Postprandial hyperglycemia stimulates neuroglial plasticity in hypothalamic POMC neurons after a balanced meal

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Highlights

- Postprandial hyperactivity of hypothalamic POMC neurons involves synaptic plasticity
- Postprandial plasticity of POMC neurons engages glial retraction
- Postprandial glial retraction around POMC neurons is triggered by hyperglycemia
- Glial retraction on POMC neurons modifies meal pattern

In Brief

State-dependent plasticity in neuronal circuits controlling hunger is well established. Nuzzaci et al. show that this process is recapitulated after a meal. Postprandial hyperglycemia induces glial retraction around hypothalamic POMC neurons, which increases the activity of these anorectic neurons. This macronutrient-dependent plasticity provides a neurobiological basis for satiety.

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SUMMARY

Mechanistic studies in rodents evidenced synaptic remodeling in neuronal circuits that control food intake. However, the physiological relevance of this process is not well defined. Here, we show that the firing activity of anorexigenic POMC neurons located in the hypothalamus is increased after a standard meal. Postprandial hyperactivity of POMC neurons relies on synaptic plasticity that engages pre-synaptic mechanisms, which does not involve structural remodeling of synapses but retraction of glial coverage. These functional and morphological neuroglial changes are triggered by postprandial hyperglycemia. Chemogenetically induced glial retraction on POMC neurons is sufficient to increase POMC activity and modify meal patterns. These findings indicate that synaptic plasticity within the melanocortin system happens at the timescale of meals and likely contributes to short-term control of food intake. Interestingly, these effects are lost with a high-fat meal, suggesting that neuroglial plasticity of POMC neurons is involved in the satietogenic properties of foods.

INTRODUCTION

Obesity is a worldwide epidemic that poses major risks for diabetes, cardiovascular diseases, and certain forms of cancer. Over the past years, genome-wide scans in human subjects have mapped several loci on chromosomes for body mass index (BMI). Identified genes in BMI-associated loci are enriched in the brain and mainly related to neurodevelopment and neuronal biology, providing support for a crucial role of the central nervous system in obesity susceptbility (Hoffmann et al., 2018; Locke et al., 2015; Willer et al., 2009). In particular, glutamatergic neurotransmission and synaptic plasticity have emerged as two major pathways implicated in the regulation of body weight (Locke et al., 2015). Fundamental studies carried out on rodents clearly evidenced synaptic plasticity in neuronal circuits controlling appetite and metabolism (Cristino et al., 2013; Horvath and Gao, 2005; Labouèbe et al., 2013; Lim et al., 2012; Pinto et al., 2004; Wang et al., 2016). For instance, synaptic connections in the melanocortin system, a master regulator of energy balance, are significantly reorganized during starvation (Kong et al., 2016; Liu et al., 2012; Yong et al., 2011; Yang et al., 2011) or over-feeding (Benani et al., 2012).

The balance between excitatory and inhibitory inputs in the two antagonistic components of the melanocortin system, anorexigenic pro-opiomelanocortin (POMC) and orexigenic agouti related peptide (AgRP) neurons, varies according to energy availability and related changes in blood hormones. Remarkably, hormones coordinate synaptic remodeling in a coherent manner with the behavioral effect. Furthermore, brain-targeted manipulation of plasticity-related molecules impairs a number of homeostatic responses following disruption of energy balance and makes mice prone to obesity (Benani et al., 2012; Brenachot et al., 2014, 2017; Rathjen et al., 2017). Therefore, synaptic plasticity of the melanocortin system is viewed as an adaptive response aimed at preserving energy homeostasis (Dietrich and Horvath, 2013; Zeilser et al., 2012). Nevertheless, the physiological relevance of this mechanism is still unclear. To date, synaptic remodeling in the melanocortin system has been described in response to large,
supraphysiological changes in blood hormone concentrations caused by drastic metabolic challenges (Benani et al., 2012; Liu et al., 2012; Vong et al., 2011; Yang et al., 2011) or by hormone replacement therapy in experimental models (Gao et al., 2007; Gyengesi et al., 2010; Pinto et al., 2004). Thus, it is still unknown whether synaptic plasticity in brain feeding circuits is triggered upon extreme metabolic conditions or whether it is also recapitulated at the timescale of meals in response to subtle metabolic changes. Answering this issue is crucial to define the value of plasticity of brain feeding circuits.

Interestingly, application of recombinant hormones on brain slices can alter the synaptic strength between neurons involved in regulation of feeding in less than 1 h (Labouèbe et al., 2013; Vong et al., 2011; Yang et al., 2011). This timescale fits with the kinetic of release of ingestion-related cues and is consistent with control of satiety by synaptic plasticity processes. POMC neurons located in the arcuate nucleus of the hypothalamus are nutritionally regulated (Beutler et al., 2017; Chen et al., 2015; Mandelblat-Cerf et al., 2015; Vong et al., 2011; Yang et al., 2011) and involved in control of satiety (Aponte et al., 2015; Mandelblat-Cerf et al., 2015; Vong et al., 2011; Yang et al., 2011). We therefore tested the assumption that plasticity-related mechanisms might occur at the timescale of meals in POMC neurons and contribute to short-term control of food intake.

RESULTS

The Postprandial State Increases the Activity of POMC Neurons via Synaptic Plasticity

We examined electrophysiological properties of POMC neurons according to prandial state in transgenic mice expressing the fluorescent protein tdTomato in POMC neurons (POMC Cre:tdTomato mice). POMC Cre:tdTomato mice were randomly assigned to three groups: one preprandial group with 2-h food restriction prior to the dark period and two postprandial groups that were further submitted to short-term, 1-h access to food at the beginning of the dark period (Figures S1A–S1C). Provided food corresponded to either a standard or a hypercaloric high-fat diet (diet compositions are given in Table S1). Body weight and blood levels of insulin, leptin, and acylated ghrelin did not differ statistically between preprandial and postprandial groups on a standard diet but not a high-fat hypercaloric diet, indicating that it depended on food composition (Figures 1A–1D).

We next tested whether the ratio of excitatory to inhibitory synaptic inputs on POMC neurons varied according to the prandial state. We analyzed the type of presynaptic puncta around individual POMC somata in fixed brain sections using electron microscopy. POMC Cre:tdTomato neurons were immunolabeled with electron-dense precipitates of diaminobenzidine, and synaptic contacts were counted (Figure 2A). We found that the synaptic density of POMC Cre:tdTomato neurons remained unchanged regardless of the prandial state of mice or the ingested diet (Figure 2B).

