Binge Eating PronenessEmerges During Puberty in FemaleRats: A Longitudinal Study

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Puberty is a critical risk period for binge eating and eating disorders characterized by binge eating. Previous research focused almost entirely on psychosocial risk factors during puberty to the relative exclusion of biological influences. The current study addressed this gap by examining the emergence of binge eating during puberty in a rat model. We predicted that there would be minimal differences in binge eating proneness during pre-early puberty, but significant differences would emerge during puberty. Two independent samples of female Sprague-Dawley rats (n = 30 and n = 36) were followed longitudinally across pre-early puberty, mid-late puberty, and adulthood. Binge eating proneness was defined using the binge eating resistant (BER)/binge eating prone (BEP) model of binge eating that identifies BER and BEP rats in adulthood. Across two samples of rats, binge eating proneness emerged during puberty. Mixed linear models showed little difference in palatable food intake between BER and BEP rats during pre-early puberty, but significant group differences emerged during mid-late puberty and adulthood. Group differences could not be accounted for by changes in nonpalatable food intake or body weight. Similar to patterns in humans, individual differences in binge eating emerge during puberty in female rats. These findings provide strong confirming evidence for the importance of biological risk factors in developmental trajectories of binge eating risk across adolescence.

Keywords: binge eating, puberty, animal models, bulimia nervosa, eating disorders

Studies of girls provide evidence that puberty is a critical risk period for the eventual development of eating disorders characterized by binge eating [e.g., bulimia nervosa (BN)] (American Psychiatric Association, 2000; Bulik, 2002). Bulimic syndromes rarely occur in prepubertal girls, and puberty marks an increase in risk for bulimic symptoms (American Psychiatric Association, 2000; Bulik, 2002). Rates of bulimic symptoms increase significantly with advancing pubertal development (Bulik, 2002; Garber, Brooks-Gunn, Paikoff, & Warne, 1994; Killen et al., 1992) and predict the development of BN later in adolescence (Bulik, 2002; Striegel-Moore, Silberstein, & Rodin, 1986). Studies further suggest that risk for BN is associated with the timing of pubertal development. Early maturing girls are at increased risk for BN and binge eating both during (Attie & Brooks-Gunn, 1989; Kaltiala-Heino, Marttunen, Rantanen, & Rimpela, 2003; Kaltiala-Heino, Rimpela, Rissanen, & Rantanen, 2001) and after puberty (Bulik, 2002; Fairburn et al., 1997; Zehr, Culbert, Sisk, & Klump, 2007). Thus, although the onset of full bulimic syndromes is typically in late adolescence (American Psychiatric Association, 2000), symptoms contributing to their development appear to increase during puberty.

Theories accounting for pubertal risk focus almost exclusively on the psychosocial effects of the physical changes of puberty (e.g., increased body dissatisfaction) (Bulik, 2002; Garber et al., 1994). Although these psychological processes play a role, puberty is associated with numerous biological changes (Wilson, Foster, Kronenberg, & Larsen, 1998) that are very likely to contribute as well. Animal models represent powerful tools for confirming a role for biological influences on behavioral phenotypes without the confounds of psychosocial factors. The presence of increased pubertal risk for binge eating in animals would provide strong confirming evidence of biological influences, as animals do not experience key psychosocial risk factors (e.g., increased body dissatisfaction) during puberty.

Fortunately, rat models for binge eating in adulthood are well established (Corwin & Buda-Levin, 2004), and several exhibit face validity for binge eating in humans. The Boggiano rat model of binge eating (Boggiano et al., 2007) is promising in this regard. This model identifies binge eating resistant (BER) and binge eating prone (BEP) female rats based on the consumption of intermittently presented, highly palatable food (PF; foods that are high in fat and sugar with little nutritional value; e.g., vanilla frosting) in adulthood. BER rats are those that consistently consume small amounts of intermittently presented PF across testing days, while BEP rats are those that consistently consume high
amounts of PF across testing days. Importantly, BER/BEP differences in PF intake are present upon the very first feeding test (Boggiano et al., 2007); thus, group differences are not simply learned preferences resulting from repeated exposure to PF but are instead preexisting differences that are immediately manifested upon first experience with PF.

