Estradiol treatment increases CCK-induced c-Fos expression in the brains of ovariectomized rats

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Received 28 May 2002; accepted in final form 16 August 2002

Eckel, Lisa A., Thomas A. Houpt, and Nori Geary. Estradiol treatment increases CCK-induced c-Fos expression in the brains of ovariectomized rats. Am J Physiol Regul Integr Comp Physiol 283: R1378–R1385, 2002; 10.1152/ajpregu.00300.2002.—The ovarian hormone estradiol reduces meal size and food intake in female rats, at least in part by increasing the satiating potency of CCK. Here we used c-Fos immunohistochemistry to determine whether estradiol increases CCK-induced neuronal activation in several brain regions implicated in the control of feeding. Because the adiposity signals leptin and insulin appear to control feeding in part by increasing the satiating potency of CCK, we also examined whether increased adiposity after ovariectomy influences estradiol’s effects on CCK-induced c-Fos expression. Ovariectomized rats were injected subcutaneously with 10 μg 17β-estradiol benzoate (estradiol) or vehicle once each on Monday and Tuesday for 1 wk (experiment 1) or for 5 wk (experiment 2). Two days after the final injection of estradiol or vehicle, rats were injected intraperitoneally with 4 μg/kg CCK in 1 ml/kg 0.9 M NaCl or with vehicle alone. Rats were perfused 60 min later, and brain tissue was collected and processed for c-Fos immunoreactivity. CCK induced c-Fos expression in the nucleus of the solitary tract (NTS), area postrema (AP), paraventricular nucleus of the hypothalamus (PVN), and central nucleus of the amygdala (CeA) in vehicle- and estradiol-treated ovariectomized rats. Estradiol treatment further increased this response in the caudal, subpostremal, and intermediate NTS, the PVN, and the CeA, but not in the rostral NTS or AP. This action of estradiol was very similar in rats tested before (experiment 1) and after (experiment 2) significant body weight gain, suggesting that adiposity does not modulate CCK-induced c-Fos expression or interact with estradiol’s ability to modulate CCK-induced c-Fos expression. These findings suggest that estradiol inhibits meal size and food intake by increasing the central processing of the vagal CCK satiation signal.

Estradiol reduces meal size, at least in part, by increasing the potency of peripheral satiation signals involved in meal termination (26). The most extensively studied such interaction involves CCK, a peptide that is released from the small intestine during meals and binds to low-affinity CCK-1 receptors on vagal afferents of the pylorus and proximal duodenum to initiate a negative-feedback satiation signal (30, 54, 56). Estradiol treatment increases the satiating potency of exogenous CCK in ovariectomized rats (9, 26, 29, 39). More importantly, the satiating potency of endogenous CCK is increased during estrus in gonadally intact rats and by estradiol treatment in ovariectomized rats (3, 18).

Neurons that may participate in the central processing of meal-generated signals controlling food intake have been identified in several brain areas by immunohistochemical detection of c-Fos protein, the product of the immediate-early gene c-fos (50, 51). In male rats, intraperitoneal injection of CCK increases CCK expression in several brain regions including the nucleus of the solitary tract (NTS), area postrema (AP), dorsal motor nucleus of the vagus (DMNV), lateral parabrachial nucleus (LPBN), paraventricular nucleus of the hypothalamus (PVN), and central nucleus of the amygdala (CeA) (12, 38, 46, 51, 52). c-Fos immunohistochemistry has also been applied to the analysis of estradiol’s inhibitory effects on feeding. We recently

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ovaRian estradiol exerts potent inhibitory effects on feeding in a variety of species. This action of estradiol is prominent in rats, in which spontaneous feeding is decreased during the nocturnal phase of estrus after the cyclic increase in estradiol secretion that begins in diestrus and peaks in the diurnal phase of proestrus (7, 17, 20, 37). This inhibition of feeding is mediated by a reduction in meal size, with meal frequency often increased (7, 17, 20, 37). Studies of ovariectomized rats directly link the estral reduction in meal size with estradiol. Ovariectomy tonically increases meal size, abolishes the cyclic estral reduction in nocturnal meal size, increases daily food intake, and contributes (together with decreases in locomotor and metabolic activity) to body weight gain (1, 7, 26, 27, 57). A cyclic regimen of estradiol treatment, designed to mimic the changes in plasma estradiol levels across the estrous cycle, normalized meal size, food intake, and body weight gain to the levels observed in gonadally intact rats (5). Thus estradiol apparently participates in the normal control of meal size in female rats.

