Published in final edited form as:

Physiol Behav. 2010 June 16; 100(4): 316–321. doi:10.1016/j.physbeh.2010.03.004.

Reinforcing efficacy of fat, as assessed by progressive ratio responding, depends upon availability not amount consumed

F.H.E. Wojnicki, R.K. Babbs, and R.L.W. Corwin

Pennsylvania State University, Nutritional Sciences, 110 Chandlee Laboratory, University Park, PA, 16802

F.H.E. Wojnicki: fhw3@psu.edu

Abstract

Intermittent limited access to an optional source of dietary fat can induce binge-type behavior in rats. However, the ability of such access to alter the reinforcing efficacy of fat has not been clearly demonstrated. In this study, performance under progressive ratio one (PR1) and three (PR3) schedules of shortening (fat) reinforcement was assessed in non-food deprived rats ($n=15/\text{group}$). One group of rats had intermittent access to a dietary fat option (INT, 1-hr shortening access in the home cage each Monday, Wednesday, and Friday), whereas the other group had daily access to the fat option (D, 1-hr shortening access daily). Chow and water were continuously available. After five weeks, the INT group consumed more shortening during the 1-hr access period than did the D group. Rats were then trained to lever press for a solid shortening reinforcer (0.1 gm). INT rats earned significantly more reinforcers than did D rats under PR1, but not under PR3. Subgroups of INT and D rats ($n=7$ each) were matched on the amount of shortening consumed in the home cage during week five of the protocol and the PR data were reanalyzed. The INT subgroup earned significantly more reinforcers than the D subgroup did under PR1, but not PR3. These results demonstrate that: 1) intermittent access to shortening in the home cage, but not the amount consumed during the access period (i.e. bingeing), increases the reinforcing efficacy of solid shortening; 2) the type of PR schedule is critical in delineating differences between the groups.

Keywords

binge eating; dietary fat; progressive ratio; reinforcing efficacy

Introduction

Binge-type eating can be induced in non-food-deprived rats by providing intermittent access to optional sources of palatable foods, e.g. fat [1-7], liquid sucrose [8-9], and shortening/sucrose mixtures [10]. That is, when non-food deprived rats are given 1-hr access to the palatable food three times per week (Intermittent or INT), they consume significantly more during the 1-hr period than do rats with daily 1-hr access to the palatable food (Daily). This differential amount of food consumption raises the question of whether the palatable food has become more

Correspondence should be addressed to: Rebecca L. Corwin, RD, PhD, The Pennsylvania State University, College of Health and Human Development, Nutritional Sciences Department, 110 Chandlee Laboratory, University Park, PA 16801, Phone: 814-865-6519, Fax: 814-863-6103, rxc13@psu.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

‘rewarding’ to the INT group than to the Daily group. Stated otherwise, does the basis of availability to an optional palatable food change the reinforcing efficacy of that food in non-food-deprived rats?

One way to assess the reinforcing efficacy of food is the use of a progressive ratio (PR) schedule of reinforcement. Under PR schedules, the response requirement increases with each subsequent reinforcer delivery according to some mathematical formula. Reinforcing efficacy is operationally defined by PR performance or the “breakpoint”, i.e. the highest ratio the animal completes, the total responses made, or the reinforcers earned. As such, PR performance serves as a measure of “how hard the animal is willing to work” or “how motivated the animal is” to obtain different reinforcers. PR schedules promote high levels of responding while limiting the number of reinforcers earned. This avoids confounds associated with physiological satiation during the tests. Several independent variables have been shown to alter performance under PR schedules such as reinforcer concentration [11-18], reinforcer magnitude [15,19], and food deprivation [14-15].

Intermittent access to and bingeing on fat can also alter PR performance [20]. Specifically, PR performance was greater in rats provided INT access to fat relative to performance in the same rats prior to INT exposure. In other words, PR performance escalated in the INT rats. In Daily rats, however, such escalation did not occur. In spite of the pre-binge versus post-binge difference within the INT group, breakpoint did not consistently differ between INT and Daily groups.

One reason for the lack of difference between the groups may have been the PR schedule that was used. The Wojnicki et al. study, [20] used the same exponential progression PR schedule that had been used in several studies of drug self-administration [21-24]. However, lower progressions have generally been used in food intake studies, e.g., PR2x [14], PR2 [15], PR3, 5 [16], PR1 or 0.5 starting at 20 [17], PR2, 5 10 [19]. One goal of the present study was to examine progressive ratio performance in INT and Daily rats under lower ratio progressions (PR1 and PR3) than were used in the Wojnicki et al. [20] study.