The BER/BEP model shows good face validity for the binge eating that occurs in BN syndromes. BER rats binge eat on highly PF but do not binge eat on standard rat chow (a less PF) (Boggiano et al., 2007; Oswald, Murabaugh, King, & Boggiano, 2011). The consumption of chow is equal in BER and BEP rats, suggesting that while both BER and BEP rats prefer PF over chow (as do humans), only BEP rats do not limit their caloric intake in the presence of PF (Boggiano et al., 2007; Oswald et al., 2011). BER rats also may experience a lack of control over their binge episodes, as they endure increasingly high levels of pain (via footshock) in order to consume PF (Oswald et al. 2011). In contrast, BER rats do not endure incremental footshock in order to consume PF (Oswald et al. 2011). In women, binge episodes are intermittent and discrete (i.e., lasting only a few hours) (Boggiano et al., 2007). The BER/BEP framework models this time course by alternating feeding test days with chow only days (making binge eating intermittent) and focusing on the first four hours of PF access (making binge eating discrete) (Boggiano et al., 2007).

The BEP rats do not differ significantly from BER rats in body weight (Boggiano et al., 2007). A similar proportion (i.e., 50% each) of BER and BEP rats are prone to diet-induced obesity (Boggiano et al., 2007), suggesting that the BEP phenotype is not simply an obesity prone group of rats. The distribution of binge eating in the BER/BEP model also resembles that observed in women. While binge eating exists on a continuum (from low to high), some women are binge prone while other women are binge resistant. The BER/BEP model includes a continuum of binge eating (from low to high) but also identifies rats who are resistant to binge eating and rats who are prone to binge eating (Boggiano et al., 2007). Finally, BER rats are more likely to binge eat in the presence of risk factors, such as stress (Boggiano et al., 2007; Smyth et al., 2007). Indeed, the effects of stress in BER/BEP rats resemble those in women for both the BER group (i.e., they are unlikely to binge eat, even in the presence of stress) and the BEP group (e.g., they are more likely to binge eat and increase binge eating in the presence of stress).

In summary, the BER/BEP model represents many of the phenomenological and distributional qualities of binge eating in women. Like other animal models of binge eating (Corwin & Buda-Levin, 2004), binge eating in BER/BEP rats cannot map entirely onto the binge eating observed in humans, as it is difficult to design an experiment to test all of the cognitive and behavioral aspects (e.g., loss of control) of binge eating in animals. Nonetheless, the BER/BEP model represents several key features of binge eating in women. The model is also highly amenable to a developmental design, as it is relatively easy to implement and does not require extensive or lengthy pretesting manipulations (e.g., repeated cycles of food restriction) (Corwin & Buda-Levin, 2004) that would be difficult to perform across the brief prepubertal and pubertal periods in rats.

In conclusion, we used the BER/BEP model to conduct a longitudinal investigation of binge eating risk across prepuberty, puberty, and adulthood in female rats. We predicted that binge eating phenotypes would emerge during puberty, such that the two phenotypes would be indistinguishable during prepuberty but would emerge during puberty and persist into adulthood. In order to confirm that observed effects were robust, we examined this hypothesis in two independent samples of rats followed longitudinally across pubertal development.

**Method**

**Animals**

Sixty-six (n = 30 for Experiment 1, n = 36 for Experiment 2) weaning female Sprague–Dawley rats were obtained from Harlan (Madison, Wisconsin) at postnatal Day 19 (i.e., P19). Animals were singly housed in clear Plexiglas cages (45 × 23 × 21 cm) and given ad lib access to water and chow (Rodent diet 8640; Harlan Teklad Global Diets, Madison, WI). Animals were maintained on a 12/12-hr light–dark cycle (lights on at 2400 h; off at 1200 h) and the temperature was maintained at 21 ± 2°C. All animals were treated in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals, and all protocols were approved by the Michigan State Institutional Animal Care and Use Committee.

**Experimental Design**

**Experiment 1**

Feeding tests followed standard BER/BEP protocols (Boggiano et al., 2007; Oswald et al., 2011) and began on postnatal Day 23 (P23). At the beginning of each test, approximately 15–25 g (with increasing amounts with age) of Betty Crocker Vanilla Frosting (General Mills Inc., Minneapolis, MN) was placed in a small petri dish in the subject’s home cage along with premeasured chow (~300–400 g) placed into a well on the wire cage top. The petri dish was secured to a wire hook that was hung over the cage wall, and the dish could not easily fall into the bedding on the cage floor. These foods were given just before lights out, and the petri dish was weighed before it was given to the rat, and again 1, 2, 4, and 24 hr later. Rats were given open access to both the frosting and the chow during the 24-hr feeding test period. The Chow and petri dishes with any remaining frosting were then removed at the 24-hr time point. Body weight was also assessed every day before lights out. Feeding tests were given 3×/wk (Monday, Wednesday, Friday) from P23 through P69, and chow was provided ad lib between feeding test days. However, during puberty (P39 and P58; see definition below), the 3×/wk feeding tests were decreased to a single maintenance feeding test that was given one day per week only. The frequency of feeding tests was decreased during the pubertal period so that preferences for PF could continue to be tracked during this time while minimizing access to high-fat food during this period of rapid body weight gain and hormonal changes associated with reproductive maturation.