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demonstrated that estradiol treatment increases feeding-induced c-Fos expression in the NTS, PVN, and CeA in ovariectomized rats (19). As reviewed above, CCK is an important component of the satiating action of ingested food, and estradiol increases the satiating potency of CCK. Therefore, in the present experiments, we used c-Fos immunohistochemistry to determine whether estradiol increases CCK-induced neuronal activation in ovariectomized rats.

We used a cyclic regimen of estradiol treatment introduced by McEwen and colleagues (43, 53). In this regimen, ovariectomized rats receive estradiol each Monday and Tuesday and are tested on Thursdays, which models estrus in intact rats. When progesterone is injected 4 h before tests, this regimen increases sexual receptivity (lordosis) to estrous levels (43, 53). In addition, even in the absence of progesterone, this estradiol regimen induces tonic and cyclic decreases in food intake and meal size (27, 44), increases running wheel activity (44), normalizes body weight (3, 27, 29, 44), and cyclically increases CCK’s satiating potency (3, 29). Both the increased sexual receptivity and the decreased feeding are evident after the first pair of estradiol injections and recur similarly through months of repeated treatments (27, 44, 53).

In male rats, treatment with leptin or insulin increases exogenous CCK’s satiating potency (6, 23, 41, 42, 49), and leptin increases CCK-induced c-Fos in the NTS, AP, and PVN (23). Leptin also increases c-Fos expression in the NTS and PVN after intragastric or intraduodenal nutrient infusions (22). These interactive effects of leptin are similar to the effects of estradiol on CCK satiation and food-induced c-Fos expression in ovariectomized rats. As leptin and insulin are thought to mediate the inhibitory effect of increased adiposity on feeding (25, 58), it is possible that increased adiposity alone might increase CCK-induced c-Fos expression in ovariectomized rats and obscure the effects of estradiol. Therefore, here we probed estradiol’s effects on CCK-induced c-Fos expression both 1 and 5 wk postovariectomy, i.e., before and after ovariectomy-induced body weight gain.

METHODS

Animals and Surgery

Forty-one adult female Long-Evans hooded rats (Charles River Breeding Laboratories, Wilmington, MA; weighing 200–225 g at study onset) were housed individually in hanging cages with wire mesh floors. Rats were given free access to rat chow (Purina 5001, St. Louis, MO) and tap water unless otherwise noted. The room was maintained at 20 ± 2°C with a 12:12-h light/dark cycle (dark onset 1400). Two red 25-W incandescent bulbs provided dim illumination during the dark period. After 1 wk of adaptation to these conditions, rats were anesthetized by intraperitoneal injection of 1 ml/kg of a mixture of 70 mg/ml ketamine (Ketaset, Fort Dodge, IA) and 4.5 mg/ml xylazine (Rompun, Mobay, Shawnee, KS) and bilaterally ovariectomized using an intra-abdominal approach. Estradiol treatment began 1 wk postoperatively. All procedures were approved by the Weill Medical College of Cornell University Institutional Animal Care and Use Committee and comply with the American Physiological Society’s “Guiding Principles for Research Involving Animals and Human Beings” (2).

Estradiol and CCK Treatment

Experiment 1: CCK-induced c-Fos expression in ovariectomized rats after acute estradiol treatment. Ovariectomized rats were assigned to one of two groups of approximately equal body weight. One group (n = 10) received intrascapular subcutaneous injections of 10 μg 17β-estradiol-3-benzoate (estradiol; Sigma) in 100 μl sesame oil vehicle (Sigma), and the other group (n = 9) received 100 μl vehicle alone. Injections were done on Monday and Tuesday at 1000. On Thursday, 22-h food-deprived rats were intraperitoneally injected with 4 μg/kg CCK-8 (generously donated by the Bristol-Myers-Squibb Pharmaceutical Research Institute) or 1 ml/kg 0.15 M saline vehicle, 1 h after dark onset (1400). Rats were anesthetized 60 min after injection of CCK or saline, and brain tissue was collected and processed for c-Fos-like immunoreactivity as described below. At this time, estradiol-treated rats had gained 13 ± 4 g since ovariectomized and vehicle-treated rats had gained 21 ± 3 g, a nonsignificant difference, t(17) = 1.41, P > 0.05.

