GLP-1 receptor signaling contributes to anorexigenic effect of centrally administered oxytocin in rats

LINDA RINAMAN AND ELIZABETH E. ROTHE
Department of Neuroscience, University of Pittsburgh, Pittsburgh, Pennsylvania 15260

Received 9 January 2002; accepted in final form 22 March 2002

Rinaman, Linda, and Elizabeth E. Rothe. GLP-1 receptor signaling contributes to anorexigenic effect of centrally administered oxytocin in rats. Am J Physiol Regulatory Integrative Comp Physiol 283: R99–R106, 2002. —The present study examined possible interactions between central glucagon-like peptide-1 (GLP-1) and oxytocin (OT) neural systems by determining whether blockade of GLP-1 receptors attenuates OT-induced anorexia and vice versa. Male rats were acclimated to daily 4-h food access. In the first experiment, rats were infused centrally with GLP-1 receptor antagonist or vehicle, followed by an anorexigenic dose of synthetic OT. Access to food began 20 min later. Cumulative food intake was measured every 30 min for 4 h. In the second experiment, rats were infused with OT receptor blocker or vehicle, followed by synthetic GLP-1 [7–36 amide]. Subsequent food intake was monitored as before. The anorexigenic effect of OT was eliminated in rats pretreated with the GLP-1 receptor antagonist. Conversely, GLP-1-induced anorexia was not affected by blockade of OT receptors. In a separate immunocytochemical study, OT-positive terminals were found closely apposed to GLP-1-positive perikarya, and central infusion of OT activated c-Fos expression in GLP-1 neurons. These findings implicate endogenous GLP-1 receptors on OT-positive nerve fibers as an important downstream mediator of anorexia in rats after activation of central OT neural pathways. The anorexigenic effect of centrally administered oxytocin in rats.

CENTRAL INFUSION of either synthetic oxytocin (OT) or glucagon-like peptide-1 (GLP-1) inhibits deprivation-induced food intake in rats (1, 2, 13, 28, 30, 31). Hypothalamic OT- and hindbrain GLP-1-containing neurons are activated in rats after various treatments that promote anorexia; such treatments include systemic administration of lithium chloride, lipopolysaccharide, or cholecystokinin octapeptide (16, 17, 19, 32). Furthermore, pharmacological studies provided evidence that central OT and GLP-1 receptor signaling pathways contribute to the anorexigenic effects of several such treatments (5, 14, 15, 25).

OT neurons that project to sites within the brain are located in parvocellular subnuclei of the paraventricular nucleus of the hypothalamus (PVN) (27). GLP-1 neurons are located in the hindbrain, within and near caudal levels of the dorsal vagal complex (DVC) (8, 9, 11). Direct, reciprocal neural connections exist between the hypothalamic and hindbrain regions where OT and GLP-1 neurons are located (19, 20, 24, 26). Hypothalamic OT neurons express GLP-1 receptors (12, 33), and central administration of GLP-1 activates c-Fos expression in OT neurons (10). These findings suggest that the anorexigenic effect of centrally administered GLP-1 might result from activation of OT neurons and signaling pathways originating in the PVN. The present study was initiated to test this hypothesis. However, we also considered the possibility that the anorexigenic effect of centrally administered OT may be due to activation of hindbrain GLP-1 neurons and signaling pathways, because OT neurons are known to project to regions of the caudal brain stem where GLP-1 neurons are located. Thus we determined the effects on feeding of centrally administered GLP-1 in rats with and without prior blockade of OT receptors, and we also determined the effects on feeding of centrally administered OT in rats with and without prior blockade of GLP-1 receptors. In addition, immunocytochemical methods were used to determine whether OT-positive nerve fibers are associated with GLP-1-positive neurons in the caudal medulla and whether central administration of OT activates c-Fos expression in these neurons. Some of the results have been presented in abstract form (23).

MATERIALS AND METHODS

Animals. Male Sprague-Dawley rats (Zivic Miller, Zelionople, PA or Harlan Laboratories, Indianapolis, IN) were initially housed individually in hanging wire cages in a controlled environment (24°C, lights on from 0700 to 1900). In this environment, rats had ad libitum access to water and pelleted rat chow (Purina). All experimental procedures were reviewed and approved by the University of Pittsburgh Institutional Animal Care and Use Committee.