We next tested whether the ratio of excitatory to inhibitory synaptic currents on POMC neurons varied according to the prandial state. We analyzed the type of presynaptic puncta around individual POMC somata in fixed brain sections using electron microscopy. Excitatory and inhibitory presynaptic terminals onto POMC Cre:tdTomato neurons were labeled using the VGluT1 (vesicular glutamate transporter 1) and VGAT (vesicular GABA transporter) markers, respectively (Figure 2C). No difference in the VGluT1:VGAT ratio on POMC Cre:tdTomato neurons was found between preprandial and postprandial groups on a standard diet (Figure 2D). Surprisingly, this ratio was dramatically increased with high-fat diet (HFD) exposure (Figure 2D), whereas the...
Figure 1. The Electrical Activity of POMC<sup>Crest</sup>Tomato Neurons Depends on the Prandial State

The activity of POMC<sup>Crest</sup>Tomato neurons was recorded in brain slices from mice in the preprandial or postprandial state. The firing rate was recorded in cell-attached configuration. Miniature excitatory postsynaptic current (mEPSC) and miniature inhibitory postsynaptic current (mIPSC) were recorded in whole-cell voltage-clamp configuration.

(A) Spontaneous firing rate in POMC<sup>Crest</sup>Tomato neurons according to the prandial state. Preprandial mice (Pre), n = 17 cells from 4 mice; 1 h SD, n = 15 cells from 3 mice; 1 h HFD, n = 15 cells from 3 mice.

(B and C) Frequency (B) and amplitude (C) of mEPSCs in POMC<sup>Crest</sup>Tomato neurons according to the prandial state. Pre, n = 16 cells from 9 mice; 1 h SD, n = 15 cells from 8 mice; 1 h HFD, n = 15 cells from 6 mice.

(D and E) Frequency (D) and amplitude (E) of mIPSCs in POMC<sup>Crest</sup>Tomato neurons according to the prandial state. Pre, n = 17 cells from 4 mice; 1 h SD, n = 10 cells from 3 mice; 1 h HFD, n = 12 cells from 3 mice.

Data are means ± SEM. Statistical analyses were performed on recorded cells. Asterisks indicate statistical differences between groups: *p < 0.05. ns, no significant difference between groups. In (A), (B), and (D), data were analyzed using Kruskal-Wallis test followed by Dunn’s test. In (C) and (E), data were analyzed using ANOVA followed by Newman-Keuls test.
POMC firing rate was not affected by the HFD at this time point (Figure 1A). The same results were obtained when ratios were computed from peri-somatic areas (Figure S2).

Astrocytes are integral components of synapses that also determine neurotransmission (Allen and Eroglu, 2017). Interestingly, astrocyte-POMC neurons interactions are sensitive to the metabolic state, and glial ensheathment seems to control POMC activity (Fuente-Martín et al., 2012; García-Cáceres et al., 2016; Kim et al., 2014). Thus we investigated whether changes in glial coverage occurred in response to food consumption. We used electron microscopy to assess the length of apposition of glial elements on arcuate dianaminobenzidine-positive POMC<sup>Cre:tdTomato</sup> somata (Figure 2E). We found a significant reduction in astrocyte-POMC neuron interaction after exposure to 1-h standard diet feeding (Figure 2F; Table S2). Astrocyte coverage on POMC neurons was not affected by the HFD after 1 h (Figure 2F).

These results show that the number of synapses and the type of presynaptic puncta on POMC neurons were not changed by balanced food at the timescale of meals. Moreover, these data suggest that the postprandial hyperactivity of POMC following a standard meal might be linked to glial retraction from POMC neurons.

**Postprandial Glial Retraction on POMC Neurons Requires Postprandial Hyperglycemia**

Integration of meal-related signals in astrocytes can modify interaction with POMC neurons (García-Cáceres et al., 2016;...
Kim et al., 2014). Here we tested whether postprandial elevation of blood glucose mediated the neuroglial remodeling we observed on a standard diet. We first continuously monitored glycemia of mice following food consumption by telemetry using glucometer implants. Despite some differences in postprandial blood glucose excursions that reflect the specific glycemic index of the diets, glycemia increased with either a standard diet or HFD, peaking similarly 20–22 min after food introduction, confirming a regulated postprandial hyperglycemic response after food consumption (Figure 3A; Figure S3A). To appreciate the role of postprandial hyperglycemia on neuroglial plasticity, mice fed a standard diet were pretreated with LX4211, a dual inhibitor of SGLT1/SGLT2 transporters that inhibits intestinal absorption and renal reabsorption of glucose (Powell et al., 2014; Powell et al., 2013), or with saline (Figure S3B). Intraperitoneal injection of LX4211 (10 mg/kg) prior to standard diet exposure limited the hyperglycemic response in comparison with saline pretreatment (Figures S3C and S3D). Remarkably, LX4211 pretreatment inhibited both standard diet-induced astrocytic retraction on arcuate $\text{POMC}^{\text{Cre:tdTomato}}$ neurons (Figure 3B) and the related increase in arcuate $\text{POMC}^{\text{Cre:tdTomato}}$ neuron activity (Figure 3C). Thus, postprandial neuroglial plasticity of POMC neurons required a surge of blood glucose.

We next tested whether elevation of blood glucose was sufficient to trigger neuroglial remodeling. We treated mice with an intraperitoneal injection of glucose (0.5 g/kg) or saline instead of giving them a standard diet (Figure S3E). This glucose load mimicked the glycemic response induced by standard diet ingestion (Figures S3F and S3G). Notably, we found a drastic astrocytic retraction on arcuate $\text{POMC}^{\text{Cre:tdTomato}}$ neurons in glucose-treated mice in comparison with control mice (Figure 3D). The glucose load also increased the firing rate of these neurons (Figure 3E). Thus, glucose administration recapitulated the effects found in response to standard diet ingestion.

Together, these results demonstrate that glucose signaling was both necessary and sufficient for postprandial neuroglial plasticity and activation of POMC neurons.