Experiment 2: CCK-induced c-Fos expression in ovariectomized rats after chronic estradiol treatment. Ovariectomized rats were assigned to one of two groups of approximately equal body weight. One group (n = 12) received intrascapular subcutaneous injections of 10 μg estradiol in 100 μl sesame oil vehicle each Monday and Tuesday for 5 wk, and the other group (n = 10) received 100 μl vehicle alone. On Thursday of the 5th wk of treatment, 22-h food-deprived rats were intraperitoneally injected with 4 μg/kg CCK or 1 ml/kg 0.15 M saline vehicle and anesthetized and perfused as above. At this time, oil-treated rats had gained significantly more body weight than estradiol-treated rats, 85 ± 5 vs. 25 ± 4 g, t(20) = 9.15, P < 0.0001.

Perfusion and Tissue Collection

One hour after injection of CCK or saline, rats were anesthetized with pentobarbital sodium (65 mg/kg ip; Nembutal, Butler, Columbus, OH) and transcardially perfused with 100 ml of a heparinized 0.9% NaCl solution containing 0.5% NaNO2, followed by 400 ml of 4% paraformaldehyde in 0.1 M phosphate buffer (PB). The brains were then removed, postfixed in 4% paraformaldehyde for 2 h at room temperature, and cryoprotected in 30% sucrose solution at 4°C for 48 h. Hindbrain blocks were mounted on a freezing, sliding microtome, and 60 consecutive 40 μm coronal sections were cut beginning at the obex and moving anterior. This area corresponds to the region between 14.4 and 12.0 mm posterior to bregma in the atlas of Paxinos and Watson (47). Forebrain blocks were cut similarly into 100 consecutive sections from the optic chiasm (0.1 mm posterior to bregma) through the median eminence (4.1 mm posterior to bregma).

Immunohistochemistry

Every second hindbrain section and every fourth forebrain section were processed for c-Fos-like immunoreactivity. Free-floating tissue sections were washed in PBS, blocked in a PBS solution containing 0.2% Triton X-100 and 1% BSA for 30 min, washed in a PBS solution containing 0.5% BSA (PBS/BSA), and incubated 20 h at room temperature with rabbit polyclonal anti-c-Fos peptide antisera (Ab-5, Oncogene Sciences, Cambridge, MA) diluted 1:20,000 in PBS/BSA. Sections were then washed in PBS/BSA and incubated 1 h at
room temperature with a biotinylated anti-rabbit goat antibody (Vector Laboratories, Burlingame, CA) diluted 1:200 in PBS/BSA. Bound secondary antibody was amplified during a 1 h incubation of the sections in an avidin-biotin complex (Vectastain ABC Elite Kit, Vector Laboratories) diluted 1:50 in PBS/BSA. Antibody complexes were visualized by immersing the tissue in 2% diaminobenzidine solution (Kirkegaard and Perry Laboratories, Gaithersburg, MD) for 5 min. This reaction was stopped by rinsing the sections in PB. Sections were then mounted on microscopeslides and placed under coverslips with Permoun (Fisher Scientific, Atlanta, GA).

Quantification of c-Fos-Like Immunoreactivity

The presence of c-Fos-like immunoreactivity was quantified using Image-Pro Plus software (V3.0, MediaCybernetics, Gaithersburg, MD). A constant set of threshold criteria based on optical density, object shape, and object size was used to identify c-Fos-positive cells containing dark, punctate, nuclear staining. c-Fos-like immunoreactivity was examined in several brain regions implicated in mediating the effects of estradiol, CCK and leptin, i.e., the NTS, the AP, the PVN, the CeA, the ventromedial hypothalamus (VMH), the medial preoptic area (MPOA), and the arcuate nucleus (ARC). To provide a more detailed account within the NTS, the preoptic area (MPOA), and the arcuate nucleus (ARC). To CeA, the ventromedial hypothalamus (VMH), the medial estradiol, CCK and leptin, i.e., the NTS, the AP, the PVN, the several brain regions implicated in mediating the effects of clear staining. c-Fos-like immunoreactivity was examined in identify c-Fos-positive cells containing dark, punctate, nu-