Rats were examined daily upon arrival in the laboratory, and the age at which vaginal opening occurred was used as the indicator of the onset of puberty. All rats experienced the onset of puberty between feeding Test 6 (P34) and 7 (P39), and so feeding Tests 1–6 (P23-P34) fell in the pre-early puberty classification, and feeding Tests 7–10 (P39-P58) were classified as mid-late puberty.
Following standard classifications of adulthood in female rats (Spear, 2000), adulthood was defined as starting at postnatal Day 60 and included feeding Tests 11–15 (P60-69). Thus, rats received six feeding tests in pre-early puberty, four feeding tests in mid-late puberty, and five feeding tests in adulthood.

**Experiment 2**

Experiment 2 was identical to Experiment 1 with two exceptions. First, we continued feeding tests 3×/week during puberty rather than conducting 1×/week maintenance tests. The purpose of this modification was to ensure that effects observed in Experiment 1 were not attributable to differences in the spacing of the feeding tests during mid-late puberty (i.e., 1×/week) versus pre-early puberty and adulthood (i.e., 3×/week).

Second, in Experiment 2, pubertal onset (day of vaginal opening) was more variable, as 11 rats experienced the onset of puberty between feeding Tests 5 (P32) and 6 (P34), 21 rats showed puberty onset between feeding Tests 6 and 7 (P37), and four rats fell between feeding Tests 7 and 8 (P39). We therefore classified which feeding tests occurred in the pre-early puberty and mid-late puberty stages for each rat individually (e.g., for the 11 early onset rats, pre-early puberty was feeding Tests 1–5, and mid-late puberty was classified as feeding Tests 6–16). Adulthood was again defined at postnatal Day 60 in all rats and included feeding Tests 17–21 (P60–P69). Thus, rats received 5–7 feeding tests during pre-early puberty, 9–11 feeding tests during mid-late puberty, and 5 feeding tests in adulthood.

**Statistical Analyses**

Statistical analyses were identical in Experiments 1 and 2. We followed the Boggiano et al. method (Boggiano et al., 2007; Oswald et al., 2011) for identifying BER and BEP rats by examining tertiles of 4-hr PF intake across the five feeding tests that took place in adulthood. Our focus on the 4-hr intakes comes from previous research with the BER/BEP model (Boggiano et al., 2007; Oswald et al., 2011) and other rat models of binge eating (Boggiano et al., 2005; Hagan, Chandler, Wauford, Rybak, & Oswald, 2003; Hagan et al., 2002) confirming that measurable binge eating can be consistently observed and measured during this time interval. After establishing tertiles for PF intake on each individual feeding test day, we identified BER rats as those that ate in the lowest tertile of PF intake on at least three of the five feeding test days (i.e., 60% of the feeding tests), and who never ate in the highest tertile for any feeding test. By contrast, BER rats were those that ate in the highest tertile of PF intake on at least three of five testing days, and never ate in the lowest tertile during any feeding test. Notably, the proportion of BER or BEP rats in a population could range from 0–100% (i.e., there is no constraint on the number of BER/BEP rats identified) because the BER/BEP definition is based on the frequency and consistency of PF intake across testing days rather than PF tertiles for any given day. This focus on binge eating frequency and consistency closely follows methods for defining binge eating status in eating disorders (e.g., binge eating disorder) where women who binge eat at least 2×/week for three consecutive months (American Psychiatric Association, 2000) are considered to be binge eaters or “binge prone” while those who rarely binge eat are considered nonbinge eaters or “binge resistant.” Much like the BER/BEP model, the cut-offs for determining these binge eating groups were based on statistical comparisons of women at the high versus low end of the binge eating distribution (American Psychiatric Association, 1997).