**Glial Retraction on POMC Neurons Alters Feeding Behavior**

To evaluate the behavioral outcome of the postprandial neuroglial plasticity of POMC neurons, we thought to interfere in the remodeling activity of astrocytes during feeding. Astrocytic...
morphism is dynamically regulated by the cyclic AMP signaling pathway (Vardjan et al., 2014). We took advantage of designer receptors exclusively activated by designer drugs (DREADD)-based chemogenetics (Roth, 2016) to selectively manipulate intracellular cAMP of astrocytes in adult animals. We chose to express the Gi-coupled designer receptor hM4D under control of the astrocytic glial fibrillary acidic protein (GFAP) promoter using viral particles containing the Gi-coupled DREADD construct fused to the mCitrine reporter (rAAV8/GFAP-Ha-hM4D(Gi)-IRES-mCitrine). This system efficiently inhibited cAMP signaling in primary cultures of murine astrocytes when activated by the clozapine N-oxide (CNO) ligand (Figure S4). Viral particles containing the DREADD construct were stereotactically injected into the arcuate nucleus of the hypothalamus. Post-mortem inspection of some injected brains revealed efficient targeting of the arcuate nucleus and showed that GFAP-positive mCitrine-transduced cells exhibited a stellate morphology consistent with that of astrocytes (Figure 4A). Moreover, several
mCitrine-transduced cells enwrapped Tomato-positive cells (Figure 4B), suggesting close interaction between transduced astrocytes and arcuate POMC neurons. Of note, immunodetection of Tomato-positive cells revealed no overlap with mCitrine staining, confirming the specificity of transduction (Figure 4B).

We then studied astrocyte-POMC interaction in the postprandial state upon CNO treatment. DREADDed POMC<sup>Crest:tdTomato</sup> mice received a single intraperitoneal injection of CNO (1 mg/kg) prior to standard diet exposure (Figure S4). Control mice received a saline injection. We found that postprandial astrocytic coverage on POMC<sup>Crest:tdTomato</sup> neurons from DREADDed mice injected with saline was low (Figure 4C), at a level similar to that obtained previously in POMC<sup>Crest:tdTomato</sup> mice without DREADD (Figure 2F). This result shows that DREADD transduction did not alter the ability of arcuate astrocytes to retract in response to standard diet ingestion. Interestingly, CNO did not inhibit this postprandial response but further increased glial retraction on POMC neurons (Figure 4C). These results suggest that CNO-mediated activation of arcuate astrocyte Gi signaling inhibited astrocyte-POMC neuron contacts.

We next assessed the effect of CNO injection on state-dependent activity of POMC neurons. As before, DREADDed POMC<sup>Crest:tdTomato</sup> mice received a single intraperitoneal injection of CNO (1 mg/kg) or saline before exposure to a standard diet for 1 h, and the brains were processed for electrophysiology. We found that the postprandial firing rate of POMC<sup>Crest:tdTomato</sup> neurons was elevated in DREADDed mice injected with saline (Figure 4D) and was similar to that in POMC<sup>Crest:tdTomato</sup> mice without DREADD (Figure 1A), showing that DREADD transduction did not alter POMC neuron functioning. In contrast, CNO pretreatment in DREADDed mice further increased the postprandial firing rate in POMC<sup>Crest:tdTomato</sup> neurons (Figure 4D). These results further suggest that CNO-mediated activation of arcuate astrocyte Gi signaling could also stimulate the activity of POMC neurons.

We finally investigated feeding behavior in DREADDed POMC<sup>Crest:tdTomato</sup> mice. Mice received a single injection of CNO or saline before food introduction, and feeding behavior was monitored over a 24-h period. At the 6-h time point, the behavioral effects of CNO were maximal. CNO pretreatment did not influence the cumulative food intake (Figure 4E), but it significantly changed the temporal organization of the feeding behavior. Although number of feeding bouts tended to decrease upon CNO administration (Figure 4F), the size of the bouts was strongly increased by the treatment. Notably, CNO increased the amount of ingested food per feeding bout (Figure 4G) and the duration of the feeding bout (Figure 4H). These effects were not detectable during the first 1-h period of feeding (Figures S4D–S4G), became significant after 3 h (Figures S4H–S4K), and decreased but were still significant after 24 h (Figures S4L–S4O).

We checked the behavioral effects of CNO per se in POMC<sup>Crest:tdTomato</sup> DREADD-free mice. One single intraperitoneal injection of 1 mg/kg CNO in unDREADDed POMC<sup>Crest:tdTomato</sup> mice did not produce any changes in the feeding behavior (Figures S5A–S5D), confirming that CNO alone is pharmacologically and behaviorally inert in mice (Alexander et al., 2009; Armbruster et al., 2007; Farrell et al., 2013; Guettier et al., 2009; Krashes et al., 2011) and that CNO-to-clozapine back-metabolism is low in mice, with blood clozapine being negligible when CNO is dosed at 1 mg/kg (Farrell et al., 2013; Marvich et al., 2018). CNO treatment in POMC<sup>Crest:tdTomato</sup> DREADD-free mice did not modify the firing rate of POMC neurons after 1-h standard diet (SD) feeding (Figure S5E).

We also tested whether CNO treatment influenced general ambulatory ability and emotionality in DREADDed POMC<sup>Crest:tdTomato</sup> mice, two parameters that can affect feeding behavior. Locomotor activity and anxiety-like behavior upon CNO treatment were assessed in a wall-enclosed open field arena (Walsh and Cummins, 1976). Following CNO or saline injection, mice were fed for 3 h and then placed in the arena during a 30-min trial (Figure S5F). CNO did not alter the total ambulatory distance of mice (Figure S5G) and did not change the number of entries in the inner zone (Figure S5H) or the time spent in this zone versus the periphery (Figure S5I). These data indicate that a single injection of 1 mg/kg CNO in mice did not produce sedative and anxiolytic effects at a time when feeding behavior was modified.

Altogether, these results indicate that CNO treatment was effective in altering the temporal pattern of meals in DREADDed mice without changing locomotor activity or emotionality and that this effect required Gi signaling in hypothalamic astrocytes.

DISCUSSION

In this study, we show that the electrical activity of arcuate POMC neurons is regulated according to the prandial state. Using electrophysiological recordings from acute brain slices, we evidenced the postprandial hyperactivity of these neurons. These data are consistent with those obtained in awake mice using direct in vivo recording, showing rapid and sustained changes in POMC activity during feeding (Chen et al., 2015; Mandelblat-Cerf et al., 2015). In addition, we found that postprandial hyperactivity of POMC neurons engages presynaptic modifications affecting the excitatory tone applied on these neurons. Such state-dependent plasticity in the melanocortin system has already been established in response to changes in nutritional state (Dietrich and Horvath, 2013; Zeltser et al., 2012). However, until then, this phenomenon has been found only after high metabolic challenges, including starvation (Liu et al., 2012; Vong et al., 2011; Yang et al., 2011) and overfeeding (Benani et al., 2012). Here we report that synaptic plasticity on POMC neurons can be recapitulated at the timescale of meals in freely behaving mice in a physiological context, meaning that this process is not only an adaptive mechanism elicited during extreme and perhaps rare metabolic situations but also develops during day-to-day life in response to subtle metabolic changes.

