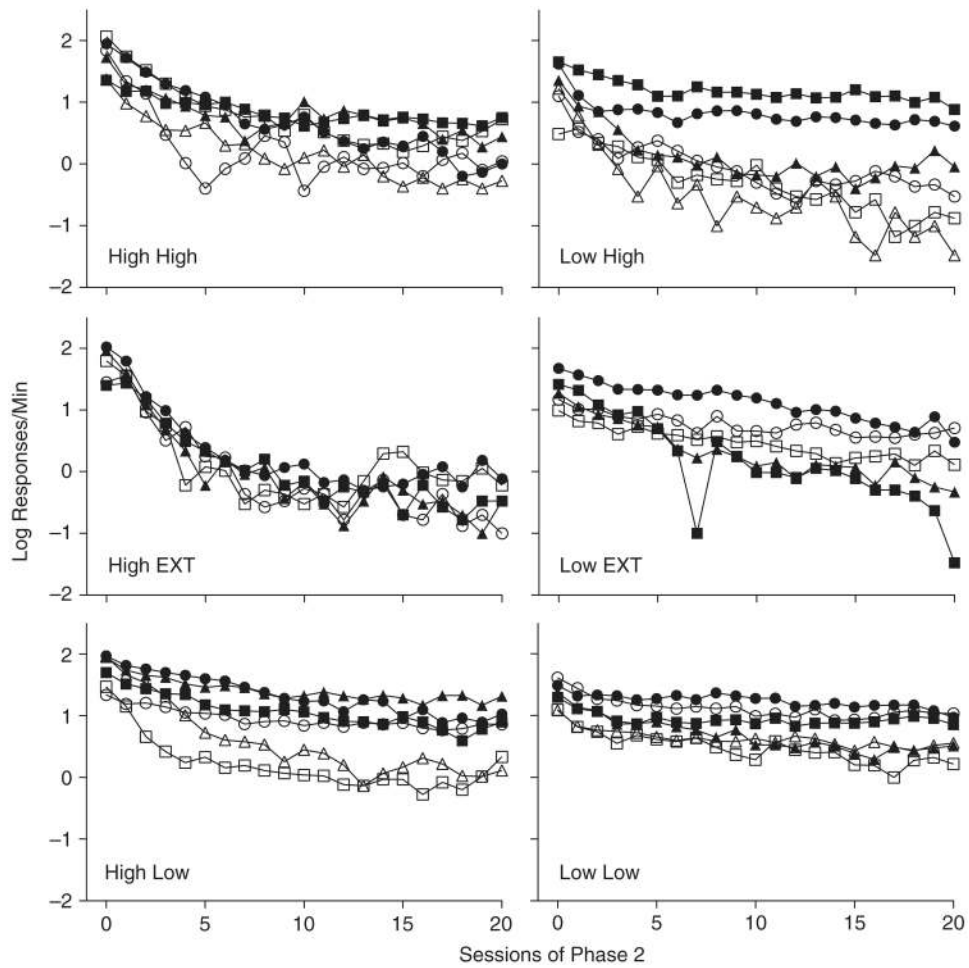
## Conclusions

To summarize, data from the present experiment demonstrate that delivery of alternative reinforcement during extinction of operant behavior can have varying effects on the degree to which behavior persists. When sufficiently high rates of alternative reinforcement are delivered, alternative reinforcement can hasten the extinction process under some circumstances. Conversely, when sufficiently low rates are delivered, alternative reinforcement can increase persistence of behavior during extinction. Further, suspension of alternative reinforcement appears to produce resurgence most reliably when those reinforcers were delivered relatively frequently. Suspension of sufficiently low-rate alternative reinforcement may not produce resurgence of target behavior at all (see also Craig et al., 2016). We conclude that neither the Shahan and Sweeney (2011) model of resurgence nor the contextual theory of resurgence provide adequate descriptions of these phenomena. Thus, at this time, the behavioral processes that give rise to persistence of target behavior during extinction plus alternative reinforcement, and resurgence once alternative reinforcement is removed, are uncertain.