Cannulation procedures. Rats weighing 225–250 g were anesthetized with halothane (1.5–2% in oxygen) and placed into a stereotaxic frame with the incisor bar positioned 3.3 mm below horizontal zero. Rats were fitted with chronic indwelling 26-gauge stainless steel guide cannulas (Plastics One) aimed at the lateral ventricle. Guide cannulas were positioned 1.5 mm lateral to bregma on the coronal suture with the tip protruding 4.5 mm below the surface of the skull.

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
Cannulas were fixed to the skull with anchor screws and dental acrylic and fitted with removable obturators that extended 0.5 mm beyond the tip of the guide cannula.

Automated food intake measurements. At least 1 wk after surgery, rats with ventricular cannulas were moved in groups of 6–10 to a new environment (24°C, lights on from 0300 to 1500). Rats were housed individually in clear Plexiglas boxes (25 × 30 cm-floor, 22-cm height) with stainless steel rod floors, each equipped with a computer-driven pellet delivery and monitoring system (Med Associates). Drinking water was available ad libitum from sipper tubes within each box, but food access was restricted to a daily 4-h period beginning at lights out (1500). At lights out, a single 45-mg chow pellet (Precision Dustless Pellets, Bio-Serv, Frenchtown, NJ) was delivered automatically to a shallow feeding trough in each cage, thereby breaking a photobeam crossing the base of the trough. A new pellet was delivered automatically each time the rat removed the preceding pellet. The cumulative number of pellet deliveries (photobeam breaks) was recorded automatically every 30 min for the 4-h feeding period. Cage trays beneath the open rod floors were routinely inspected to ensure that delivered pellets were consumed. Data were collected and stored using Med PC software (Med Associates). Rats were acclimated to the new environment and feeding schedule for at least 1 wk before experimental manipulations, by which time stable 4-h daily food intakes of ~7–8% body wt were achieved. Rats were handled every 2 days for a brief period between 0100 and 0200 to record body weights, which remained steady or increased throughout each study. Because the rats’ body weights ranged from 261 to 293 g on testing days in these studies, food intake is expressed as percent body weight in each experiment.

Evaluation of antagonist efficacy and selection of peptide doses. Lyophilized peptides were dissolved in sterile 0.15 M NaCl no more than 30 min before infusion and were delivered intracerebroventricularly in a volume of 5 μl. The efficacy of the antagonists used to block OT receptors [d(CH2)5, Tyr(Me)2, Orn3]vasotocin; Peninsula Laboratories] and GLP-1 receptors (des His1 Glu5-exendin 4; American Peptides) has been reported (14, 15, 25, 29). The potency of each batch of the antagonists used to block OT receptors [d(CH2)5, Tyr(Me)2, Orn3]vasotocin; Peninsula Laboratories] and GLP-1 receptors (des His1 Glu5-exendin 4; American Peptides) has been reported (14, 15, 25, 29). The potency of each batch of antagonist used in the present study was also tested in pilot experiments associated with the present work. In the first pilot study (n = 6 rats), we determined that intracerebroventricular infusion of 10 μg of the OT receptor blocker by itself did not significantly affect cumulative 4-h food intake, but it did block the feeding-suppressive effect of synthetic OT (1 μg; Peninsula Laboratories) (Fig. 1A). Interestingly, the OT receptor antagonist did not attenuate the grooming behavior that was consistently elicited within 2–3 min after intracerebroventricular infusion of OT. In this first pilot experiment, we also determined that intracerebroventricular infusion of vehicle (0.15 M NaCl) did not affect cumulative 4-h food intake compared with the noninfused control condition (Fig. 1A). In the second pilot study (n = 5 rats), a similar approach was used to determine that 10 μg of GLP-1 receptor blocker infused alone did not significantly affect food intake, but it did block the feeding-suppressive effect of synthetic GLP-1 (7–36) amide (1 μg; Peninsula Laboratories) (Fig. 1B).

Feeding experiment 1. Rats (n = 11) were infused intracerebroventricularly with either 0.15 M NaCl vehicle or GLP-1 receptor antagonist (10 μg) followed 15 min later by synthetic OT (1 μg). Food access began 20 min after OT infusion, at lights out (1500). Cumulative pellet intake values were collected every 30 min for 4 h. Rats were tested twice, so that all 11 rats were included in both treatment conditions over 2 testing days, with 6 baseline days intervening. Baseline 4-h intakes were recorded on the day before each of the 2 testing days.