To evidence synaptic plasticity in POMC neurons at the timescale of meals, we used ex vivo electrophysiology in living brain slices. This approach has been widely used to reveal and study the plasticity of the melanocortin system in response to many metabolic changes, including those related to aging, obesity, hormone treatment, fasting, overfeeding, or physical activity (Baqueiro et al., 2015; Benani et al., 2012; Dodd et al., 2018; He et al., 2018; Liu et al., 2012; Newton et al., 2013; Pinto et al., 2004; Suyama et al., 2017; Vong et al., 2011; Yang et al., 2011,
In the present study, postprandial electrophysiological changes in POMC neurons (Kong et al., 2016; Liu et al., 2012). Limitations of our study include the fact that synaptic counting was performed on POMC somata or peri-somatic areas only. Thus, we cannot exclude synaptic remodeling far from somata, in the dendritic arborization. Moreover, to examine the type of synapses impinging on POMC neurons, we stained presynaptic puncta only. Although the method is appropriate to appreciate a shift between excitatory and inhibitory terminals onto neurons, quantification of presynaptic puncta does not denote bona fide bi-partite synapses because presynaptic puncta may be present without being co-localized with a postsynaptic marker. This methodological issue limits the accuracy of the measure. Nevertheless, this method is sensitive enough to highlight morphological remodeling in a neuronal system, either in the melanocortin system or elsewhere (Baquero et al., 2015; Cristino et al., 2013; Melnick et al., 2007; Newton et al., 2013). Keeping these issues in mind, our histological data are in favor of an absence of morphological remodeling of presynaptic terminals onto POMC neurons after a standard meal. Indeed, constant effervescence for molding new synapses and eliminating others to generate new configurations at the timescale of meals would represent a high cost for the organism.

In many neuroendocrine systems, modification of astrocytic coverage on synapses is a way to efficiently and rapidly modulate the synaptic strength onto neurons with no need of building new synapses (Clasadanote and Prevot, 2018; Oliet et al., 2001, 2002; Theodosis et al., 2008). Time-lapse imaging shows that peri-synaptic astrocytic processes that embraces synapses are highly reactive and motile structures, to an even higher degree than dendritic spines (Bernardinelli et al., 2014). Furthermore, astrocytes surrounding POMC and AgRP somata are known to change their morphology according to metabolic cues (Fuente-Martín et al., 2012; García-Cáceres et al., 2016, 2019; Horvath et al., 2010; Kim et al., 2014). Here we found that consumption of standard food induced robust glial retraction around POMC somata, showing that structural astroglial plasticity happens over the course of meals. Moreover, glial retraction was invariably associated with an increase in POMC firing rate, as was the case after feeding an SD but also after glucose injection or chemogenetic manipulation. Inversely, large glial coverage was detected during the preprandial state or after feeding an HFD, two situations where POMC activity was low. These results suggest the existence of a structure-function relationship in the astrocyte/POMC dyad. This is consistent with previous reports showing massive glial ensheathment of POMC neurons associated with reduced functioning of POMC neurons during diet-induced obesity (Enniori et al., 2007; Horvath et al., 2010; Paeger et al., 2017). Furthermore, we found that more than 80% of POMC neurons undergo postprandial astrocytic retraction after a standard meal. The low variability in this response contrasts with the well-known heterogeneity of POMC neurons (Dodd et al., 2018; Lam et al., 2017; Sohn and Williams, 2012; Williams et al., 2010). Thus, our data suggest that taking into account the prandial state of animals could minimize the apparent functional heterogeneity of POMC neurons.

In this study, we used chemogenetic tools to interrogate the function of hypothalamic astrocytes. As already reported by others (Jones et al., 2018), we found that artificial chemogenetic manipulation with the inhibitory hM4D(Gi) receptor rapidly reduces intracellular cyclic AMP in GFAP-expressing cells such as astrocytes. We also found that CNO injection in mice transduced with the inhibitory DREADD induced robust glial retraction around POMC somata. This is consistent with previous pharmacological studies showing that astrocyte stellation is regulated within minutes by intracellular cyclic AMP level (Vardjan et al., 2014). Accordingly, postprandial neuroglial plasticity might implicate a cyclic AMP-dependent signaling pathway in astrocytes. In addition, a change in blood glucose appears to be crucial to initiate postprandial glial retraction. Although we did not determine whether this process requires direct astrocytic glucose sensing, this result is consistent with others showing that glial cells can be shaped by glycemic fluctuations (Dauzas-Meyer et al., 2018; Langlet et al., 2013). Specifically, these data complete the current model in which hypothalamic astrocytes respond to metabolic cues, including leptin and insulin, to adjust the activity of the melanocortin system via changes in astrocyte-neuron interaction and, ultimately, to maintain energy homeostasis (García-Cáceres et al., 2016; Kim et al., 2014). In addition, we show that this glucose-dependent neuroglial plasticity can be initiated during normal physiology at the timescale of meals. Moreover, we found that in vivo activation of the CNO/hM4D(Gi) system expressed in arcuate GFAP-expressing cells stimulated activity of POMC neurons. Using similar GFAP-driven chemogenetic tools, other groups have reported previously that application of CNO acutely on brain slices modifies the firing rate of AgRP and POMC neurons, confirming that astrocytes control the activity of the melanocortin system (Chen et al., 2016; Yang et al., 2015). In our work, DREADD-mediated activation of Gq signaling has not been examined. GFAP-driven hM3D(Gq) viral particles have been used successfully to study gliotransmission in a neuronal system (Adamsky et al., 2018; Agulhon et al., 2013; Scofield et al., 2015) and arcuate astrocyte-AgRP/POMC neuron interaction more specially (Chen et al., 2016; Yang et al., 2015). At the molecular level, the effects of hM3D(Gq) activation are likely to be mediated by intracellular Ca²⁺ elevation in astrocytes (Adamsky et al., 2018; Agulhon et al., 2013; Bonder and McCarthy, 2014; Chen et al., 2016).
On the other hand, activation of hM4D(Gi) is known to decrease cAMP level in cells (Armbruster et al., 2007; Jones et al., 2018), which was confirmed in the present study. Interestingly, activation of Gq- and Gi-coupled DREADD receptors produces opposite effects in neurons, such as neuronal firing or silencing (Armbruster et al., 2007). In astrocytes, these tools elevate calcium and stimulate gliotransmission similarly (Durkee et al., 2019). Thus, the physiological effects of Gq- and Gi-coupled DREADD receptors in astrocytes are not as straightforward as in neurons, and additional studies are needed to characterize the molecular signaling pathways in astrocytes that regulate hunger state.