Many people enjoy sweet and fatty foods, but not all people binge on those foods. Does intermittent access to these foods enhance their ‘reward value’? Intermittent access can stimulate binge-type consumption of palatable food, as mentioned above. However, it is not known if intermittent access enhances the reinforcing efficacy of those foods, even in the absence of binge-type behavior. Like people, not all INT rats binge; INT rats with relatively low intakes consume about the same amount during the 1-hr period of availability as do Daily rats with relatively high intakes, i.e. there is invariably some overlap between the groups. Therefore, a second goal of the present study was to determine if progressive ratio performance differed in INT and Daily rats with comparable home cage intakes.

Materials and Methods

Animals

Thirty male Sprague Dawley (Harlan, Indianapolis, IN) rats, 60 days of age and weighing 277-312g (+/- 1.6 g) at the start of the study, were individually housed in hanging stainless steel wire cages in a temperature- and humidity-controlled environment placed on a 12:12 light:dark cycle. All rats had continuous access to a nutritionally complete commercial laboratory rodent diet (Laboratory Rodent Diet 5001, PMI Feeds, Richmond IN; percent of calories as protein: 28.05%, fat: 12.14%, carbohydrate: 59.81%; 3.3 kcal/g) placed in hanging metal food hoppers at the front of the cage. Tap water also was freely available. All procedures were approved by the Pennsylvania State University Institutional Animal Care and Use Committee.

After seven days of adaptation to the vivarium, body weights were recorded and solid vegetable shortening (Crisco® All-Vegetable shortening, J.M Smucker Co., Orrville, OH) was provided during a single overnight period. Two groups of 15 rats each were then matched by body weight and the amount of shortening consumed [t-test; p NS for both measures].

Bingeing Procedure

For the next five weeks chow and water were available ad libitum to both groups. Shortening was provided for 1 hr in glass jars clipped to the front of the home cage, starting 2.5 hours prior to the start of the dark cycle. For one group of rats (n=15) shortening was provided for 1 hr on an intermittent (INT) basis (Mondays, Wednesdays, and Fridays), while for the other group (n=15) shortening was provided for 1 hr on a daily (D) basis. For purposes of clarity, the term “basis” will denote shortening availability in the home cage, i.e., INT vs. D. The term “schedule” will denote a reinforcement schedule used in the traditional operant sense.

Apparatus

The rats were tested in six identical operant chambers (Model H10-11R-TC; Coulbourn Instruments, Allentown, PA) located in a room adjacent to the vivarium. The back wall of each chamber contained a house light (Model H11-01R) located in the middle panel at the top of the chamber. The front wall of each chamber contained a response lever (Model H21-03R) located in the middle panel and a triple cue lamp (H11-02R) located on the right panel above the response lever. Whipped vegetable shortening was used as the reinforcer for lever pressing. It was delivered in 0.1 g units from a 20 cc glass syringe (Popper & Sons, New Hyde Park, NY) driven by an infusion pump (Model E73-01-3.3 rpm) into a receptacle located below the triple cue lamp adjacent to the response lever. Care was taken to minimize any air pockets in the 20 cc syringe that would affect the amount delivered. When a reinforcer was scheduled to be delivered all three cue lamps flashed for 2 sec prior to the start of the reinforcer delivery, during the 2 sec while the whipped shortening was being delivered, and for 1 sec after the delivery. All experimental contingencies were programmed with Graphic State 2™ state notation (Coulbourn Instruments, Allentown, PA).

Operant Procedures

After the fifth week of the bingeing procedure rats were food-deprived overnight, allowed a ½ hr acclimation period to the operant chamber, and given 5 g of rat chow in their home cages after the session. During the next 1 or 2 sessions, all animals were trained to lever press for 0.1 g of whipped vegetable shortening on a Fixed-Ratio one (FR1) schedule of reinforcement. Ad libitum chow was provided in the home cages for rats that learned to lever press after the first session and 5 g of chow was provided for rats that had not learned to lever press after the first session. All rats were trained to lever press by the second session.