After identifying BER and BEP rats in adulthood, our primary analyses used mixed linear models (MLM) to compare changes in PF intake, chow intake, and body weight across pre-early puberty, mid-late puberty, and adulthood in BER versus BEP rats. We used an autoregressive (lag 1) error structure to model the residual covariance from one feeding trial to the next. In the MLM analysis, the upper-level unit of analysis was the rat (i.e., the level at which observations are independent) and the lower-level unit of analysis was the feeding test (i.e., level at which outcome scores are measured). BER/BEP status was an upper-level predictor (i.e., it varied from rat to rat), and developmental stage was a lower-level predictor (i.e., it varied across feeding tests). When the outcome was PF intake, we expected to find a significant stage by BER/BEP group interaction, where differences in PF intake would be minimal during pre-early puberty and would increase significantly during mid-late puberty and into adulthood. We conducted these same analyses with chow intake and body weight as dependent variables to ensure that observed effects were not due to changes in these other potentially relevant variables.

Similar to previous work (Boggiano et al., 2007; Oswald et al., 2011), our primary analyses focused on the 4-hr PF and chow intakes as dependent variables. However, because our prepubertal rats were significantly younger than the adult rats examined in previous work (Boggiano et al., 2007), we conducted follow-up analyses using the 24-hr PF intake in the prepubertal rats and the 4-hr intake in pubertal and adult rats. These analyses were used to confirm that biological constraints on the amount of food that could be consumed in a short period of time (i.e., 4 hours) early in development did not unduly influence results. By examining the 24-hr intake in prepubertal rats only, we were able to account for prepubertal rats’ smaller size and directly test whether effects remain when prepubertal rats are given more time to consume PF.1

Although previous work with the BER/BEP model has focused entirely on the categorical BER and BEP groupings, this categorical approach results in a loss of data, as rats that score intermediate to these groups are excluded from analyses. Moreover, methodologists have argued against breaking continuous measures into dichotomies for a number of reasons (see MacCallum, Zhan, Preacher, & Rucker, 2002). We therefore made use of the continuous “binge proneness” variable that counted the number of times each rat scored in the highest tertile of PF intake during the five adult feeding tests (score range = 0–5). This variable was calculated for all rats in both experiments (n = 30 in Experiment 1, n = 36 in Experiment 2) and then grand mean centered and included as the upper-level predictor in the MLM in place of the BER/BEP categorical variable.

Because of the relatively large number of statistical tests conducted across all analyses, we used a conservative p value of .01.

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1 We also conducted these analyses using 24-hr PF intake across all three developmental states (i.e., prepuberty, puberty, and adulthood). Results remained largely unchanged from those reported herein (data not shown), albeit with somewhat decreased BER/BEP group differences in PF intake during puberty in Study 2 only (p = .03 vs. p < .01).
Results

Experiment 1

We identified 10 BER (10/30; 33%) and 10 BEP (10/30; 33%) rats in adulthood. This proportion is on par with rates observed in previous work (Boggiano et al., 2007; Oswald et al., 2011) and suggests that roughly 1/3 of rats consistently consume high levels of PF across multiple testing days (BEP rats), 1/3 consistently consume low levels of PF (BER rats), and the remaining 1/3 were inconsistent in their PF intake and/or ate only moderate amounts of PF.

Table 1 includes means and standard deviations for BER/BEP rats at each developmental stage, and $F$ tests from the MLM for the main effects of stage, the main effects of BER/BEP status, and the interaction between these two variables. The main effects of developmental stage and BER/BEP group were significant such that 1) all rats ate more PF as they developed, and 2) BEP rats ate more PF than did BER rats. These differences would be expected given the advancing age of the animals and the ways in which the BER/BEP groups were determined. More importantly, there was a significant stage $\times$ BER/BEP group interaction, indicating that PF intake differed significantly across stage by BER/BEP group status. As shown in the top panel of Figure 1, in pre-early puberty, BER and BEP rats did not differ in the amount of PF they consumed, but at both mid-late puberty and adulthood, BER rats ate substantially more PF than did BER rats. Tests of simple main effects confirmed these impressions, as there were no significant differences in PF intake between BER and BEP rats in pre-early puberty, $t(31) = 0.08, p = .94$, but significant mean differences between groups during mid-late puberty, $t(27) = 2.54, p < .01$, and adulthood, $t(34) = 7.03, p < .01$. These findings remained unchanged when models included 24-hr PF intake in prepubertal rats and 4-hr PF intake in pubertal and adult rats. The interaction between BER/BEP status and developmental stage remained statistically significant, $F(2, 124) = 8.37, p < .01$, and mean differences in BER (M = 4.42, SD = 1.12) and BEP (4.78, SD = 1.41) rats’ consumption of PF were nonsignificant during prepuberty, $F(1, 23) = 0.49, p = .52$.