Feeding experiment 2. A separate group of rats (n = 9) was infused centrally with either 0.15 M NaCl vehicle or OT receptor antagonist (10 μg) followed 15 min later by infusion of GLP-1 (7–36) amide (1 μg). Food access began at lights out (1500), 20 min after GLP-1 infusion. Cumulative pellet intake values were collected every 30 min for 4 h. Rats were tested twice, so that all nine rats were included in both treatment conditions over 2 testing days, with 6 baseline days intervening. Baseline 4-h intakes were recorded on the day before each of the 2 testing days.

Food intake data analysis. Pellet delivery data for each rat were converted to grams (number of pellets × 45 mg), ex-
pressed as percent body weight (% BW), and then combined by experimental treatment group. Values are expressed as group means ± SE. Treatment-related differences in food intake within each experiment were tested for statistical significance by using one-way ANOVA, with the first infusion substance [vehicle, receptor blocker, or no infusion (baseline day)] as the independent variable. When F values indicated significant overall main treatment effects, ANOVA was followed up with post hoc t-tests using Dunn’s (Bonferroni) correction procedure to control for multiple comparisons. Differences were considered significant when P ≤ 0.05.

Veriﬁcation of intraventricular cannula placement. At the conclusion of each feeding study, rats were anesthetized (83 mg ketamine and 17 mg xylazine ip; Fort Dodge Labs), infused centrally with 5 μl of India ink (50% in distilled water), and perfused transcardially with 0.15 M NaCl (50 ml) followed by 4% paraformaldehyde (300 ml). Brains were removed from the skull and inspected visually for evidence of ventricular diffusion of ink. Ink was observed in the lateral, third, and fourth ventricles in each animal included in this report.

Immunocytochemical study. A separate group of rats with chronic lateral ventricular guide cannulas was infused centrally with 5 μl of vehicle (0.15 M NaCl; n = 5) or vehicle containing 1 μg OT (n = 5) between 1000 and 1100. Three additional rats were handled and had their guide cannula obturators loosened and retightened, but they received no central infusions. Four hours later, rats were anesthetized, infused centrally with 5 μl of 50% India ink, and perfused transcardially with 0.15 M NaCl (50 ml) followed by fixative (2% paraformaldehyde, 1% acrolein; 250 ml). Fixed brains were removed from the skull, bisected coronally at the level of the pineal gland, and inspected visually for evidence of ventricular diffusion of ink. Ink was observed in the lateral, third, and fourth ventricles in each animal included in this report.

Fixed brains were postfixed overnight in 4% paraformaldehyde (4°C), cryoprotected overnight in 20% aqueous sucrose (4°C), frozen, and sectioned coronally at 25-μm intervals using a sliding microtome. Tissue sections were collected serially into six adjacent sets. With the use of methods described previously (19), one set of brain stem sections was processed for dual immunoperoxidase localization of nuclear c-Fos (1:50,000; rabbit polyclonal antiserum kindly provided by Dr. P. Larsen; see Ref. 21) and perikaryal GLP-1 (1:10,000; rabbit polyclonal antiserum, Peninsula; see Ref. 19). In five rats, a second set of brain stem sections was processed for dual immunoperoxidase localization of OT (1:20,000; rabbit polyclonal antiserum, Peninsula) and GLP-1. For dual staining, c-Fos or OT immunolabels were generated using a nickel-enhanced diaminobenzidine (DAB) reaction to create a black immunoprecipitate, whereas GLP-1 immunolabel was subsequently generated using a nonenhanced DAB reaction to create a brown immunoprecipitate. Immunolabeled tissue sections were mounted onto Superfrost Plus glass slides (Fisher Scientific), cleared in graded alcohols and xylene, and placed under coverslips using Histomount (VWR).

The speciﬁcities of the rabbit polyclonal c-Fos, GLP-1, and OT antisera were veriﬁed in our laboratory by preabsorbing each antiserum at its working dilution with a 10 mg/ml solution of the appropriate synthetic immunogen. In each case, forebrain and brain stem immunoperoxidase labeling was abolished, providing evidence for antisera speciﬁcity.