Ad libitum chow was then provided for two days following lever-press training. On the third day all rats were overnight food-deprived and then exposed to a FR3 schedule of reinforcement. From this point forward, ad libitum chow was provided to all rats, i.e., the results reported below were obtained under non-food-deprived conditions. All rats were then exposed to the following sequence of reinforcement schedules during 1/2 hr sessions, starting the 4th day of ad libitum chow: one session of FR3, four sessions of Progressive ratio 1 (PR1), four sessions of PR3, and one session of PR1. All operant sessions were conducted on Mondays, Wednesdays and Fridays. The INT and D groups were alternated as to which group started the first experimental session of the day. The fifth group of rats consisted of 3-INT and 3-D animals and this group was always tested in the last test session of the day. For both the PR1 and PR3 schedules the first ratio requirement was 1 so as not to provide any immediate cue regarding the schedule in effect, and the ratio requirement was then increased as appropriate to the schedule requirement, i.e., PR1: 1, 2, 3, etc.; PR3: 1, 4, 7, 10, etc. Sessions took place during

the late light period. All rats were provided ½-hr of access to shortening in their home cages at least ½ h after a test session in order to maintain binge behavior. On non-test days, the D group was given 1-hr access to shortening in their home cages at 2.5 hr prior to the start of the dark cycle.

Statistics

SAS v.9.1 (SAS Institute, Cary, NC) was used to analyze the data. Between group t-tests were used to determine differences between INT and D groups for: 1) the average 1-hr shortening intake (g) for week five of the shortening binge protocol, 2) the total shortening intake on test days (home cage plus reinforcers earned) and 3) total number of reinforcers earned during PR sessions. Separate analyses were completed for data that included all subjects (n=15/group) or that included only the subgroups with equal 1-hr shortening intakes during week 5 (n=7/group). In addition, since PR1 tests were conducted before exposure to PR3 and after exposure to PR3, 2-way analysis of variance (ANOVA) [group (INT vs. D) × time (two different PR1 data sets)] was used to determine if shortening intake or the number of reinforcers earned during the PR1 sessions changed across the study. One-way ANOVA followed by post-hoc tests (as specified in the results) were used to determine differences across the different PR sessions within each group. The data included in the datasets were as follows: 1) the “1st PR 1” dataset consisted of the average of the last two PR1 sessions prior to the start of PR3 testing. 2) The “2nd PR1” dataset consisted of the single PR1 session that took place after PR3 testing. 3) The PR3 dataset consisted of the average of the last two PR3 sessions. The last two sessions of the PR1 and PR3 conditions were used so as to avoid using what might be considered transitional data during the first two sessions of exposure to each schedule. A 1-way repeated measures analysis determined there were no differences across sessions in operant performance within groups under both schedules with one exception. For the D group, session 2 under the PR1 was different from the other sessions. Hence, we chose to use the last two sessions in the analyses, as they were unequivocally identical.

Results

Home cage intake – all subjects

Home cage consumption of shortening during the 1-hr access period for week 5 of the binge period (before PR testing was initiated) was significantly affected by the basis of shortening availability (Fig. 1, top graph, week 5 data). During this 1-hr period the INT group (Monday, Wednesday, Friday access) consumed significantly more shortening than did the D (daily) group (t-test: $p < 0.0088$).

The total shortening intake (home cage shortening intake after an experimental session plus the amount earned during an experimental session) also was significantly affected by the basis of shortening availability. To determine if intake changed across time, data from just the PR1 sessions were analyzed. This analysis revealed no effect of dataset (1st or 2nd PR1); thus, shortening intake remained stable across the PR1 sessions, even though PR3 testing intervened, rats had gotten older, etc. There also was no group by test day interaction. There was, however, a main effect of group (INT vs. D) [$F(1,28)=11.88$, $p < 0.00180$] due to greater consumption of INT relative to D rats (t-test, $p < 0.05$) (Fig. 1, top graph, 1st PR1 and 2nd PR1). During exposure to the PR3 reinforcement schedule, the INT group again consumed significantly more total shortening than did the D group (t-test $p < 0.0015$; Fig. 1, top graph, PR3). Thus, under both PR1 and PR3 test conditions, INT rats “binged” relative to D rats.

Reinforcers earned – all subjects

The number of reinforcers earned during PR testing was also significantly affected by the basis of shortening availability. Again, to determine if responding changed across time, only data

collected during the PR1 sessions were analyzed. This analysis revealed no effect of dataset (1st or 2nd PR1 testing), demonstrating that responding remained stable across time. There also was no group by test day interaction. There was, however, an effect of group [$F(1,28) = 19.12$, $p < 0.0002$], due to greater responding by INT relative to D rats (t-test, $p < 0.05$) (Fig. 1, bottom graph, 1st and 2nd PR 1). The total reinforcers earned during PR1 sessions by the INT group (~12) and the D group (~7) represented about 1.2 and 0.7 g of shortening consumed, respectively. The amount of shortening normally consumed in the home cage was greater than this (Fig 1, top graph, Week 5); therefore, ceiling effects on intake were not a confound during the PR sessions. During PR3 sessions, the total reinforcers earned did not differ between the INT and D groups (t-test $p < 0.0534$; Fig.1, bottom graph, PR3).