## Acknowledgments

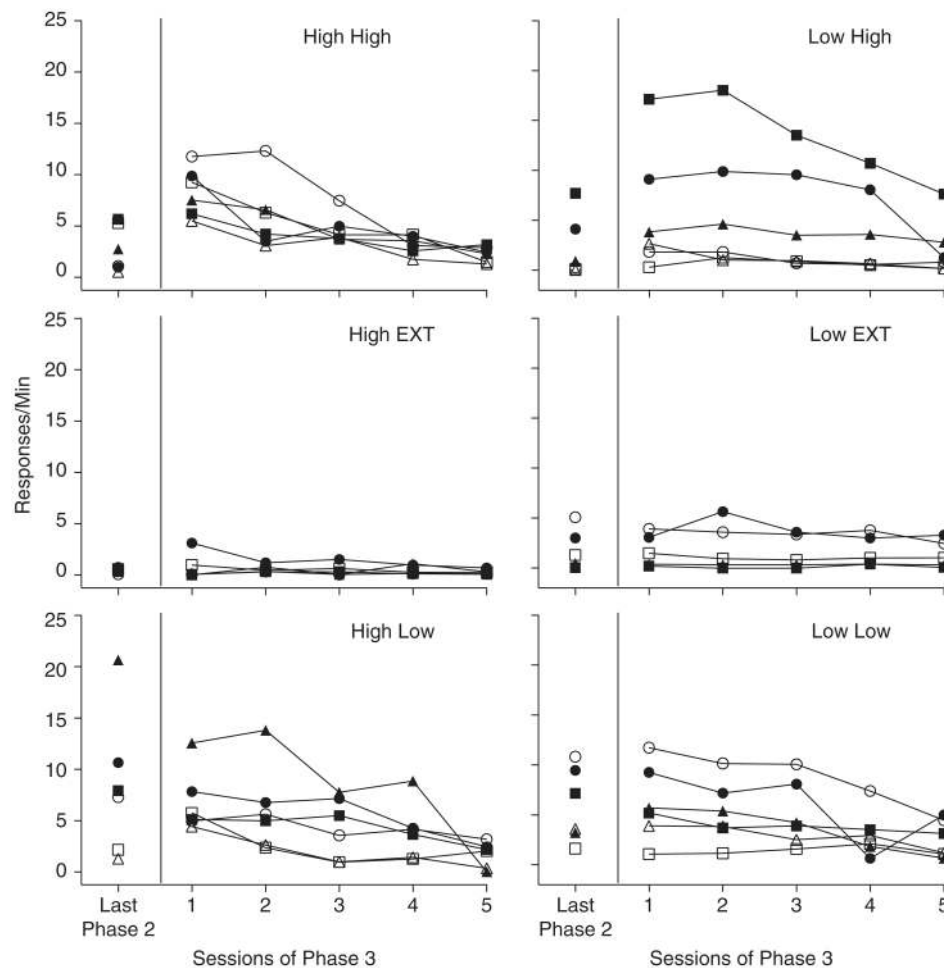
This research was supported by grant 1R21DA037725-01.

### Appendix A



Log-transformed target-lever responses per min across sessions of Phase 2 for every individual subject organized by group

## Appendix B



Target-level responses per min during the last session of Phase 2 and all sessions of Phase 3 for every individual subject organized by group