Immunocytochemical data analysis. General patterns of treatment-related c-Fos expression were evaluated qualitatively by microscopic inspection of immunolabeled brain stem and forebrain sections. In addition, a quantitative analysis of c-Fos expression was conducted in brain stem tissue sections reacted for c-Fos and GLP-1. For this purpose, GLP-1-positive neurons in each rat were counted in six to eight hindbrain tissue sections (at 150-μm intervals) from the level of the pyramidal decussation caudally through the mid-area postrema rostrally. GLP-1-positive cells were identiﬁed by the presence of brown cytoplasmic immunoreactivity and were counted only when they displayed a visible nucleus. Cells were considered c-Fos positive when their nucleus contained blue-black nuclear immunoreactivity, regardless of intensity, and they were considered c-Fos negative when they displayed a visible nucleus lacking blue-black immunoreactivity. The number of GLP-1-positive neurons and the proportion that expressed c-Fos were determined for each rat; percentage activation values were then combined by treatment group and presented as means ± SE. Group differences in GLP-1 neuronal activation were tested for statistical signiﬁcance by using one-way ANOVA, with treatment condition (no central infusion, vehicle infusion, or OT infusion) as the independent variable. When F values indicated signiﬁcant overall main treatment effects, ANOVA was followed up with post hoc comparisons using Dunn’s (Bonferroni) correction procedure to control for multiple comparisons. Differences were considered signiﬁcant when P ≤ 0.05.

In five rats, an additional set of brain stem sections was processed for dual immunoperoxidase labeling of OT-containing fibers and terminals along with GLP-1-containing neurons, as described above. Each GLP-1-positive perikaryal profile (whether or not its nucleus was present in the section) was examined in all focal planes, using a ×40 microscope objective, to determine whether OT-immunolabeled fibers or terminals were present in close apposition. The proportion of GLP-1 neurons that were closely apposed by one or more OT-positive proﬁles was determined in each of the ﬁve cases. Combined values are presented as means ± SE.

RESULTS

Feeding experiment 1. Average cumulative baseline intakes on the days preceding each of the 2 experimental treatment days did not differ signiﬁcantly at any time point; thus these were combined to generate a single set of baseline values. As shown in Fig. 2, central administration of saline vehicle followed by OT (1 μg) signiﬁcantly suppressed food intake compared with baseline at each 30-min time point during the 4-h monitoring period (P ≤ 0.05 for each comparison). Central administration of GLP-1 receptor antagonist (10 μg) blocked the anorexigenic effect of OT, such that intake values in rats receiving the GLP-1 receptor blocker followed by OT (1 μg) were not signiﬁcantly different from baseline at any time point.

Feeding experiment 2. As in experiment 1, average baseline intakes on the days preceding each experimental treatment day did not differ signiﬁcantly, and so these data were combined to generate a single set of baseline values. As shown in Fig. 3, central administration of saline vehicle followed by GLP-1 (7–36) amide (1 μg) signiﬁcantly suppressed food intake relative to baseline at each time point examined during the 4-h monitoring period (P ≤ 0.05 for each comparison). Prior administration of OT receptor antagonist (10 μg) did not signiﬁcantly alter the anorexigenic effect of GLP-1 (7–36) amide at any time point during the 4-h monitoring period, such that food intake re-
R102 GLP-1 SIGNALING IN OT ANOREXIA

Fig. 3. Effect on food intake of centrally infused GLP-1 [(7–36) amide] (Saline; GLP-1) compared with the effect of central GLP-1 preceded by central OT receptor antagonist (OT rec X; GLP-1). Cumulative food intake was measured every 30 min for 4 h, beginning 20 min after the second intracerebroventricular infusion. Baseline intakes were recorded on the day before each experimental treatment day (see text). Intakes are expressed as % BW ± SE. GLP-1 dose = 1 µg in 5 µl saline vehicle; OT rec X dose = 10 µg in 5 µl saline vehicle. Cumulative intake values after central infusion of saline followed by OT are significantly smaller at each time point compared with baseline (P ≤ 0.05 for each comparison). Conversely, cumulative intakes are similar to baseline when central OT infusion is preceded by GLP-1 receptor blocker.

Fig. 4. Percentage of GLP-1-immunoreactive neurons activated to express c-Fos immediate-early gene product. Relatively few GLP-1-immunopositive fibers and terminals were coextensive with GLP-1-positive perikarya (Fig. 5C). Quantitative analysis revealed that OT-immunopositive fibers and/or terminals were closely apposed to the majority (81 ± 8%) of GLP-1-immunolabeled perikarya identified in the DVC and adjacent reticular formation.