More reinforcers were earned when the PR1 schedule was in effect than when the PR3 schedule was in effect for both the INT and D groups ($p < 0.05$ Tukey's HSD) (Fig. 1, bottom panel). In contrast, the final ratios achieved during PR1 and PR3 sessions did not consistently differ (data not shown). Specifically, the average final ratios achieved by the INT group during the first and second PR1 tests were 11.8 ± 1.2 and 12.4 ± 1.1 , respectively. During the PR3 tests, the INT group achieved an average final ratio of 13.7 ± 2.0 . None of these were significantly different from each other. The average final ratios achieved by the D group during the first and second PR1 tests were 6.7 ± 0.7 and 6.3 ± 1.0 , respectively. During the PR3 tests, the D group achieved an average final ratio of 9.0 ± 1.3 . Among these, the final ratio achieved during PR3 was significantly greater than that achieved during the second PR1 testing in the D group ($p < 0.05$ Tukey's HSD).

Response and reinforcer distributions

Response distributions throughout the PR1 and PR3 sessions were similar for both groups for both schedules of reinforcement (data not shown). During the PR1 and PR3 sessions, 93% and 96% of the responses, respectively, occurred by the end of the 4th quintile (minute 24) for both groups. Despite similar response distributions throughout the session, the absolute number of responses (including reinforced responding as well responding that occurred after the response requirement was met) differed between the two groups for each of the reinforcement schedules. Under the PR1 schedule, D rats emitted an average of 37 ± 7 responses per session (per rat) while INT rats emitted an average of 102 ± 20 responses per session (per rat). Under the PR3 schedule the average number of responses per session was 26 ± 6 and 57 ± 13 for D and INT rats, respectively.

Reinforcer distributions also were similar between the groups for both PR schedules. During the PR1 sessions, the INT group earned 94% of the reinforcers and the D group earned 96% of the reinforcers by the end of the 4th quintile. During PR3 sessions, both groups earned 96% of the reinforcers by the end of the 4th quintile.

Home cage intake - matched subgroups

Data were also analyzed for subgroups of 7 INT and 7 D rats in which week 5 1-hr shortening intakes were matched. Intakes did not differ statistically between these two groups at any time during the study (Fig. 2, top graph).

Reinforcers earned - matched subgroups

In contrast to the intake results, PR performance of the matched subgroups was comparable to that of the entire cohort. That is, for PR1, there was an effect of group ($F(1,12) = 7.62$ $p < 0.0173$; Fig. 2, bottom graph, 1st and 2nd PR 1), with the INT subgroup earning significantly more reinforcers than the D subgroup did during PR1 testing (t-test, $p < 0.05$). There was no effect of test day (1st or 2nd PR1) and no subgroup by test day interaction. There was no difference

between the INT and D subgroups with respect to reinforcers earned during PR3 (Fig. 2, bottom graph, PR3).

More reinforcers were earned by the INT group when the PR1 schedule was in effect than when the PR3 schedule was in effect ($p < 0.05$ Tukey's HSD; Fig. 2, bottom graph). For the D group, ANOVA comparing performance during PR1 and PR3 testing revealed significant differences among the different sessions ($F(2,12) = 4.26$, $p < 0.0401$); however, significant differences were not shown with Tukey's HSD post-hoc test. Differences were evident with Duncan's Multiple Range Test, showing that more reinforcers were earned by the D group when the PR1 schedule was in effect relative to PR3 ($p < 0.05$ comparing PR1 vs. PR3) (Fig. 2, bottom graph).

Discussion

As expected from previous research [1-7,25] the Intermittent (INT) group consumed significantly more shortening during the 1-hr availability period than did the Daily (D) group during week 5 of the study. These results fit the definition of bingeing: consumption of a greater quantity of a given substance in the same time period than normally would be consumed under similar circumstances [26]. In addition, several new findings are reported: 1) the size of the PR increment appears to be critical when assessing differences between binge and control rats, and 2) intermittent access enhances the reinforcing efficacy of a fatty food, even in the absence of operationally defined binge-type consumption of that food.