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Data Analysis

Data are presented as means ± SE. In experiment 1 (acute treatment), the numbers of c-Fos-positive cells were analyzed using separate two-factor ANOVAs (steroid treatment by peptide treatment) in each brain region. In experiment 2 (chronic treatment), c-Fos data were first analyzed using separate three-factor ANOVAs (body weight gain by steroid treatment by peptide treatment) in each brain region because we were interested in the possibility that ovariectomy-in-

RESULTS

Experiment 1: CCK-Induced c-Fos Expression in Ovariectomized Rats After Acute Estradiol Treatment

There was little c-Fos expression in the NTS and AP after saline injection in both estradiol- and vehicle-treated rats. Intraperitoneal injection of CCK induced large increases in c-Fos expression in the cNTS, spNTS, and iNTS and a smaller increase in the rNTS (Figs. 1 and 2). In the cNTS, spNTS, and iNTS, estradiol treatment increased the number of CCK-induced c-Fos-positive cells but did not affect c-Fos expression in saline-treated control rats (Fig. 2, A–C); interaction effects, \(F(1,15) = 6.51–9.40, P < 0.05, \text{SED} = 4–5\) cells. The magnitude of the increase in c-Fos expression in estradiol-treated rats ranged from 105 to 185%. In contrast, estradiol treatment did not affect CCK-induced c-Fos expression in the rNTS or the AP (Figs. 2D and 4A); main effects of CCK, \(F(1,15) = 4.71, P < 0.05, \text{SED} = 1\) cell, and \(F(1,15) = 7.39, P < 0.01, \text{SED} = 11\) cells, respectively; main effects of estradiol and interaction effects, not significant. 

There were low levels of c-Fos expression in the PVN and CeA after saline injection in both estradiol-treated and untreated rats. Intraperitoneal injection of CCK increased c-Fos expression in the PVN and CeA (Figs. 3 and 4). In both regions, estradiol treatment increased the number of CCK-induced c-Fos-positive cells but did not affect c-Fos expression in saline-treated control rats (Fig. 4, B and C); interaction effects, \(F(1,15) = 5\) cells.
Fig. 2. Estradiol treatment increased CCK-induced c-Fos expression within regions of the NTS of ovariectomized rats. Data, means ± SE, are from experiment 1, in which rats were tested 2 wk postovariectomy, 2 days after subcutaneous injections of 10 µg estradiol benzoate or sesame oil vehicle on 2 consecutive days. Intraperitoneal injection of 4 µg/kg CCK significantly increased c-Fos expression within each region of the NTS, relative to saline-treated (SAL) rats. Estradiol treatment significantly increased the amount of CCK-induced c-Fos expression in the caudal NTS (cNTS, A), subpostremal NTS (spNTS, B), and intermediate NTS (iNTS, C), but not in the rostral NTS (rNTS, D).

*Greater than saline-treated rats, P < 0.05; †estradiol-treated rats greater than vehicle-treated rats, P < 0.05.

Fig. 3. Representative photomicrographs of coronal hemisections through the paraventricular nucleus (PVN; A-C) and central nucleus of the amygdala (CeA, D-F) after intraperitoneal injection of 4 µg/kg CCK in estradiol- and vehicle-treated rats in experiment 1, in which rats were tested 2 wk postovariectomy, 2 days after subcutaneous injections of 10 µg estradiol benzoate or sesame oil vehicle on 2 consecutive days. CCK induced large increases in c-Fos expression in the PVN and CeA. Estradiol treatment increased this response in both regions. Boxes in A and D depict the area of the PVN and the CeA photographed at higher magnification in (B, C, E, F). Scale bar = 100 µm. SON, supraoptic nucleus of the hypothalamus; SCN, suprachiasmatic nucleus; opt, optic tract; III, third ventricle.
14.55 and 5.90, *P < 0.05, SED = 15 and 11 cells, respectively. The magnitude of the increase in c-Fos expression in estradiol-treated rats was ~75% in the PVN and ~50% in the CeA. There were no apparent differences in the number of c-Fos-positive cells in the magnocellular or parvocellular subdivisions of the PVN. Examination of the VMH, MPOA, and ARC failed to reveal any c-Fos expression after CCK treatment.