Importantly, BER/BEP group differences also could not be accounted for by differences in chow intake or body weight during any stage. Although there were significant main effects of stage, there were no main effects of BER/BEP group status, and the stage $\times$ BER/BEP group interaction was nonsignificant for both variables (see Table 1, and middle and bottom panels of Figure 1). The lack of significant difference in body weight is similar to what has been observed previously (Boggiano et al., 2007) and is likely attributable to the fact that 1) access to PF is only provided intermittently every 3 days and 2) BEP rats did not consume larger amounts of chow on nonfeeding test days, $F(1, 205) = 0.81, p = .37$. Overall, these findings suggest that differences in PF intake by stage and BER/BEP status are unlikely to be attributable to differences in chow intake or body weight.

Identical results were obtained using the continuous binge proneness variable in the full sample of rats ($n = 30$). As with the categorical BER/BEP groupings, the main effects of stage, $F(2, 199) = 338.37, p < .01$, and binge proneness, $F(1, 131) = 41.14, p < .01$, and the stage $\times$ binge proneness interaction, $F(2, 199) = 22.21, p < .01$, were significant for PF intake. By contrast, for chow intake and body weight, there were no significant main effects of binge proneness [Chow: $F(1, 97) = .02, p = .90$; Body weight: $F(1, 24) = .00, p = .95$] and no significant stage $\times$ binge proneness interactions [Chow: $F(2, 197) = .55, p = .58$; Body weight: $F(2, 412) = .04, p = .96$]. These findings suggest that our results are not attributable to the dichotomization of BER and BEP rats but instead reflect the full distribution of binge proneness.

Table 1
Means, Standard Deviations (SD), and $F$-Tests Comparing BER Rats to BEP Rats Over Three Stages of Development for Experiment 1

<table>
<thead>
<tr>
<th>BER/BEP group</th>
<th>Pre-early puberty</th>
<th>Mid-late puberty</th>
<th>Adulthood</th>
<th>Stage main effect</th>
<th>BER/BEP main effect</th>
<th>Stage by BER/BEP interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palatable food</td>
<td></td>
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</tr>
<tr>
<td>BER M</td>
<td>2.20</td>
<td>4.07</td>
<td>4.97</td>
<td>$F(2, 131) = 217.07^{**}$</td>
<td>$F(1, 89) = 41.36^{**}$</td>
<td>$F(2, 131) = 17.74^{**}$</td>
</tr>
<tr>
<td>(SD)</td>
<td>(.89)</td>
<td>(1.36)</td>
<td>(1.27)</td>
<td></td>
<td></td>
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<tr>
<td>BEP M</td>
<td>2.18</td>
<td>5.00</td>
<td>7.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(SD)</td>
<td>(.93)</td>
<td>(1.72)</td>
<td>(1.69)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Chow</td>
<td></td>
<td></td>
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<tr>
<td>BER M</td>
<td>2.20</td>
<td>4.02</td>
<td>4.35</td>
<td>$F(2, 125) = 33.37^{**}$</td>
<td>$F(1, 63) = .70$</td>
<td>$F(2, 125) = .24$</td>
</tr>
<tr>
<td>(SD)</td>
<td>(1.16)</td>
<td>(1.26)</td>
<td>(1.75)</td>
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<tr>
<td>BEP M</td>
<td>2.20</td>
<td>3.76</td>
<td>4.01</td>
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<td></td>
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<tr>
<td>(SD)</td>
<td>(1.05)</td>
<td>(1.01)</td>
<td>(2.00)</td>
<td></td>
<td></td>
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<tr>
<td>Body weight</td>
<td></td>
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<td></td>
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<tr>
<td>BER M</td>
<td>67.52</td>
<td>150.60</td>
<td>193.77</td>
<td>$F(2, 273) = 46.52^{**}$</td>
<td>$F(1, 15) = .001$</td>
<td>$F(2, 273) = .02$</td>
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<tr>
<td>(SD)</td>
<td>(19.36)</td>
<td>(23.71)</td>
<td>(10.11)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>BEP M</td>
<td>68.64</td>
<td>150.54</td>
<td>193.53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(SD)</td>
<td>(17.65)</td>
<td>(25.55)</td>
<td>(16.65)</td>
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</table>

Note. BER = binge eating resistant; BEP = binge eating prone; Stage = pre-early puberty, mid-late puberty, or adulthood. Pre-early puberty included feeding tests 1–6, mid-late puberty included feeding tests 7–10, and adulthood included feeding tests 11–15.