Fig. 2. Effect on food intake of centrally infused OT (Saline; OT) compared with the effect of central OT preceded by central GLP-1 receptor antagonist (GLP-1 rec X; OT). Cumulative food intake was measured every 30 min for 4 h, beginning 20 min after the second intracerebroventricular infusion. Baseline intakes were recorded on the day before each experimental treatment day (see text). Intakes are expressed as % BW ± SE. OT dose = 1 µg in 5 µl saline vehicle; GLP-1 rec X dose = 10 µg in 5 µl saline vehicle. Cumulative intake values after central infusion of saline followed by OT are significantly smaller at each time point compared with baseline (P ≤ 0.05 for each comparison). Conversely, cumulative intakes remain significantly depressed compared with baseline when central GLP-1 infusion is preceded by OT receptor blocker (P ≤ 0.05 for each comparison).
DISCUSSION

Results from this study indicate that the anorexigenic effect of centrally infused OT is significantly attenuated in rats after pharmacological antagonism of central GLP-1 receptors, whereas the anorexigenic effect of centrally infused GLP-1 is fully maintained after blockade of central OT receptors. Our immunocytochemical data demonstrate that the majority of hindbrain GLP-1 neurons are activated to express c-Fos after central infusion of an anorexigenic dose of OT. Furthermore, the close apposition of OT-immunoreactive fibers and terminals with GLP-1-positive perikarya suggests that GLP-1 neurons might respond directly to endogenous OT released at synapses in the caudal medulla (a possibility that must be confirmed by ultrastructural analysis). The new findings presented here support the hypothesis that central GLP-1 neurons and signaling pathways play a functionally important role in treatment-induced anorexia in rats, including the well-known anorexia that results from activation of central OT neural signaling pathways.

No abnormal motor effects were produced by the dose of OT used in the present report (1 μg). This dose significantly suppressed food intake relative to baseline, although the magnitude of this effect (~26% average suppression across all time points) was smaller than the 50–60% suppression reported after central infusion of a higher dose of OT (13). We elected to use the lower effective dose in the present work because we found that a higher dose of synthetic OT (10 μg) sometimes caused barrel-rolling and seizurelike activity lasting ~5–10 min.

The 4-h postinfusion survival time used in the c-Fos expression study was based on preliminary work in which lateral ventricular infusion of 0.15 M NaCl vehicle activated c-Fos expression in the majority of hindbrain GLP-1-immunopositive neurons in rats killed 60–90 min after the intracerebroventricular infusion (23). Subsequent experiments indicated that vehicle-induced c-Fos expression in GLP-1 neurons was significantly reduced when rats were perfused 4 h after the intracerebroventricular infusion. Because the anorexigenic effect of centrally administered OT persisted for at least 3–4 h (see Fig. 2), a 4-h postinfusion survival interval was considered valid for analysis of OT-induced c-Fos expression that was temporally related to OT-induced anorexia but separable from the nonspecific effects of the intracerebroventricular infusion itself. Even in rats killed 4 h after infusion, however, approximately six times as many GLP-1 neurons were activated in rats after intracerebroventricular infusion of saline vehicle compared with the proportion activated in control rats that were handled but received no infusion. Nevertheless, central infusion of OT activated significantly more GLP-1 neurons compared with either control condition (i.e., ~18 times more than in noninfused controls and 3 times more than in vehicle-infused controls; see Fig. 4).

Despite our findings that central infusion of saline vehicle activated c-Fos expression in GLP-1 neurons,
vehicle infusion did not inhibit food intake in our pilot study (Fig. 1A). It is possible that intracerebroventricular saline produced a relatively transient anorexigenic effect that was not apparent in this study. Alternatively, the neuronal activation produced by intracerebroventricular saline infusion may simply be insufficient to suppress feeding in the absence of some other necessary signal. In this regard, vehicle-induced c-Fos expression in GLP-1 neurons is not accompanied by significant activation of either hindbrain catecholaminergic neurons or hypothalamic OT-positive neurons (23). In contrast, GLP-1-positive neurons, hindbrain catecholaminergic neurons, and OT-positive neurons are commonly activated by several treatments that inhibit food intake, such as systemic administration of lithium chloride (LiCl), cholecystokinin, or lipopolysaccharide (16, 17, 19, 22, 32).