The results of the present study indicate that the size of the incremental value of the PR schedule is critical in delineating differences between INT and D groups. While the PR1 schedule allowed for distinctions to be made ($INT > D$), the PR3 schedule did not. The PR3 results are similar to those reported by Wojnicki, et al. [20] when an exponential PR schedule was used. In that study, PR performance did not differ between INT and D groups when shortening was the only reinforcer available. The lower ratio increment required by the PR1 in the present study appears to be more appropriate for assessing differences in the reinforcing efficacy of shortening in non-food-deprived rats, than are higher ratio increments such as those required by PR3 or exponential schedules.

There are several procedural differences between the previous [20] and present studies. The former study examined operant performance during both pre- and post-binge periods, while the present study examined operant performance during only the post-binge period. Due to the pre-binge assessment in the former study, the rats in the former study were older and had more operant experience during the post-binge operant assessment period than the rats in the present study. The former study established responding on a fixed-ratio schedule of reinforcement (5, 10, 15, 20, 25, 30 and 40) for a shortening reinforcer under food-deprivation conditions. The present study established responding on only FR1 and FR3 schedules of reinforcement for shortening under food-deprivation conditions. The former study used 1-h operant sessions, while the present study used ½ hour sessions. The former study only used one PR schedule after extensive FR training, whereas the present study used two PR schedules after relatively brief FR training. Schedules were not crossed over (FR to PR, or PR to PR) in either the former or the present study due to the training involved. However, in the present study, even when rats were returned to PR1 after more extensive operant experience, differences between the INT and D groups still were seen. Thus, while order effects cannot be ruled out, the amount of operant experience did not appear to be critical to the results obtained.

Despite the differences noted above, the combined results suggest that the PR1 schedule of reinforcement is the most appropriate reinforcement schedule to evaluate reinforcing efficacy of shortening in non-food deprived rats, even with limited operant experience. Results were

not due to non-specific motoric impairment in the Daily rats, as they emitted an average of 85 ± 16 responses during the non-food-deprived FR3 session (data not shown). That is, the D rats clearly were capable of emitting far more than the 37 responses emitted during PR1. The present results confirm the statement of Richardson and Roberts [27] that “Which PR series is appropriate depends not only on the drug [reinforcer] under investigation, the type of subjects used and the length of the testing session, but on how the PR schedule is implemented.”

While the full cohort of INT rats earned more reinforcers during PR1 than did the full cohort of D rats ($n = 15/\text{group}$), the same result was obtained with the subgroups of INT and D rats that were matched for shortening intake during week 5 ($n = 7$ per group). Thus, the present study demonstrates that intermittent access to an optional fatty food, not bingeing on that food, is sufficient to enhance the reinforcing efficacy of the fatty option.

The differential responding under the PR1 reinforcement schedule by the subgroups, despite the near identical consumption of shortening in the home cage, suggests that one may apply the concepts of establishing operations [28] or potentiating variables [29]. These concepts encompass those contingency and environmental variables that can affect behavior in the context in which it occurs. For example, one can potentiate food as a reinforcer through the procedure of deprivation as measured by either time since the last meal or food-deprived body weight as a percentage of free-feeding weight. One can also potentiate food as a reinforcer by changing the magnitude of the reinforcer, e.g., access time or solute concentration when liquids are used, or by altering a solution from one substance that readily serves as a reinforcer to another that does not readily serve as a reinforcer, e.g., decreasing the concentration of a sucrose solution over sessions while increasing the alcohol concentration. In the present study, the intermittent presentation of shortening in the home cage when no experimenter operant was required potentiated shortening as a reinforcer in the operant chamber when an experimenter defined operant was required. While the INT and D subgroups consumed identical amounts of shortening during the 1-h period of access in the home cage, the breakpoint for the INT subgroup was significantly greater than the breakpoint for the D group.

The concepts of establishing operations and/or potentiating variables can be applied to studies that have used PR schedules to study drug self-administration. For example, Deroche-Gamonet et al., [30] divided rats into two groups based on levels of responding for cocaine during reinstatement after a period of withdrawal. The “high reinstatement” group had significantly higher break-points on progressive ratio than did the “low reinstatement” group. Stated otherwise, there was a higher potentiation for cocaine responding in the “high reinstatement” group than there was in the “low reinstatement” group. Similarly, Brennan et al., [13] reported that the PR breakpoint for various solutions of sucrose was higher in rats that spontaneously consumed higher amounts of freely available sucrose than in rats that consumed lower amounts.