** $p < .01$. 

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Experiment 2

In Experiment 2, we again identified a sizable number of BER (7/36; 19%) and BEP (11/36; 30%) rats in adulthood. The proportion of BER rats was somewhat smaller in Experiment 2 (19%) than Experiment 1 (30%); this highlights the fact that, similar to what is observed in women, the proportion of BER and BEP rats can vary by population despite general trends toward particular prevalence rates (e.g., ~20–30%) across samples (Boggiano et al., 2007; Oswald et al., 2011).

In the MLM, there were significant main effects of stage and BER/BEP group status, and the stage × BER/BEP group interaction was again statistically significant (see Table 2). Figure 2 and tests of simple effects confirmed that BEP/BER differences in PF intake increased across development, as group differences were not statistically significant during pre-early puberty, $t(17) = 2.04$, $p = .06$, but were statistically significant during both mid-late puberty, $t(23) = 3.26$, $p < .01$, and adulthood, $t(25) = 6.94$, $p < .01$. Consistent with Experiment 1, these findings did not appear to be unduly influenced by our use of 4- versus 24-hr intakes of PF during prepuberty. When 24-hr PF intakes during prepuberty only were included in the models, the stage by BER/BEP group interaction continued to be significant, $F(2, 166) = 4.56$, $p = .01$. Although group differences in prepuberty and 24-hr PF intakes between BER ($M = 4.69$, $SD = 0.80$) and BEP ($M = 5.77$, $SD = 1.26$) rats were larger than those observed in Experiment 1, $t(20) = 2.86$, $p = .01$, they were smaller than the group differences observed during mid-late puberty and adulthood (see Tables 1 and 2).

Also similar to findings for Experiment 1, the main effects of BER/BEP group and the stage by BER/BEP group interactions were nonsignificant for both chow intake and body weight (see Table 2 and Figure 2). The lack of significant BER/BEP group differences in body weight again appears to be attributable to the fact that BER rats did not consume significantly larger amounts of chow than BER on nonfeeding test days, $F(1, 129) = 4.04$, $p = .05$. Indeed, the small group differences that were observed were attributable to slightly larger amounts of 24-hr chow intakes in the BER ($M = 13.45$, $SD = 0.21$) relative to the BEP rats ($M = 12.93$, $SD = 0.16$) on nonfeeding test days.

Finally, analyses of the continuous binge proneness variable in the full sample of rats ($n = 36$) yielded very similar findings. As with the categorical BER/BEP groupings, the main effects of stage [$F(2, 300) = 193.38$, $p < .01$] and binge proneness [$F(1, 103) = 77.06$, $p < .01$], and the stage × binge proneness interaction [$F(2, 299) = 11.02$, $p < .01$] were significant for PF intake. Chow consumption and body weight showed no significant main effects of binge proneness [Chow: $F(1, 181) = .13$, $p = .72$; Body weight: $F(1, 30) = .01$, $p = .91$] and no significant stage by binge proneness interactions [Chow: $F(2, 287) = .34$, $p = .72$; Body weight: $F(2, 712) = .29$, $p = .75$].

Discussion

This is the first study to examine the emergence of binge eating proneness during puberty in animals. Results revealed dramatic increases in the binge prone phenotype across puberty, such that there was little evidence of individual differences in binge proneness during pre-early pubery but significant differences during mid-late puberty and adulthood. Developmental effects were robust across two independent samples and categorical as well as continuous definitions of binge prone status. These findings are significant in suggesting that increases in binge eating and eating disorders characterized by binge eating during and after puberty may be at least partially attributable to biological factors. Indeed, the presence of these phenotypic effects in animals strongly suggests that factors other than psychological influences (e.g., increased body dissatisfaction) contribute to individual differences in binge eating risk in females during puberty.