Two previous reports indicated that endogenous central GLP-1 receptor signaling is an important factor underlying LiCl-induced anorexia (18, 25). However, the precise brain location(s) of receptors that mediate the presumed anorexigenic and/or nauseogenic effects of endogenous GLP-1 remain unclear. The present study was inspired by previous work suggesting a possible interaction of GLP-1 signaling pathways with central OT neurons. Hypothalamic regions that contain OT neurons are specifically targeted by GLP-1-immunoreactive axon terminals (9), and OT neurons are activated after central infusion of synthetic GLP-1 (10). Furthermore, pretreatment of rats with a central OT receptor antagonist reduces the anorectic effects of LiCl (14). Because the anorectic effects of LiCl are also attenuated after blockade of central GLP-1 receptors, we hypothesized that GLP-1 may inhibit food intake due to activation/recruitment of central OT signaling pathways. However, blockade of central OT receptors did not attenuate the anorexigenic effect of centrally infused GLP-1 in the present study. Instead, the converse was true: the anorexigenic effect of centrally infused OT was completely eliminated after pharmacological antagonism of central GLP-1 receptors.

These findings suggest that anorexigenic responses in which central OT neuronal pathways have been implicated may also include a functionally “downstream” role for GLP-1. In addition to its role in LiCl-induced anorexia, central OT receptor signaling contributes to anorexia in rats after systemic administration of hypertonic saline (14) and after central infusion of corticotropin-releasing factor (CRF) (15). Importantly, these anorexigenic treatments also inhibit vagally mediated gastric motility and emptying (4, 5), as does central infusion of GLP-1 (7). The present study confirmed that OT-immunopositive nerve terminals are closely apposed to GLP-1-positive neurons in the DVC and that these neurons are activated by central infusion of an anorexigenic dose of OT. The OT-containing projection from the PVN to the DVC provides a tonic inhibitory influence over vagally mediated gastric motility that is further amplified by anorexigenic treatments (3, 4). Thus experimental treatments that activate central OT signaling pathways may inhibit gastric motility and food intake, at least in part, due to OT-mediated recruitment/activation of hindbrain GLP-1 neurons. If so, then functional blockade of central GLP-1 signaling pathways should also attenuate the gastric inhibitory effects of centrally infused OT and other anorexigenic treatments, such as systemically administered LiCl or centrally infused CRF, parallel with attenuation of treatment-induced anorexia. This has not yet been examined. However, the ability of restraint stress to stimulate colonic motility and fecal output in rats is completely reversed after blockade of central GLP-1 receptors (6), implicating GLP-1 more generally as a candidate neurotransmitter in stress-induced changes in gut motility.

Perspectives

“A treatment-induced anorexia” refers to a significant suppression of food intake, relative to baseline conditions, that is directly associated with a controlled experimental condition intended (ideally) to model some natural circumstance associated with inhibition of food...
intake. For example, to the extent that LiCl treatment is a valid experimental model of toxemia and nausea and considering evidence that both OT and GLP-1 central signaling mechanisms are involved in the inhibition of food intake produced by LiCl, we interpret our findings as evidence that GLP-1 is an important downstream mediator of toxemia/nausea-related suppression of food intake. We do not know whether OT and/or GLP-1 signaling pathways are involved in the inhibition of feeding associated with more natural physiological conditions or whether these central pathways are involved in anorexigenic responses to social or cognitive stressors. We are not aware of any experimental anorexias for which central OT or GLP-1 signaling has been demonstrated not to play a role. However, in most cases, the potential involvement of these neural pathways has not been investigated.

Among the many brain areas that potentially mediate treatment-induced anorexia, it is likely that the DVC (including its GLP-1 neural constituents) plays a central role. As the major brain stem relay center for visceral sensory information and descending projections from the hypothalamus and limbic forebrain, the DVC is well positioned to integrate interoceptive cues with cognitive/emotional states and thereby serve a "comparator function" for organizing appropriate behavioral and autonomic responses. Direct and relayed projections from the DVC to somatic and autonomic motor nuclei provide potential routes by which the DVC might exert context-dependent control over both the ingestion and digestion of food. The present findings should serve to focus greater attention on the DVC and particularly on its resident GLP-1 neurons as an integral component of the central neural circuits that underlie ingestive behavior.

This work benefited from the excellent technical assistance of J. S. Yen and V. Malkovman. This project was supported by National Institute of Mental Health (NIMH) Grant MH-39011 to L. Rinaman and by an NIMH Undergraduate Research Fellowship awarded to E. E. Rothe through the University of Pittsburgh.

REFERENCES