**Experiment 2: Effects of Estradiol on CCK-Induced c-Fos Expression After Chronic Estradiol Treatment**

The results closely paralleled those of experiment 1. Intraperitoneal injection of CCK induced large increases in c-Fos expression in the cNTS, spNTS, and iNTS, and a small increase in the rNTS (Table 1). In the cNTS, spNTS, and iNTS, estradiol treatment increased the number of CCK-induced c-Fos-positive cells but did not affect c-Fos expression in saline-treated control rats (Table 1); interaction effects, $F(1,19) = 4.48–5.32$, *P < 0.05, SED = 5–7 cells. In contrast, estradiol treatment did not affect CCK-induced c-Fos expression in the rNTS or the AP (Table 1); main effects of CCK, $F(1,19) = 10.46$, *P < 0.01, SED = 1 cell, and $F(1,19) = 23.71$, *P < 0.001, SED = 6 cells, respectively; main effects of estradiol and interaction effects, not significant.

Intraperitoneal injection of CCK also increased c-Fos expression in the PVN and CeA (Table 1). In both regions, estradiol treatment increased the number of CCK-induced c-Fos-positive cells but did not affect c-Fos expression in saline-treated control rats (Table 1); interaction effects $F(1,19) = 4.29$ and 4.28, *P < 0.05, SED = 13 and 10 cells, respectively. There were no apparent differences in the number of c-Fos-positive cells in the magnocellular or parvocellular subdivisions of the PVN. Examination of the VMH, MPOA, and ARC failed to reveal any increase in c-Fos expression after CCK treatment.

**DISCUSSION**

The satiating action of CCK on meal size is increased by estradiol treatment in ovariectomized rats (9, 26, 29, 39) and during estrus in intact, cycling rats (3, 18).

**Table 1. CCK-Induced c-fos expression in the NTS, AP, PVN, and CeA of ovariectomized rats after chronic estradiol or vehicle treatment**

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<td>Caudal NTS</td>
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<tr>
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Data, means ± SE, are from experiment 2. Ovariectomized rats received 5 wk of cyclic estradiol (2 daily subcutaneous injections of 10 μg estradiol benzoate per week) or sesame oil vehicle treatment. Ovariectomy-induced body weight gain was significantly reduced by estradiol treatment. Two days after the final injections of estradiol or vehicle, rats were injected with CCK or saline and perfused 1 h later. Brain tissue was processed for c-Fos immunohistochemistry and the number of c-Fos-positive cells per hemisection was quantified. CCK increased c-Fos expression in the nucleus of the solitary tract (NTS), area postrema (AP), paraventricular nucleus (PVN), and central nucleus of the amygdala (CeA). Chronic estradiol treatment increased this response in the caudal, subpostremal, and intermediate NTS, the PVN, and the CeA. *P < 0.01 compared with vehicle (Veh/saline (Sal) and E2/Sal. †P < 0.01 compared with Veh/CCK.

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*Fig. 4. Estradiol treatment increased CCK-induced c-Fos expression in the PVN and CeA, but not in the AP. Data, means ± SE, are from experiment 1, in which rats were tested 2 wk postovariectomy, 2 days after subcutaneous injections of 10 μg estradiol benzoate or sesame oil vehicle on 2 consecutive days. Intraperitoneal injection of 4 μg/kg CCK increased c-Fos expression in the AP (A), PVN (B), and CeA (C) relative to saline-treated rats. Estradiol treatment significantly increased the number of c-Fos-positive cells but did not affect c-Fos expression in saline-treated control rats. Estradiol treatment significantly increased the number of c-Fos-positive cells but did not affect c-Fos expression in saline-treated control rats (Table 1); interaction effects $F(1,19) = 4.29$ and 4.28, *P < 0.05, SED = 13 and 10 cells, respectively. There were no apparent differences in the number of c-Fos-positive cells in the magnocellular or parvocellular subdivisions of the PVN. Examination of the VMH, MPOA, and ARC failed to reveal any increase in c-Fos expression after CCK treatment.

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Here, we investigated whether estradiol treatment would also increase CCK-induced c-Fos expression in the brain. We concentrated our search on the NTS, the AP, the PVN, the VMH, the MPOA, and the CeA, areas that have been implicated in the control of feeding by CCK or estradiol (10, 11, 15, 34, 51). In addition, because the putative adiposity signals leptin and insulin increase CCK’s satiating potency (6, 23, 42, 49) and because leptin increases CCK’s potency to stimulate c-Fos expression in the NTS and the PVN (23), we tested ovariectomized rats both before and after significant body weight gain. We also examined c-Fos expression in the ARC, the site of leptin receptors affecting feeding (23).