The BER/BEP rats we identified in adulthood closely resembled those identified previously in terms of their patterns of PF intake, chow intake, and body weight. The BEP phenotype also resembles several aspects of binge eating observed in humans, including a preferential increases in PF (but not chow) consumption, particularly in response to stress (Boggiano et al., 2007; Oswald et al., 2011). Nonetheless, the percentage (~30%) of adult rats identified as binge prone in our and previous research (Boggiano et al., 2007; Oswald et al., 2011) is higher than estimates of binge eating in older adolescent and young adult women (~10–19%) (Gauvin, Steiger, & Brodeur, 2009; Haines, Neumark-Sztainer, Eisenberg, & Hannan, 2006; Hay, Mond, Buttner, & Darby, 2008; Jones, KLUMP, SUISMAN, CULBERT, KASHY, AND SISK
BENNIT, OLMSTED, LAWSON, & RODIN, 2001). In addition, the BEP rats do not experience the weight losses and gains commonly observed in women with binge eating. These differences highlight the continuing gaps in our knowledge regarding the face validity of the BER/BEP and other animal models of binge eating.

However, an alternative interpretation is that these differences may not be surprising when one considers that BER rats do not experience the negative environmental (e.g., social disapproval) and psychological (e.g., guilt, self-blame, fears of weight gain) consequences (Fairburn, Marcus, & Wilson, 1993) of binge eating that are common in women who binge eat. These negative consequences likely act as social and physical constraints on binge eating in women, such that a smaller proportion of women develop binge eating, and they engage in compensatory behaviors (e.g., dieting) that cause physical (i.e., weight fluctuations) and psychological (e.g., weight suppression; Butryn, Lowe, Safer, & Agras, 2006; Lowe, Thomas, Safer, & Butryn, 2007) features of women. Associations have been observed across the menstrual cycle where it can be confirmed that changes in ovarian hormones drive changes in binge eating rather than the reverse.

Of these two classes of hormones, it seems more likely that ovarian hormones play a role in the pubertal manifestation of binge eating phenotypes. Ovarian hormones drive pubertal development in females in both rats and humans (Wilson et al., 1998). Of these two classes of hormones, it seems more likely that ovarian hormones play a role in the pubertal manifestation of binge eating phenotypes. Ovarian hormones drive pubertal development in females in both rats and humans (Wilson et al., 1998) and show phenotypic (Edler, Lipson, & Keel, 2007; Klump, Cubert, Edler, & Keel, 2008) as well as genetic associations (Klump, Keel, Sisk, & Burt, 2010) with binge eating. For example, binge eating is negatively associated with estradiol levels, and positively associated with progesterone levels, in clinical (i.e., BN women) (Edler, Lipson, & Keel, 2007) and nonclinical (Klump et al., 2008) samples of women. Associations have been observed across the menstrual cycle where it can be confirmed that changes in ovarian hormones drive changes in binge eating rather than the reverse. These apparent causal relationships are not surprising given extant animal data showing that experimental manipulations of both hormones (via ovariectomy, hormone administration) cause predictable changes in food intake in a variety of species (Asarian &

### Table 2

<table>
<thead>
<tr>
<th>BER/BEP group</th>
<th>Pre-early puberty</th>
<th>Mid-late puberty</th>
<th>Adulthood</th>
<th>Stage main effect</th>
<th>BER/BEP main effect</th>
<th>Stage by BER/BEP interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palatable food</td>
<td></td>
<td></td>
<td></td>
<td>F(2, 159) = 69.69**</td>
<td>F(1,47) = 39.20**</td>
<td>F(2, 159) = 7.86**</td>
</tr>
<tr>
<td>BER M</td>
<td>2.25</td>
<td>3.41</td>
<td>4.72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(SD)</td>
<td>(0.47)</td>
<td>(1.18)</td>
<td>(1.26)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BER M</td>
<td>2.72</td>
<td>4.69</td>
<td>7.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(SD)</td>
<td>(0.76)</td>
<td>(1.38)</td>
<td>(1.26)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BER M</td>
<td>2.04</td>
<td>4.83</td>
<td>5.47</td>
<td>F(2, 138) = 93.5**</td>
<td>F(1,83) = .70</td>
<td>F(2, 138) = .34</td>
</tr>
<tr>
<td>(SD)</td>
<td>(1.13)</td>
<td>(1.30)</td>
<td>(1.66)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BER M</td>
<td>1.88</td>
<td>4.80</td>
<td>5.19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(SD)</td>
<td>(0.91)</td>
<td>(1.47)</td>
<td>(1.81)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body weight</td>
<td></td>
<td></td>
<td></td>
<td>F(2, 354) = 15.27**</td>
<td>F(1,14) = .000</td>
<td>F(2, 354) = .37</td>
</tr>
<tr>
<td>BER M</td>
<td>81.09</td>
<td>164.59</td>
<td>214.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(SD)</td>
<td>(19.97)</td>
<td>(25.90)</td>
<td>(15.65)</td>
<td></td>
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<tr>
<td>BER M</td>
<td>85.14</td>
<td>163.42</td>
<td>214.39</td>
<td></td>
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</tr>
<tr>
<td>(SD)</td>
<td>(20.02)</td>
<td>(25.90)</td>
<td>(13.32)</td>
<td></td>
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</tr>
</tbody>
</table>