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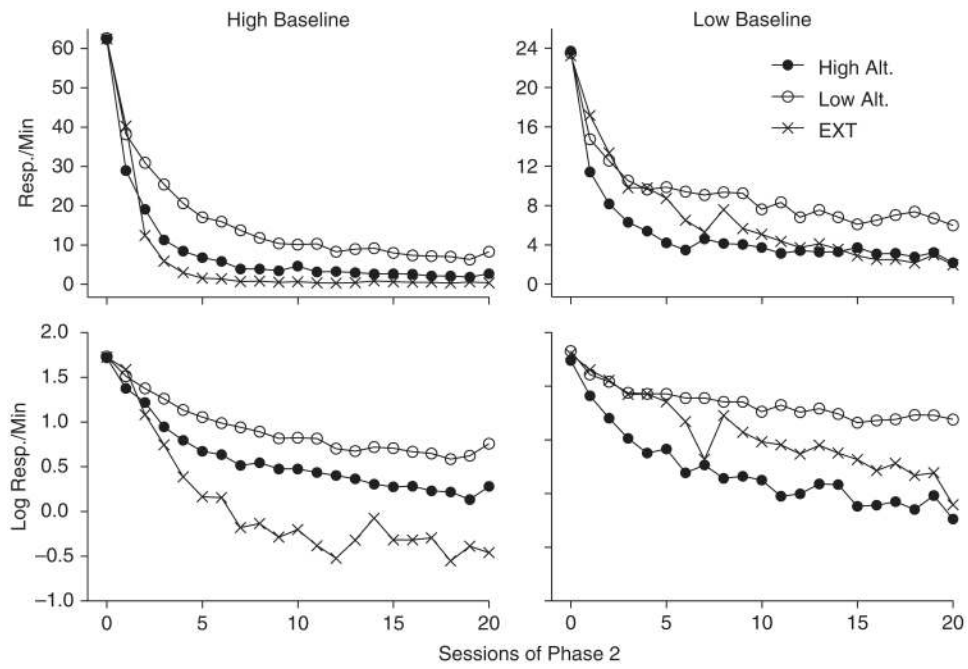
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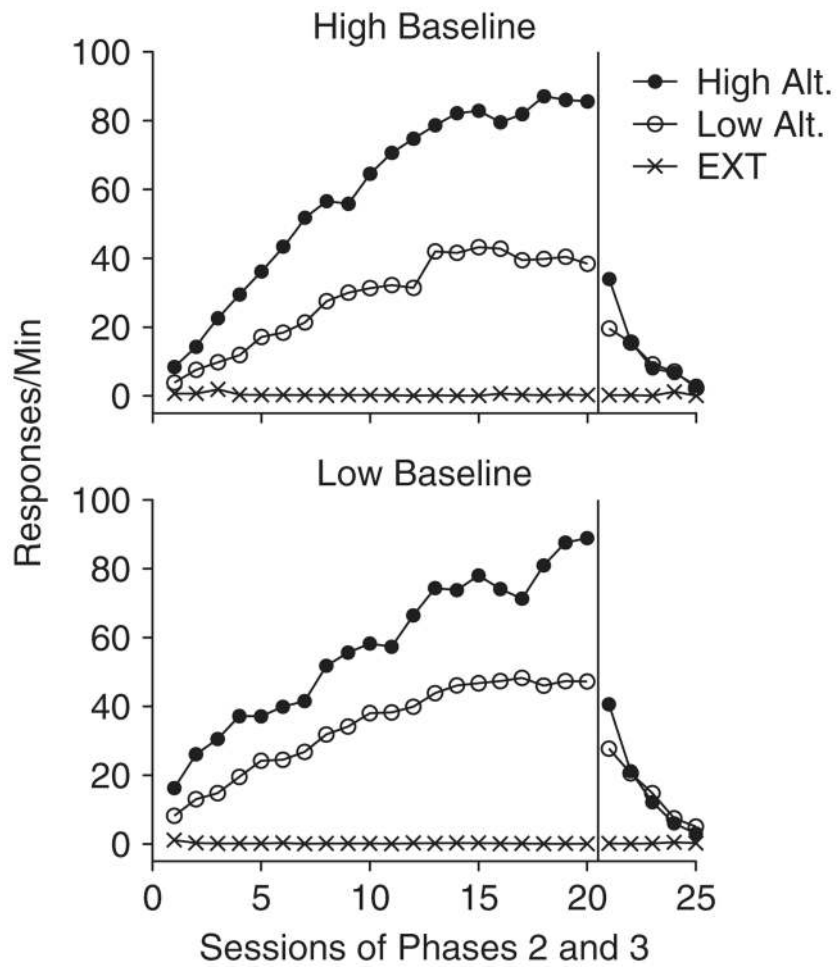
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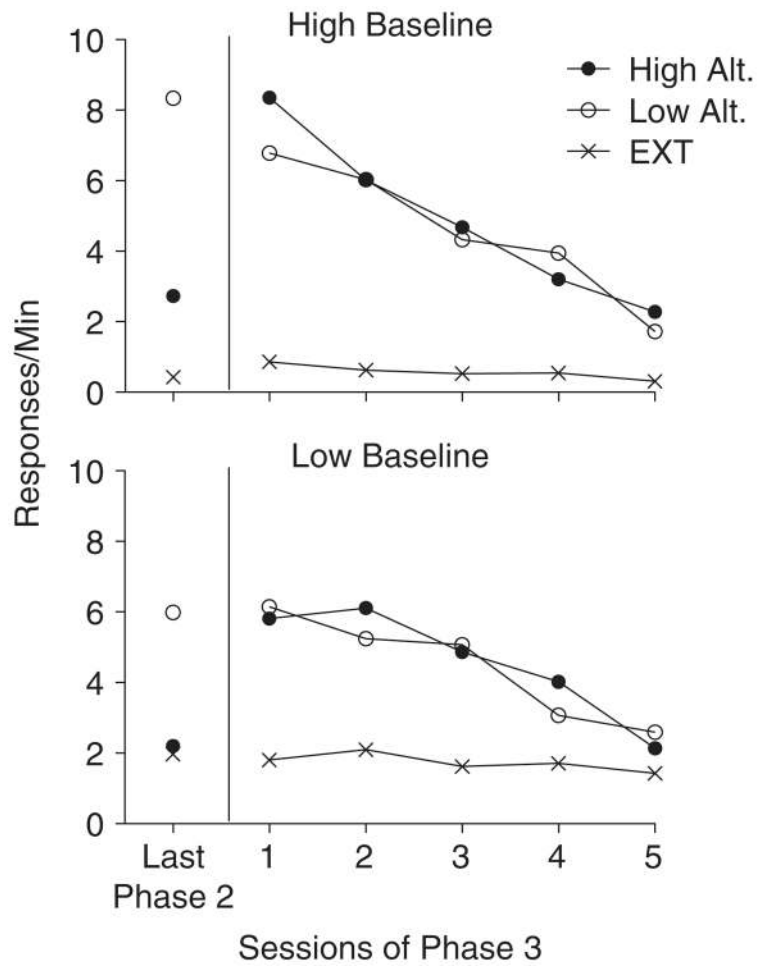
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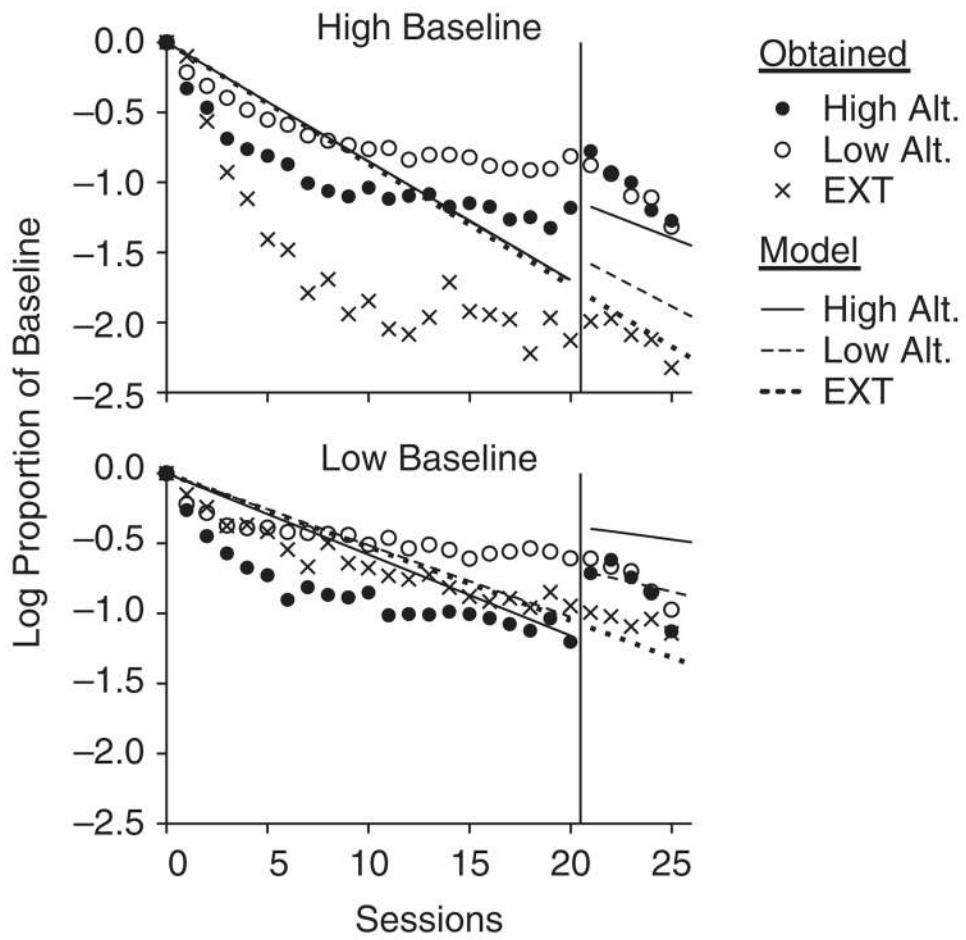
**Fig. 1.** Top panels: Mean target-lever presses per min across sessions of Phase 2 (note the y-axes are differently scaled). Bottom panels: Mean, log-transformed target-lever presses per min across sessions of Phase 2. The left panels show data from groups that experienced high-rate Phase-1 reinforcement, and the right panels show data from groups that experienced low-rate Phase-1 reinforcement.