Our major finding was that estradiol treatment increased CCK-induced c-Fos expression in the cNTS, the spNTS, the iNTS, the PVN, and the CeA and that postovariectomy body weight gain did not appear to affect this action of estradiol. This parallels previous observations that estradiol increases the satiating potency of CCK in tests of scheduled and spontaneous feeding (9, 26, 29, 39). As increases in c-Fos expression reflect increases in neuronal activity, these data suggest that estradiol decreases meal size and food intake in part by increasing the central processing of the CCK satiation signal. We also found that CCK increased c-Fos expression in the rostral NTS and the AP, but these responses were not modulated by estradiol treatment. Finally, CCK failed to increase c-Fos expression in the VMH, MPOA, or ARC of either estradiol- or vehicle-treated rats.

Intrapertoneal injection of 4 μg/kg CCK, which inhibits meal size by ~30–45% in female rats (24, 29), increased c-Fos expression in the NTS, AP, PVN, and CeA of ovariectomized rats, but in none of the other brain areas we investigated. This is similar to effects of 5–8 μg/kg CCK on c-Fos expression in male rats (38). Larger (10–100 μg/kg) doses of CCK induce more intense c-Fos expression in these areas in male rats and also recruit c-Fos expression in additional areas, including the dorsal motor nucleus of the vagus, ventrolateral medulla, and supraoptic nucleus of the hypothalamus (40, 51). This is likely due to the nonsatiating, aversive effects of such doses of CCK (56).

Our findings extend previous analyses of CCK’s effects on c-Fos responsivity in male rats (12, 38, 46, 51, 52) to female rats and provide a more detailed account of the distribution of c-Fos expression induced by satiating doses of CCK within the NTS than did previous studies. The intense c-Fos expression in the cNTS, spNTS, and iNTS and relatively weak expression in the rNTS observed here is consistent with the projection of abdominal vagal afferents thought to mediate satiation. That is, the terminal fields of the majority of vagal afferent fibers from the stomach, small intestine, and liver are in the cNTS, spNTS, and iNTS, whereas oropharyngeal vagal afferents terminate in the rNTS (8, 45). This suggests that the effects of CCK on neuronal activation within the NTS observed here mimic the effects of feeding-related signals in the upper abdomen, including food stimuli causing CCK secretion, increasing CCK-related vagal afferent electrophysiological activity, and causing satiation (54).

Estradiol treatment increased c-Fos expression elicited by CCK in the cNTS, spNTS, iNTS, PVN, and CeA. Because estradiol increases the satiating potency of CCK (9, 26, 29, 39), these increases in CCK-induced CCK in estradiol-treated rats may reflect increases in the activity of the neural networks mediating CCK satiation. The effects of food ingestion are parallel: CCK is an important mediator of the satiating action of ingested food (56), estradiol selectively increased the satiating action of intralipid, whose satiating effect is mediated by endogenous CCK (4), and estradiol increased the c-Fos expression that is induced by sweet milk ingestion in these same areas (19).

Our data extend two previous tests of the effects of estradiol on CCK-induced c-Fos expression. Flanagan-Cato et al. (24) reported that estradiol decreased CCK-induced c-Fos expression in the NTS and PVN of ovariectomized rats. It is difficult to suggest an explanation for the apparent discrepancy between these results and ours because the procedures of the two experiments were very similar. Our findings are consistent, however, with the report that estradiol treatment increased CCK-induced CCK expression in the NTS of ovariectomized mice (28). In this study, mice with an ER-α null mutation and their wild-type littermates were ovariectomized and implanted with slow-release pellets containing estradiol or vehicle. Intraperitoneal CCK injection increased c-Fos expression in the NTS of both ER-α knockout and wild-type mice, but estradiol treatment increased CCK-induced CCK only in the wild-type mice and not in the ER-α null mice, indicating that ER-α is necessary for this action of estradiol and that ER-β alone is not sufficient (28).