The present study differs from these previous reports in that the two groups of rats were matched on two variables, i.e., body weight and overnight consumption of solid shortening, prior to the start of the study. The groups were only distinguished by their respective exposure to different bases of shortening availability in the home cage after the initial matching had taken place. This differential shortening experience resulted in different breakpoints (earned reinforcers) for shortening under the PR1 schedule. The present study cannot distinguish effects of access history from effects of current access. Nonetheless, the present results demonstrate that intermittent access to an optional source of dietary fat potentiates fat as a reinforcer in non-food deprived rats, as evidenced by higher PR breakpoints.

Few studies have examined differences in the reinforcing efficacy of food between binge and control subjects in humans. In one study, bulimic women responded differently under variable ratio schedules for food compared to control women. However, cumulative responding did not

differ between the two groups [31]. Several reports have shown increased reward sensitivity [32–34] and enhanced reactivity to food hedonics [35] among subjects with binge eating disorder compared to non-bingeing controls. Such differences between binge eaters and controls may well involve traits that promote binge vulnerability [35]. However, the present results indicate that a “state” induced by intermittent access to an optional fatty food can enhance the reinforcing efficacy/reward value of that food, and may also contribute to binge eating.

Why intermittent access to an optional fatty food would enhance the reinforcing efficacy of that food is not known. One explanation might involve uncertainty. Recent research has indicated the involvement of dopamine in neuronal processing involving reward probability and uncertainty [37–38]. In humans, binges are not always planned [26] and binge-to-binge intakes can vary widely for any given individual [36], i.e. there is a certain degree of uncertainty associated with bingeing. Furthermore, women with bulimia nervosa do not activate forebrain dopamine target regions appropriately when tested for self-regulatory control [39]. It is possible, then, that the intermittent and unpredictable consumption of fatty optional foods may induce dysfunctional dopamine signaling, enhance the reinforcing efficacy of fatty foods, and contribute to the escalation of binge behavior. Indeed, recent data from our group suggest differential involvement of dopamine in rats with INT and Daily fat access histories [10, 40–41]. In addition, the present data indicate that intermittent (and possibly unpredictable) consumption of fatty optional foods can enhance the reinforcing efficacy of those foods even in the absence of binge eating. If true in humans, this could make it difficult to reduce consumption of optional fatty snack-type foods, even among those who do not binge on those foods.

While the mechanisms that account for INT vs. Daily behavioral differences are not clear, the present results provide a sensitive behavioral assay for distinguishing these two groups that is not dependent upon the home cage binge behavior. This is an important advance, as measures of intake can be confounded by ceiling effects. The present results clearly demonstrate that, even when the home cage intakes are matched, the PR1 reinforcement schedule effectively distinguishes differences in behavior maintained by fat reinforcement induced by intermittent and daily access to an optional fatty food.

Acknowledgments

Support for this study by RO1-MH67943 (RLC)

References

1. Corwin RL. Binge-type eating induced by limited access in rats does not require energy restriction on the previous day. *Appetite* 2004;42:139–142. [PubMed: 15010177]
2. Corwin RL, Wojnicki FHE, Fisher JO, Dimitriou SG, Rice HB, Young MA. Limited access to a dietary fat option affects ingestive behavior but not body composition in male rats. *Physiol Behav* 1998;65:545–553. [PubMed: 9877422]
3. Davis JF, Melhorn SJ, Shurdan JD, Heiman JU, Tschop MH, Clegg DJ, Benoit SC. Comparison of hydrogenated vegetable shortening and nutritionally complete high-fat diet on limited access-binge behavior in rats. *Physiol Behav* 2007;92:924–30. [PubMed: 17689576]
4. Thomas MA, Rice HB, Weinstock D, Corwin RL. Effects of aging on food intake and body composition in rats. *Physiol Behav* 2002;76:487–500. [PubMed: 12126984]
5. Dimitriou SG, Rice HB, Corwin RL. Effects of limited access to a fat option on food intake and body composition in female rats. *Int J Eat Disord* 2000;28:436–445. [PubMed: 11054791]
6. Wojnicki FHE, Charny G, Corwin RL. Binge-type behavior in rats consuming trans-fat-free shortening. *Physiol Behav* 2008;94:627–9. [PubMed: 18499201]