Note. BER = binge eating resistant; BEP = binge eating prone; Stage = pre-early puberty, mid-late puberty, or adulthood. Pre-early puberty and mid-late puberty varied by rat, but occurred between feeding tests 1–7 and 6–16, respectively, for the full sample. Adulthood occurred between feeding tests 17 and 21 for all rats. **p < .01.
Geary, 2006). Indeed, a recent study confirmed that estradiol reduces fat intake under binge-like conditions in ovariectomized, adult female rats (Yu, Geary, & Corwin, 2008).

Ovarian hormones also exhibit genetic associations with binge eating. Previous research suggests that the heritability of disordered eating is activated at puberty, such that genes account for 0% of the heritability during prepuberty and ~50% during and after puberty (Culbert, Burt, McGue, Iacono, & Klump, 2009; Klump, McGue, & Iacono, 2003; Klump, Perkins, Burt, McGue, & Iacono, 2007). Follow-up research has confirmed a role for estradiol in these effects. After dividing twins by high versus low estradiol levels during puberty, Klump et al. (2010) found no evidence for genetic effects on binge eating and disordered eating in twins with low estradiol levels but significant genetic effects in twins with high estradiol levels. Findings remained unchanged when controlling for age, body mass index, and the physical changes of puberty (e.g., breast development), suggesting direct effects of estradiol on genetic risk for binge eating and disordered eating.

Taken together, previous data suggest that the emergence of individual differences in binge eating during puberty may be attributable to increases in ovarian hormones in females during this important developmental stage. These increases may "activate" genetic risk in vulnerable individuals and lead to increased expression of, and individual differences in, binge eating in both rats and humans. Unfortunately, our data are unable to directly examine this hypothesis, as we did not directly manipulate ovarian hormone exposure or examine gene expression. Future animal research should directly examine these possibilities by experimentally manipulating ovarian hormones (e.g., via ovariectomy) before, during, and after puberty to determine whether the emergence of individual differences in binge proneness is dependent upon the presence of these hormones. Ideally, these investigations would also investigate gene expression patterns within the central nervous system (CNS) in order to identify neural systems that contribute to individual differences in binge proneness.

Despite the strengths of our study (e.g., longitudinal data, replication across two samples), there are limitations that must be noted. First, although the BER/BEP model appears promising for understanding biological influences on binge eating, it cannot be determined for certain that the phenotype is the same as that observed in humans. Additional work examining the validity of the model is needed, including continued efforts to model cognitive (e.g., loss of control) and behavioral (e.g., weight suppression; Butryn et al., 2006; Lowe et al., 2007) symptoms of eating disorders in BEP versus BER rats.

Second, sample sizes in our BER/BEP groups were small in both experiments. Although our use of categorical and continuous measures of binge proneness partially addressed this concern, future research should examine larger samples of rats to replicate our results. Finally, because of limited resources for this internally funded project, we were unable to identify causal mechanisms underlying puberty’s effects. Additional research should investigate the role of ovarian hormones and other biological factors to understand the mechanisms underlying developmental changes in binge eating across puberty.

### References


![Figure 2. Patterns of mean PF intake (top panel), chow intake (middle panel), and body weight (bottom panel) as a function of binge eating resistant (BER) and binge eating prone (BEP) status across development for Experiment 2. Because of the large number of feeding tests in Experiment 2 (i.e., 21 tests), every other feeding test (rather than every feeding test) is pictured in the graph.](image-url)

Figure 2. Patterns of mean PF intake (top panel), chow intake (middle panel), and body weight (bottom panel) as a function of binge eating resistant (BER) and binge eating prone (BEP) status across development for Experiment 2.


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