At the behavioral level, activation of the CNO/hM4D(Gi) system in arcuate astrocytes did not affect total food intake. This corroborates previous studies showing that chemogenetic manipulation of hypothalamic astrocytes via Gi signaling does not alter basal food intake (Chen et al., 2016; Yang et al., 2015). However, further examination of feeding behavior revealed that activation of the CNO/hM4D(Gi) system in glia induced larger but less frequent feeding bouts over the next few hours, suggesting that arcuate astrocytes contribute to satiety. This behavioral effect might rely on the associated hyperactivity of POMC neurons induced by the treatment. A role of POMC neurons in control of satiety has already been evidenced elsewhere (Fenselau et al., 2017; Richard et al., 2011). This does not rule out a concomitant effect on adjacent AgRP neurons and on arcuate glutamatergic neurons, which are also involved in the control of satiety (Chen et al., 2016; Fenselau et al., 2017; Yang et al., 2015). Interestingly, CNO-induced behavioral effects appeared after a delay of few hours and were maximal 6 h post-CNO injection, suggesting that postprandial neuroglial plasticity is not involved in termination of the first feeding bouts but affects hunger slowly. This also argues for involvement of arcuate POMC neurons in CNO-induced behavioral effects because these neurons are known to alter feeding behavior long term (Aponte et al., 2011; Zhan et al., 2013). Together, our data strongly suggest that glial retraction onto POMC neurons is part of the slow and sustained neurobiological mechanisms that contribute to control of satiety.

We also found that postprandial changes in mEPSC frequency in POMC neurons were not in line with those of the VGlut:VGaT ratio on POMC somas. Actually, the VGlut:VGaT ratio remained unchanged after a standard meal, whereas mEPSC frequency increased. Because a reduction in astrocytic coverage was found simultaneously, this result suggests a prominent role of the dynamic glial response in regulation of POMC activity after a meal instead of a synaptic rearrangement on POMC neurons. In support of this, recent studies have shown that astrocytes can directly activate POMC neurons (Bouyakdan et al., 2019; Sweeney et al., 2016). Furthermore, an elegant study performed in hippocampal neurons has shown that astrocyte activity is not only necessary for synaptic plasticity but can be sufficient to generate de novo synaptic plasticity (Adamsky et al., 2018). Inversely, we found that 1-h HFD feeding induced a robust synaptic switch around POMC neurons, increasing excitatory and decreasing inhibitory synaptic puncta on POMC somata, whereas the net firing rate of POMC neurons as well as the frequency of miniature currents remained unchanged. The discrepancy between the functional and histological analyses probably reflects a delay for novel synapses to be operative. Again, in this study, we quantified presynaptic puncta, and it does not denote bona fide synapses. Thus, more accurate identification of mature synapses, by labeling post-synaptic elements, for instance, would help to clarify. Nevertheless, the structural synaptic remodeling found here after 1-h HFD feeding, increasing excitatory inputs on POMC neurons, likely represents an adaptive response against energy balance deviation and excessive calorie intake. In fact, forced consumption of an HFD for a few days firmly increases POMC neuron activity according to synaptic plasticity-related processes (Benani et al., 2012; Suyama et al., 2017), which is in line with the early synaptic remodeling found here.

Strikingly, consumption of an HFD for 1 h did not modify the activity of POMC neurons. Furthermore, HFD did not change excitatory and inhibitory tones applied on POMC neurons or cause glial retraction. Thus, postprandial functional and structural changes on POMC neurons were essentially lost when consuming high-fat, energy-dense foods. This lack of effect appears not to be linked to food neophobia because mice were trained with an HFD before the trial, ate normal amounts of food during the trial, and displayed postprandial hyperglycemia. Moreover, HFD-related signals were sensed in the brain, as evidenced by the HFD-induced synaptic switch around POMC somata. Rather, these results suggest that postprandial neuroglial plasticity integrates food composition. This result is also in line with a recent study showing that macronutrients produce specific effects on the melanocortin system (Su et al., 2017), with gastro-intestinal infusion of glucose resulting in higher and more prolonged reduction of AgRP neuron activity than lipids. According to the present study, in mice kept on an SD, blood glucose was required to trigger glial retraction. Because the HFD also raised glycemia, why did it not initiate such postprandial neuroglial plasticity? In contrast to that on the SD, HFD-induced hyperglycemia was very brief and returned to basal values as soon as 30–40 min, whereas glycemia was still elevated after 1 h on the SD (Figure 3A). Thus, one can propose that long-lasting elevation of glycemia is critical to provoke morphological changes in hypothalamic astrocytes and to activate POMC neurons. However, we observed that 1-h exposure to a high-sucrose, low-fat diet, which contains fast-release carbohydrates like those in the HFD, or a single intraperitoneal injection of glucose increased the POMC firing rate as well. Accordingly, blood glucose kinetics would not be key factors for neuroglial plasticity, and a low glycemic index does not appear to be an indispensable prerequisite to activate POMC neurons. Another possibility is that interfering factors derived from the HFD but not from the SD, such as lipids or inflammatory mediators, might have inhibited the response. Further studies are needed to understand this specificity. In all cases, postprandial neuroglial plasticity appears to be a slow, macronutrient-dependent mechanism that produces delayed effects on food intake and follows fast, macronutrient-independent integration of post-ingestive signals (Beutler et al., 2017; Su et al., 2017). In this scheme, satiogenic properties of macronutrients would be also based on their ability to induce neuroglial remodeling.
In conclusion, these findings reveal that neuroglial plasticity within circuits controlling appetite happens at the timescale of meals. Moreover, our results strongly suggest that dynamic interactions between neurons and glial cells influence feeding behavior. Finally, this macronutrient-dependent plasticity provides a neurobiological basis for satiety, and alteration of this mechanism might be a factor in maladaptive eating disorders and obesity.

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SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.celrep.2020.02.029.

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AUTHOR CONTRIBUTIONS


DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES


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KEY RESOURCES TABLE

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LEAD CONTACT AND MATERIALS AVAILABILITY

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Alexandre Benani (alexandre.benani@u-bourgogne.fr). This study did not generate new unique reagents.
EXPERIMENTAL MODEL AND SUBJECT DETAILS

Mice
Transgenic POMC<sup>Cre:tdTomato</sup> mice were obtained by crossing Pomc<sup>Cre</sup> (Stock No. 005965) with tdTomato<sup>Cre/+</sup> (Stock No. 007914) mice, which were purchased from Jackson Laboratories. Experiments were made on 7/10-week old male that were heterozygous for POMC (cre+) and homozygous for tdTomato. Animals were housed at 22.5 ± 1°C on a 12h-12h reversed light-dark cycle (light off at 10h30; light on at 22h30). Before experiments, animals had free access to standard diet (A04, SAFE) and water. Telemetry studies were performed on male mice C57BL/6J from Charles River. These mice were housed individually in a room maintained at 22.5 ± 1°C with light from 7:00 am to 7:00 pm. Food (#A04; Safe) and water were given ad libitum. Mice were kept individually for at least 7 days in their own cages before surgical procedure. All protocols including animals were reviewed by our local ethic committee in strict accordance with European Community guidelines and agreed by the French Ministry of Higher Education and Research (accreditation No. 00853.01).