7. Wojnicki FHE, Johnson DS, Corwin RLW. Access conditions affect binge-type shortening consumption in rats. *Physiol Behav* 2008;95:649–657. [PubMed: 18851983]
8. Avena NM, Rada P, Hoebel BG. Evidence for sugar addiction: behavioral and neurochemical effects of intermittent, excessive sugar intake. *Neurosci Biobehav Rev* 2008;32:20–39. [PubMed: 17617461]
9. Wojnicki FHE, Stine JG, Corwin RLW. Liquid sucrose bingeing in rats depends on the access schedule, concentration, and delivery system. *Physiol Behav* 2007;92:566–74. [PubMed: 17612580]
10. Wong KJ, Wojnicki FHE, Corwin RLW. Baclofen, raclopride, and naltrexone differentially affect intake of fat/sucrose mixtures under limited access conditions. *Pharmacol Biochem Behav* 2009;92:528–536. [PubMed: 19217918]
11. Yoneda T, Taka Y, Okamura M, Mizushige T, Matsumura S, Manabe Y, Tsuzuki S, Inoue K, Fushiki T. Reinforcing effect for corn oil stimulus was concentration dependent in an operant task in mice. *Life Sci* 2007;81:1585–1592. [PubMed: 17963789]
12. Ward SJ, Dykstra LA. The role of CB1 receptors in sweet versus fat reinforcement: effect of CB1 receptor deletion, CB1 receptor antagonism (SR141716A) and CB1 receptor agonist (CP-55940). *Behav Pharmacol* 2005;16:381–388. [PubMed: 16148442]
13. Brennan K, Roberts DCS, Anisman H, Merali Z. Individual differences in sucrose consumption in the rat: motivational and neurochemical correlates of hedonia. *Psychopharmacology* 2001;157:269–276. [PubMed: 11605082]
14. Cheeta S, Brook S, Wilner P. Effects of reinforcer sweetness and the D2/D3 antagonist raclopride on progressive ratio operant performance. *Behav Pharm* 1995;6:127–32.
15. Hodos W. Progressive ratio as a measure of reward strength. *Science* 1961;34:943–4. [PubMed: 13714876]
16. Reilly S. Reinforcement value of gustatory stimuli determined by progressive ratio performance. *Pharmacol Biochem Behav* 1999;63(2):301–11. [PubMed: 10371660]
17. Sclafani A, Ackroff K. Reinforcement value of sucrose measured by progressive ratio operant licking in the rat. *Physiol Behav* 2003;79:663–70. [PubMed: 12954407]
18. McGregor IS, Saharov T, Hunt GE, Topple AN. Beer consumption in rats: the influence of ethanol content, food deprivation, and cocaine. *Alcohol* 1999;17:47–56. [PubMed: 9895037]
19. Hodos W, Kalman G. Effects of increment size and reinforcer volume on progressive ratio performance. *J Exp Anal Behav* 1963;6(3):387–92. [PubMed: 13963807]
20. Wojnicki FHE, Roberts DCS, Corwin RLW. Effects of baclofen on operant performance for food pellets and vegetable shortening after a history of binge-type behavior in non-food deprived rats. *Pharmacol Biochem Behav* 2006;84:197–206. [PubMed: 16782181]
21. Brebner K, Phelan R, Roberts DCS. Effect of baclofen on cocaine self administration in rats reinforced under fixed-ratio 1 and progressive ratio schedules. *Psychopharmacology* 2000a;148:314–21. [PubMed: 10755745]
22. Brebner K, Phelan R, Roberts DCS. Intra-VTA baclofen attenuates cocaine self-administration on a progressive ratio schedule of reinforcement. *Pharmacol Biochem Behav* 2000b;66:857–62. [PubMed: 10973526]
23. Mobini S, Chiang TJ, Ho MY, Bradshaw CM, Szabadi E. Comparison of the effects of clozapine, haloperidol, chlorpromazine, and d-amphetamine on time-constrained progressive ratio schedule on a locomotor behaviour in the rat. *Psychopharmacol* 2000;152:47–54.
24. Roberts DCS, Andrews MM, Vickers GJ. Baclofen attenuates the reinforcing effects of cocaine in rats. *Neuropsychopharmacology* 1996;15(4):417–23. [PubMed: 8887996]
25. Buda-Levin A, Wojnicki FHE, Corwin RL. Baclofen reduces fat intake under binge-type conditions. *Physiol Behav* 2005;86:176–84. [PubMed: 16140347]
26. APA (American Psychiatric Association). *Diagnostic and Statistical Manual-IV-Text Revision*. American Psychiatric Association; Washington, DC: 2000.
27. Richardson NR, Roberts DCS. Progressive ratio schedules in drug self-administration studies in rats: a method to evaluate reinforcing efficacy. *J Neurosci Methods* 1996;66:1–11. [PubMed: 8794935]
28. Michael J. Distinguishing between discriminative and motivational functions of stimuli. *J Exp Anal Behav* 1982;57(1):149–55. [PubMed: 7057126]