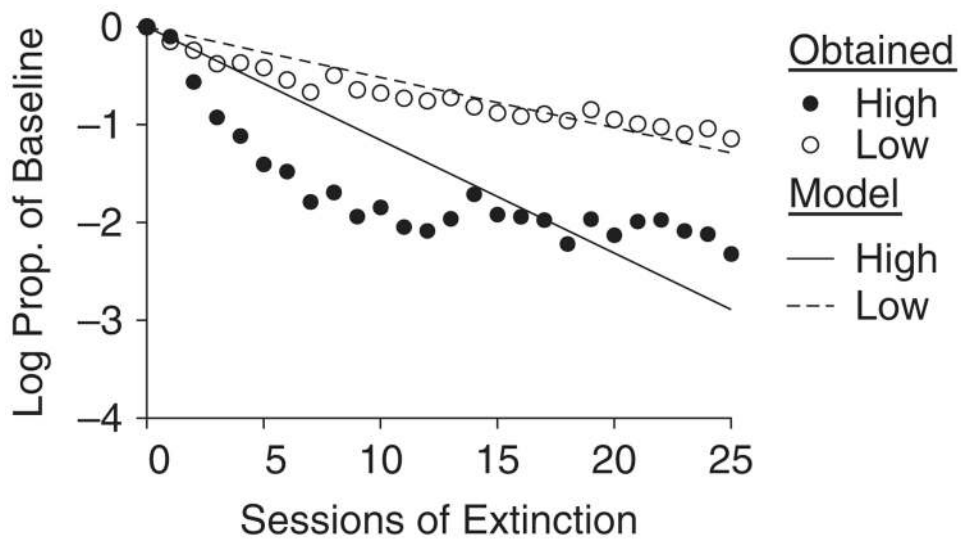
**Fig. 2.** Mean alternative nose-poke response rates across sessions of Phases 2 and 3 for each group. Data in the top panel are from groups that experienced high-rate Phase-1 reinforcement, and data in the bottom panel are from groups that experienced low-rate Phase-1 reinforcement.