Experimental design
Three groups of mice were designed to compare prandial states (Figure S1A). For experiments, mice were submitted to a 2-hour food restriction just before lights off. This procedure was designed to standardize the metabolic state of mice and minimize variation in their sensation of hunger. This also ensures substantial and reliable food intake after food reintroduction. This physiological “no food condition” does not alter level of metabolic hormones. Preprandial mice (Pre) were killed just after food restriction. Postprandial mice received food at lights off and were killed after 1 hour and were killed after the feeding period. Food was either a standard diet (SD; Cat. No. A04; Safe), a high-fat diet (HFD; semi-synthesized diet, Cat. No. U8954 v7; Safe) or a high-sucrose low-fat diet (HSD; Cat. No. AIN76A; Safe). Diet compositions are given in the Table S1.

Before experiments, mice were housed individually for 3 days in their regular cages and were trained for the 2-hour food restriction. To prevent food neophobia, mice received some HFD pellets for 10 minutes 1 day before the experiment. An additional group of fasted mice was generated as a reference. These mice were killed after 24-hour fast. In graphs, preprandial mice were noted: “Pre-prandial,” while mice receiving standard and HFD for 1 hour were noted: “1h-SD” and “1h-HFD,” respectively.

Primary astrocyte culture
Primary glial cell cultures were prepared from newborn C57BL/6J mouse brains (Harlan) as described elsewhere (Loscuito et al., 2012). Sex of newborn mice was not determined. Microglial cells were removed from the cultures using a magnetic separation kit (Miltenyi Biotec) according to the manufacturer’s instructions. Precisely, confluent cultures were washed with PBS, trypsinized and centrifuged. Cell pellet was resuspended in a rinsing solution (AutoMACS Rinsing Solution, Miltenyi Biotec) and was further rinsed with 3x3 ml. Unbound cells corresponding to astrocytes, were eluted from the column, centrifuged at 300 g at 4°C for 10 min, and resuspended in complete medium before plating. In order to vastly reduce microglial contamination, a second magnetic cell sorting (as done before) was performed after 6-7 days, to obtain pure astrocyte cultures with less than 0.5% microglia and virtually no others brain cells. Astrocytes were then cultured for 1 week. At 70% confluence, the medium was renewed and astrocytes were transduced with 3 × 10<sup>5</sup> vg/ml AAV8/GFAP-HA-hM4D(Gi)-mCitrine (Translational Vector Core, Nantes, France). After 48 h, astrocytes were treated with 10 μM Forskolin (Sigma) and/or 10 μM CNO (Sigma) for 20 minutes before viability assay or cAMP assay.

METHOD DETAILS

Stereotactic injections
Mice were anesthetized by ip injection of a ketamine-xylazine mix (80mg/kg - 12 mg/kg). They were then placed on a stereotaxic frame. AAV8/GFAP-HA-hM4D(Gi)-mCitrine (Translational Vector Core, Nantes, France) virus were injected bilaterally into the arcuate nucleus of the hypothalamus. Stereotactic co-ordinates relative to bregma were: x: ± 0.3 mm; y: +1.5 mm; z: − 6 mm. Injection were done at a rate of 0.5 μl/min for 1 min per side. At the end of surgical procedures, mice received 1 mg/kg i.p. atipamezole and 5 mg/kg s.c. ketoprofen.

Drug administration
Glucose was prepared in water and injected at 0.5 g/kg (ip, 100 μl), 30-45 minutes before lights off. LX4211 (Sotagliflozin; dual SGLT1/ SGLT2 inhibitor) was purchased from Advanced Chemblocks. LX4211 was prepared in NaCl 0.9% containing 2.5% DMSO, 22.5% PEG300. LX4211 was injected at 10 mg/kg (ip, 100 μl), 30-60 minutes before lights off. CNO was purchased from ENZO Life Sciences. CNO was prepared in water at a stock concentration of 5 mg/mL (20X) and stored at −80°C. CNO working solutions were performed on male mice C57BL/6J from Charles River. These mice were housed individually in a room maintained at 22.5 ± 1°C with light from 7:00 am to 7:00 pm. Food (#A04; Safe) and water were given ad libitum. Mice were kept individually for at least 7 days in their own cages before surgical procedure. All protocols including animals were reviewed by our local ethic committee in strict accordance with European Community guidelines and agreed by the French Ministry of Higher Education and Research (accreditation No. 00853.01).
were diluted in water. CNO was injected at 1 mg/kg (ip, 100 μl), 30-45 minutes before lights off. Before all experiments, mice were trained 3 times with i.p. injections of saline once a day, before light off.

**Blood biochemistry**

Blood samples were collected in awake animals at the tail tip after incision. Plasmas were obtained by centrifugation at 2650 g for 10 min at 7 °C. For acyl ghrelin determination, blood samples were collected on EDTA (1 mg/mL final) and p-Hydroxy-mercuribenzoic acid (0.4 mM final), a serine protease inhibitor. After centrifugation plasma was acidified with HCl (0.1 N final) to preserve acylation. Aliquots were stored at –80 °C until use. Plasma insulin was measured using the bead-based AlphaLISA Insulin immunoassay kit (Cat. No. AL204C; Perkin Elmer). Plasma leptin was measured using the Leptin Quantikine ELISA kit (Cat. No. MOB00; R&D Systems). Acylated ghrelin was measured using the Acylated Ghrelin Express EIA Kit (Cat. No. A05117; Bertin Pharma).

**Continuous monitoring of feeding behavior**

Food intake was recorded in undisturbed mice using the automated BioDAQ System (Research Diets, Inc.). Mice were habituated for one week to single housing in a regular cage and feeding through a food hopper. Cages contained enrichment and bedding material. Food was given *ad libitum* from regular bottles placed on the top of the cage. Mice showed normal food intake and body weight gain within 3 days of habituation. During habituation and experiments, food hoppers were closed for 2 hours before light off. Data were collected continuously during experiments and were analyzed using the BioDAQ DataViewer software (Research Diets, Inc.). For analysis, the minimum food amount was filtered at 0.02 g and the minimum inter-bout interval, which separates two feeding bouts, was defined as 5 s. For pharmacogenetics studies, mice were randomly assigned to receive a single injection of CNO or NaCl per day. Treatment and vehicle were injected alternatively in the same mice, allowing paired analyses.