29. Goldiamond, I. The Blue Books: Goldiamond & Thompson's Functional Analysis of Behavior. Andronis, editor. Cambridge Center for Behavior Analysis; 2004.
30. Deroche-Gamonet V, Belin D, Piazza V. Evidence for addiction-like behavior in the rat. *Science* 2004;305:1014–17. [PubMed: 15310906]
31. Bulik CM, Brindley EC. The effect of food deprivation on the reinforcing value of food and smoking in bulimic and control women. *Physiol Behav* 1994;55(4):665–72. [PubMed: 8190792]
32. Davis C, Levitan RD, Kaplan AS, Carter J, Reid C, Curtis C, Patte K, Hwang R, Kennedy JL. Reward sensitivity and the D2 dopamine receptor gene: A case-control study of binge eating disorder. *Prog Neuropsychopharmacol Biol Psychiatry* 2008a;32:620–8. [PubMed: 18262320]
33. Davis C, Levitan RD, Carter J, Kaplan AS, Reid C, Curtis C, Patte K, Kennedy JL. Personality and eating behaviors: a case-control study of binge eating disorder. *Int J Eat Disord* 2008b;41:243–50. [PubMed: 18095308]
34. Schienle A, Schäfer A, Hermann A, Vaitl D. Binge-eating disorder: reward sensitivity and brain activation to images of food. *Biol Psychiatry* 2009 Apr 15;65(8):654–61. [PubMed: 18996508]
35. Davis CA, Levitan RD, Reid C, Carter JC, Kaplan AS, Patte KA, King N, Curtis C, Kennedy JL. Dopamine for “Wanting” and Opioids for “Liking”: A Comparison of Obese Adults With and Without Binge Eating. *Obesity* (Silver Spring). 2009 Mar 12; Epub ahead of print.
36. Kirkley BG, Burge JC, Ammerman A. Dietary restraint, binge eating, and dietary behavior patterns. *Int J Eat Dis* 1988;7:771–778.
37. Fiorillo CD, Tobler PN, Schultz W. Discrete coding of reward probability and uncertainty by dopamine neurons. *Science* 2003;299:1898–902. [PubMed: 12649484]
38. Schlösser RG, Nenadic I, Wagner G, Zysset S, Koch K, Sauer H. Dopaminergic modulation of brain systems subserving decision making under uncertainty: a study with fMRI and methylphenidate challenge. *Synapse* 2009;63:429–42. [PubMed: 19184997]
39. Marsh R, Steinglass JE, Gerber AJ, Graziano-O'Leary K, Wang Z, Murphy D, Walsh BT, Peterson BS. Deficient activity in the neural systems that mediate self-regulatory control in bulimia nervosa. *Arch Gen Psychiatry* 2009;66:51–63. [PubMed: 19124688]
40. Corwin RL, Wojnicki FH. Baclofen, raclopride, and naltrexone differentially affect intake of fat and sucrose under limited access conditions. *Behav Pharmacol* 2009;20:537–48. [PubMed: 19724193]
41. Rao RE, Wojnicki FHE, Coupland J, Ghosh S, Corwin RLW. Baclofen, raclopride, and naltrexone differentially reduce solid fat emulsion intake under limited access conditions. *Pharm Biochem Behav* 2008;89:581–590.

Figure 1.

Shortening intake and reinforcers earned when all rats ($n=15$ each group) were included in the analysis. Top panel: total shortening consumed during home cage sessions (week 5, prior to operant sessions) and total shortening consumed in the home cage and the operant sessions (1st PR1, PR3, 2nd PR1). Bottom panel: reinforcers earned during operant sessions. Asterisks indicate differences between D and INT groups ($p < 0.05$). Different letters indicate significant differences among different operant sessions in the D group; different numbers indicate significant differences among different operant sessions in the INT group ($p < 0.05$).

Figure 2.
Shortening intake and reinforcers earned when matched subgroups (n=7 each group) were included in the analysis. See Figure 1 for labeling details.