**Fig. 3.** Mean target-lever responses per min from the last session of Phase 2 and all sessions of Phase 3 for each group. Data in the top panel are from groups that experienced high-rate Phase-1 reinforcement, and data in the bottom panel are from groups that experienced low-rate Phase-1 reinforcement.



**Fig. 4.** Fits of Equation 2 to log-transformed proportion-of-baseline target-lever response rates across sessions of Phases 2 and 3. The top panel shows fits to data from the rats that experienced high-rate Phase-1 reinforcement, and the bottom panel fits to data for rats that experienced low-rate Phase-1 reinforcement.



**Fig. 5.** Fits of Equation 1 to log-transformed proportion-of-baseline response rates across sessions of Phases 2 and 3 for the High EXT and Low EXT groups.

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**Table 1**  
**Summary of Reinforcement Conditions across Phases for All Groups**

Group	Phase 1		Phase 2		Phase 3	
	Target Lever	Alternative Poke	Target Lever	Alternative Poke	Target Lever	Alternative Poke
High High	VI 15 s	-	EXT	VI 15 s	EXT	EXT
High Low	VI 15 s	-	EXT	VI 60 s	EXT	EXT
High EXT	VI 15 s	-	EXT	EXT	EXT	EXT
Low High	VI 60 s	-	EXT	VI 15 s	EXT	EXT
Low Low	VI 60 s	-	EXT	VI 60 s	EXT	EXT
Low EXT	VI 60 s	-	EXT	EXT	EXT	EXT

**Table 2**  
**Summary of Response and Reinforcement Rates from the Last Five Sessions of Phase 1**

Group	Target Responses/Min		Target Reinforcers/Min		Alt. Responses/Min		Inactive Responses/Min	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
High High	62.31	15.03	3.55	0.09	0.11	0.06	0.75	0.30
High Low	62.65	13.41	3.59	0.10	0.08	0.03	1.56	1.03
High EXT	62.43	16.14	3.50	0.19	0.02	0.02	0.33	0.17
Low High	23.74	6.82	0.88	0.03	0.11	0.03	0.83	0.28
Low Low	23.54	4.64	0.92	0.01	0.15	0.05	1.98	1.06
Low EXT	23.26	6.55	0.92	0.01	0.22	0.07	1.04	0.26

**Table 3**  
**Summary of Alternative and Inactive Response Rates, and Alternative Reinforcement Rates, from the Last Five Sessions of Phase 2**

Group	Alt. Responses/Min		Alt. Reinforcers/Min		Inactive Responses/Min	
	Mean	SEM	Mean	SEM	Mean	SEM
High High	84.05	19.51	3.40	0.18	0.24	0.05
High Low	40.22	8.59	0.90	0.01	1.20	0.49
High EXT	0.41	0.21	-	-	0.18	0.04
Low High	80.58	26.36	3.41	0.12	0.23	0.09
Low Low	47.28	7.39	0.91	0.02	1.78	1.22
Low EXT	0.15	0.06	-	-	0.22	0.07

**Table 4**  
**Parameter Estimates from Fits of Equation 2 to Obtained Data**

Parameter	Estimate
$k$	0.0061
$c$	0.00064
$d$	0.012
$b$	0.64
$R^2$	0.41

*Note:* Estimates were rounded to two significant digits.

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