**Continuous monitoring of glycemia**

Telemetric devices (Data Sciences International) were implanted according to the manufacturer instructions. Briefly, mice were anesthetized with isoflurane and received ip injection of 10 mg/kg buprenorphine (Buprecare® 0.3 mg/ml) and 10 mg/kg ketoprofen (Ketofen® 10%). The sensor (HD-XG; Data Sciences International) was placed into the left carotid toward the aortic arch. After surgery, animals were allowed to recover at 35 °C and received a daily ip injection of ketoprofen (Ketofen® 10%) for 3 days. During a 7-day recovery period, individualized mice were carefully monitored for body weight and behavior and had facilitated access to food. Implanted animals were then installed on their own receiver. An initial calibration was accomplished through an oral glucose tolerance test (2 g/kg of 30% glucose). Blood was sampled from the tail vein at two times points (before gavage and at 3 min after glucose load) in order to assay glucose concentration with a glucometer. Data was collected using the Ponemah® software (DSI).

**Open Field Test**

An open field test was used to assess locomotor activity and anxiety-like behavior in mice. The open field consisted of a plexiglas chamber (43.5 cm x 43.5 cm x 30.5 cm) placed inside a frame containing infrared photobeams sources and sensors, which detect the presence of animal in a spatial and temporal manner along the three axis (x, y, z) (Activity Monitor system; Med Associates, Inc.). Animal activity was monitored and analyzed with the Activity Monitor software (Med Associates, Inc.). For analysis, arena was divided into two zones: center and periphery. For trial, food was removed 2 hours at the end of the light period, as indicated before. Mice received a single injection of either NaCl or CNO solution intraperitoneally, one hour before light off. At light off, animals were fed for 3 hours using standard diet and then placed into the arena, in a randomized corner. Behavior was recorded during 30 minutes. Between each trial, arena was cleaned and dried. Numbers of entries in the center, percentage of time spent in the center compared to the periphery and total ambulatory distance were measured.

**Electrophysiology**

Experiments were performed on brain slices from 7/9-week old mice. Animals were anesthetized with a ketamine/xylazine mix (80 mg/kg - 8 mg/kg) and transcardially perfused with an ice-cold and oxygenated (95% O2 / 5% CO2) Slicing Solution (SS; 20 ml) which contains (in mM): 200 sucrose, 28 NaHCO3, 2.5 KCl, 7 MgCl2, 1.25 NaH2PO4, 0.5 CaCl2, 5 HEPES, 1 ascorbate; 8 D-glucose; 3 Na-pyruvate (pH = 7.25-7.30, adjusted with HCl 5N). After perfusion, brains were rapidly extracted and placed on the stage of a thermostated vibrating microtome (Vibroslice, Leica VT1000S). Frontal brain sections containing the arcuate nucleus of the hypothalamus (250 μm thick) were cut at 4 °C in the oxygenated SS. Slices were then incubated in an oxygenated bath of 5 mM glucose Extracellular Solution (5G-ES), which contains (in mM): 118 NaCl, 3 KCl, 1.2 NaH2PO4, 1 MgCl2, 25 NaHCO3, 1.5 CaCl2, 5 HEPES, 5 glucose (pH = 7.3-7.4, adjusted with HCl 5N; osmolarity = 300-310 mOs/mol, adjusted with sucrose), for 30 min at room temperature. Slices were further incubated in an oxygenated bath of 2.5 mM glucose Extracellular Solution (2.5G-ES) for 1 hour at least, at room temperature, until ready to record. For recording, slices were placed into a chamber (RC-40LP; Warner Instruments) and perfused with 2.5G-ES (flow rate = 3 ml/min). Cells were visualized using a microscope (BX-RFA; Olympus) equipped with a 60X water-immersion objective (LUMPlanFLN; Olympus) and an IR-DIC-sensitive camera (Rolina Bolt; QImaging). Fluorescent cells were identified using a fluorescent lamp (X-Cite 120Q; Excelitas) with an excitation filter for tdTomato protein (mCherry HC Filter Set, Cat. No. F36-508; AHF). Microscope images were acquired and enhanced with QCapture Pro software (QImaging). Electrodes were made from borosilicate glass capillaries (outer diameter: 1.5 mm; inner diameter: 0.86 mm; length: 10 cm; Sutter Instruments) with a
pipette-puller (Model P-1000; Sutter Instruments). Only electrodes with a resistance between 5 to 7 MΩ were used. Small positive pressure was applied to electrodes before their insertion into the slices with a micromanipulator (MP225; Sutter Instruments).

For recording of spontaneous cell firing activity in cell-attached configuration, electrodes were filled with 2.5G-ES. For recording of mEPSC in whole-cell configuration (voltage-clamp −65 mV), electrodes were filled with a K-gluconate Intracellular Solution (KGlu-IS), which contains (in mM): 138 K-gluconate, 4 Na-gluconate, 4 MgCl₂, 10 HEPES, 5 EGTA, 2 Na₂-ATP, 0.4 Na₂-GTP (EK+ = −100.7 mV; ECl⁻ = −72.0 mV; pH = 7.2–7.3, adjusted with KOH 1N; osmolarity 290 mOsmol/L, adjusted with sucrose) in presence of picrotoxin (25 μM) and tetrodotoxin (TTX; 500 nM). For recording of mIPSC in whole-cell configuration (voltage-clamp −65 mV), electrodes were filled with a cesium-chlorure Intracellular Solution (Cs-IS), which contain (in mM) 140 CsCl; 3.6 NaCl, 1 MgCl₂, 10 HEPEs; 0.1 Na₁-EGTA, 2 Na₂-ATP, 0.4 Na₂-GTP; (EK⁺ = −∞; ECl⁻ = 3.68 mV; osmolarity = 280 mOsmol/L, adjusted with sucrose; pH = 7.2–7.3 adjusted with NaOH 1N) in presence of TTX (500 nM).

Electrical activities were recorded with an amplifier (EPC10; Heka Elektronik) connected to an acquisition interface (LIH 8+8; Heka Elektronik). Acquisitions were done with Patchmaster software (Heka Elektronik) and data were analyzed with Clampfit software (10.3.0.2, Molecular Device Inc.). For cell-attached recordings, neuronal activities were recorded during 10 minutes, after 3 to 5 minutes of stabilization post-sealing. Analysis was done on the last 2 minutes of recording. For whole-cell recordings of miniature postsynaptic currents, the amplifier filter was adjusted to 2 kHz. For mEPSC, picrotoxin was applied for 6 minutes, and then TTX was applied for 10 minutes. For mIPSC, TTX was equally applied for 10 minutes. Neuronal activities were recorded for 10 minutes and analyses were done over the last 3 minutes of recording.