ER-α is expressed in numerous areas of the rat brain (55). Because the NTS, PVN, and CeA are among these areas, our results are consistent with the possibility that estradiol may act in any of these sites to initiate its effect on meal size. The site(s) of the receptors mediating the estrogenic inhibition of feeding remains unclear. Some data implicate PVN estradiol receptors (10, 11), but other data (14, 36) are inconsistent with the hypothesis that PVN estradiol receptors are sufficient to account for the estrogenic inhibition of feeding. CCK injection slightly increased c-Fos expression in the rNTS, but estradiol did not affect this response. This selectivity of estradiol to the cNTS, spNTS, and iNTS is consistent with other evidence that estradiol selectively increases the satiating potency of gastrointestinal food stimuli without affecting the control of meal size by oropharyngeal food stimuli (35). CCK injection markedly increased c-Fos expression in the AP, as has previously been reported (38, 40). This is similar to the effects of consumption of several foods (chow, balanced liquid diets, and sucrose solutions) on c-Fos expression in male rats (16, 50), but differs from the effect of sweetened condensed milk ingestion, which did not increase c-Fos expression in the AP in female rats (19). Estradiol tended to increase c-Fos expression in response to CCK, but this was not significant. Thus the
role of the AP in satiation and in estradiol's influence on satiation requires further study.

Leptin, the protein product of the ob gene, and pancreatic insulin are secreted in proportion to body adiposity and appear to function as feedback signals involved in the control of food intake and body adiposity (58). Like estradiol, both leptin and insulin reduce food intake in rats by selectively reducing meal size with little effect on meal frequency (21, 58). Again like estradiol, leptin and insulin appear to reduce meal size by altering the potency of meal-generated signals involved in the promotion of satiation (6, 23, 42, 49). Moreover, exogenous leptin administration in male rats increases the potency by which CCK induces c-Fos expression (23). This suggested to us that estradiol's effects on CCK-induced c-Fos expression might be different in less adipose ovariectomized rats, which presumably secrete less leptin and insulin, than in more adipose rats. But we saw no difference in the patterns of c-Fos expression in ovariectomized rats tested 2 wk postovariectomy and rats tested 6 wk postovariectomy, which had gained >50 g more weight. This has two implications. First, it suggests that estradiol's effects on CCK-induced c-Fos expression are independent of body weight and adiposity. If estradiol interacts with adiposity signals, this interaction apparently fails to affect CCK-induced c-Fos expression. One study suggests that leptin insensitivity may be involved in the hyperphagia and body weight gain after ovariectomy (1), but other studies have failed to reveal changes in exogenous leptin's effect on food intake after ovariectomy (13, 48) or across the estrous cycle of gonadally sterilized rats. The finding of similar expression of c-Fos in ovariectomized rats before and after significant body weight gain is consistent with these reports that estradiol does not interact with leptin to control meal size in female rats. Second, the independence of CCK-induced c-Fos and body weight suggests that the effect of exogenous leptin on exogenous CCK-induced c-Fos expression (23) does not reflect a similar interaction between endogenous leptin and exogenous CCK.

Perspectives

We report here that estradiol treatment increased CCK-induced c-Fos expression in the cNTS, the spNTS, the iNTS, the PVN, and the CeA. Because CCK apparently mediates a major part of the estrogenic inhibition of feeding, which is expressed as decreased meal size (7, 27), these data suggest that estradiol affects neural activity in a widely distributed neural network controlling satiation. It is not yet possible to say what specific contribution to the process of satiation is made by any of these areas or what the relationships among the neural activities in different areas are. Because CCK satiation depends on vagal afferents (54) and because vagal afferents project to the NTS, the most parsimonious hypothesis appears to be that estradiol increases the responsivity of NTS neurons that are postsynaptic to vagal afferents encoding CCK satiation and that neurons in other brain areas in which activity is increased are downstream from these. This could occur whether estradiol acts locally in the NTS or acts in some other brain site containing ER-α that directly or indirectly projects to the NTS, such as the PVN or CeA. The latter alternative, that estradiol acts in the hypothalamus or limbic forebrain, would seem more in line with the known mechanisms of estradiol's actions on ovarian cycling and sexual receptivity. The former alternative, that estradiol acts in the NTS to affect feeding, is especially interesting in relation to the demonstrations by Grill and colleagues (31–33) that leptin, melanocortin-3/4 receptor agonists, urocortin, and other treatments that are usually assumed to act in the hypothalamus to affect feeding in fact have potent feeding effects when delivered locally to the fourth ventricle or NTS/dorsal vagal complex.

This work was supported by National Institutes of Health Grant DK-54523 (to N. Geary) and a Medical Research Council of Canada Fellowship (to L. A. Eckel).

REFERENCES
47. Paxinos G and Watson C. The Rat Brain in Stereotaxic Coor-

Differences in behavioral sensitivity to oxytocin...