Electrophysiological recordings were performed on 2-3 arcuate nucleus-containing brain slices per day collected from one mouse. Slice preparation lasted 40 minutes, and each slice was then recorded during 1 hour after a minimal 1h-recovery (Table S3).

**Electron microscopy**

Animals were anesthetized by ip injection of a ketamine-xylazine mix (80mg/kg - 12 mg/kg) and perfused intracardially with PBS (15 ml) and with 4% paraformaldehyde - 0.5% glutaraldehyde prepared in 0.1M PB (40 ml). Brains were removed and postfixed overnight at 4°C in the fixative solution. Brains were then cut in 50-μm thick frontal sections using a vibratome (VT 1200S, Leica) and sections containing the arcuate nucleus were collected. Immunohistochemistry against Tomato was performed. Briefly, free-floating sections were first treated in the dark with H₂O₂ diluted in PBS (0.1%, 15 min) at room temperature, and incubated for 2 hours at room temperature in a blocking solution containing 1% BSA, 1% NGS, 0.01% saponin in PBS. Sections were then incubated overnight at 4°C with primary antibody against tdTomato diluted in the blocking solution containing saponin (1/2500, rabbit polyclonal anti-DsRed; Ozyme). After washing in PBS (3x20 min), sections were incubated for 2 hours at room temperature with the secondary antibody diluted in the blocking solution containing saponin (1/800, biotinylated goat polyclonal anti-rabbit IgG; #BA-1000, Vector Laboratories). After washing in PBS (3x20 min), immune complexes were amplified using the avidin-biotin enzyme system (Vectastain ABC Elite (HRP) kit, #PK6100; Vector laboratories), for 1 hr at room temperature. Immune complexes were detected with diaminobenzidine (Vector DAB Kit, #SK4100; Vector Laboratories), for 1h at room temperature. Immune complexes were washed in PBS (3x15 min), and then incubated with secondary antibodies (peroxidase conjugated). Secondary antibodies were goat Alexa Fluor 488-conjugated goat anti-mouse, (Life Technologies). After further washes in PBS (3x5 min), sections were finally held with mounting medium (Fluoromount, Dako) and coverslip. Acquisitions were done with a confocal laser-scanning microscope (SP2, Leica) using a X63 oil-immersion objective. Z stack acquisition was done with 0.5 μm interval.
For assessment of viral transduction in astrocytes, 30 μm thick fixed brain coronal sections were cut on a vibratome, blocked for 1h with 5% BSA in PBS containing 0.1% Triton X-100 and incubated with primary antibodies overnight at 4°C. Primary antibodies were against GFP (1:100; #11814460001, Roche) and GFAP (1:300; #Z0334, Dako). Adequate AlexaFluor conjugated secondary antibodies were used for immunofluorescence microscopy. Sections were mounted in Vectashield solution (H-1000, Vector Laboratories). Images were acquired with confocal laser-scanning microscope (Leica TCS SP5).

Image analysis
All image analyses were carried out blindly, i.e., without disclosing the experimental group of mice, by one experimenter. For electron microscopy analysis, one ultrathin section per embedded block was observed to avoid counting the same neuron, and 1-3 blocks have been used per animal. Synaptic and glial elements were identified on printed images, which were acquired at an original x 30,000 magnification, according to standard morphological criteria. Synapses were detected as small and round objects around somas, enriched in mitochondria and vesicles, and presenting electron-dense pre- and post-synaptic structures. Glia was defined as light filament around somas, with cloudy glycogen-related granulation. Number of synapses and glial elements was counted directly on printed images. Morphometric study for determination of neuronal perimeter and glial coverage was computed with the open source ImageJ software on digitalized images acquired at x 6,000-8,000 original magnification.

For synaptic puncta analysis, microphotographs from confocal microscopy were analyzed with Imaris software (Bitplane). Surface rendering was done for each channel prior to contact analysis. Contacts between pre-synaptic puncta and POMC neurons were determined using the “Surface Surface Contact Area” plug-in (Imaris, Bitplane). To assess somatic puncta, numbers of contacts between VGAT-positive elements and VGlut1-positive elements were counted on a single tdTomato-positive soma. To assess perisomatic puncta, contacts between synaptic puncta and tdTomato-positive fibers were determined on 3 regions of interest (ROI) per image. Each standardized ROI (300 μm²) were designated to exclude tdTomato-positive soma. In these ROIs, contacts between tdTomato-positive objects and VGAT-positive elements or VGlut1-positive elements were counted. Scores were standardized by calculating the ratio between VGlut1-positive elements and VGAT-positive elements per soma or per ROI.

Cytotoxicity assay in primary astrocyte culture
Toxicity of treatments in primary astrocyte cultures were checked with a cytotoxicity detection kit (Roche Applied Science) based on the measurement of LDH activity released from damaged cells. According to the manufacturer’s instructions, a fraction of the culture supernatants was used after treatments and incubated for up to 30 min at room temperature with a freshly prepared reaction mixture (v/v). Absorbance was determined at 490 nm using a microplate reader (Tecan). Viability was estimated from the absorbance of treated versus untreated cells (100%).

cAMP assay in primary astrocyte culture
Intracellular levels of 3',5'-cyclic adenosine monophosphate (cAMP) was measured after treatments in primary astrocyte cultures using the luminescence-based cAMP-GloTM Max Assay (Promega). According to the manufacturer’s protocol, intracellular cAMP levels were measured and quantified using a cAMP standard curve. Luminescence was measured using a microplate reader (FLUOstar OPTIMA, BMG Labtech).

QUANTIFICATION AND STATISTICAL ANALYSIS
Statistical analyses were performed using Prism 5.0 software (GraphPad Software, Inc.). No statistical method was used to predefined sample size. Results on graphs were expressed as means and error bars indicated standard errors of the mean (SEM). Comparisons between 2 groups were carried out using two-tailed Student test or nonparametric Mann-Whitney test, as appropriate. Multiple comparisons of groups were carried out using one-way analysis of variance (ANOVA) followed by post hoc Newman-Keuls test or using nonparametric Kruskal-Wallis test followed by post hoc Dunns test, as appropriate. Equality of variances and normality of distribution were checked prior each analysis. No correction was applied on data for analyses. A p value < 0.05 was considered statistically significant. Significant difference was noted *, **, or *** on the graphic representation when p value was < 0.05, 0.01, and 0.001, respectively.

DATA AND CODE AVAILABILITY
This study did not generate any unique datasets or code.