Title

Synaptic plasticity in the medial preoptic area of male mice encodes social experiences with female and regulates behavior toward young

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Summary

A dramatic shift from aggressive infanticidal to paternal behaviors is an essential event for male mice after mating. While the central part of the medial preoptic area (cMPOA) has been shown to critically mediate the paternal behaviors in mice, how this brain region becomes activated by mating and subsequent interaction with pups has not been investigated. Here, we demonstrate that the reduction in inhibitory synaptic strength towards the cMPOA provided by posterior-dorsal medial amygdala (MePD) neurons is a key event for the post-mating behavioral shift in males. Consistent with this, we found optogenetic disinhibition of Me^{Cartpt} to the cMPOA synapses reduces male aggression

towards pups. The cMPOA of paternal mice mediated pup-induced neural plastic changes in the bed nucleus of the stria terminalis. These findings provide possible functions of cMPOA neural circuits required for the reception to young in male mice.

Introduction

Reproductive behavior in male includes courting, mating and parental behavior. Polygynous male mammals, which form reproductive groups with one male and multiple females, often show aggressive behavior toward un-familiar infant conspecifics[1-5]. Infanticide of non-offspring young is commonly believed to improve reproductive success by achieving a shorter inter-birth interval for females, a situation more favorable to breeding lower competition for resources, and the avoidance of misdirected paternal investment[3,6]. After mating, however, the same male gradually stops committing infanticide and becomes paternal, even toward non-biological offspring[5]. This behavioral transition from infanticide to paternal care in C57BL/6 male mice is shown to require not only the experience of ejaculation but also cohabitation with the pregnant female[7,8]. The exact neural mechanisms governing this behavioral transition through social experiences with female and infant remained unknown.

The medial preoptic area (MPOA) has been identified as one of the most important brain regions regulating parental behavior[9]. Within the MPOA, the central part (cMPOA), located ventral to the cluster of magnocellular oxytocin neurons (the anterior commissural nucleus), appears to play a pivotal role in parental behavior because bilateral cMPOA lesions abolished this behavior and promoted infanticide in both maternal and paternal mice[10,11]. Likewise, optogenetic activation of the MPOA in virgin male mice delayed infanticidal behavior[11,12]. However, the neural circuit mechanisms controlling the MPOA neuronal activities were unclear. Previously, we reported that behavioral mode transition from infanticide to parental was initiated by lesions of vomeronasal organ (VNO), which transmits olfactory information to the accessory olfactory bulb[8]. Similar results were obtained in the experiment using genetically mutated mice with impaired vomeronasal signaling[12]. Tracing studies using classical retrograde tracer or rabies virus indicate that sensory information from accessary olfactory system is mediated by the bed nucleus of the stria terminalis (BST) and the medial amygdala (Me) and is transmitted to the MPOA[13-15]. It is reported that aggressive behavior toward pup is elicited by activation of GABAergic Me[16,17].

The present study evaluates the efficacy of synaptic transmission from the Me to putative cMPOA neurons from three groups: (i) virgin males, (ii) males that experienced mating and pup exposure, and (iii) an intermediate stage, males that experienced mating but had not pup exposure, referred to as "father in gestation experiences (FGE)" [18]) (Fig. 1A). We observed that inhibitory inputs from the Me to cMPOA were suppressed before pup delivery, leading to cMPOA disinhibition. Optogenetic inhibition of Me–cMPOA synapses significantly reduced the proportion of mice showing aggressive behavior toward pups. Furthermore, we found paternal experiences increased synaptic inhibition in the rhomboid nucleus of the bed nucleus of the stria terminalis (BSTrh), one of a downstream structure of the MPOA[11]. Together, findings indicate that alterations in plasticity at Me–

cMPOA synapses occur as a result of social experience with a female partner, which may function to prime a shift in behavioral response toward pups. This is followed by paternal experience with pups inducing changes in BSTrh.

Results

Cart positive Me neurons project to the cMPOA and respond to pup exposure

To map the projections from the Me to cMPOA, we took advantage of the high expression of the peptide, cocaine and amphetamine regulated transcript (Cart), in the subpopulation of posterior-dorsal Me (MePD) neurons[19,20]. Within the Me, clusters of Cart-positive neurons were visualized in the MePD by immunostaining with an anti-Cart antibody (Fig. S1A). We infused biotin dextran amine (BDA), an anterograde neuron tracer, into the Cart-positive area of the Me (Fig. 1B) and observed neural projections descending between fornix and anterior commissure (AC) and entering the cMPOA were observed (Fig. 1C, D). The cMPOA is located ventral to the anterior commissural nucleus, which contains magnocellular oxytocin neurons and thus could be visualized using an antibody for the oxytocin-associated protein neurophysin I (NPI)[10]. In contrast to the Cart-positive area of the Me, the Cart-negative area did not send a dense projection to the cMPOA regardless of tiny BDA leak in the Cart-positive area of the Me (Fig. S1B-E). We observed neural activity marker, cFos expression in MPOA regions receiving projection from Me in Cart-positive regions, with different trends between the paternal and virgin groups, with cFos expression tending to be higher in the paternal group in cMPOA (Fig. 1E, F). Next, we infused an AAV vector encoding Cre-dependent eYFP into the Me of Cartpt (which encodes Cart)-Cre mice for pathway identification, and we observed a clear Cre-dependent eYFP expression in Me^{Cartpt} neurons and eYFP-labeled projections into the cMPOA (Fig. 1G), consistent with the tracer study (Fig. 1B and 1D).

Furthermore, we investigated the neural activity of Me^{Cartpt} neurons after exposure to pups. Cartpt-Cre: Ai9 reporter mice showed that 21.2% of NeuN-positive neurons in MePD were Cartpt (tdTomato) positive (Fig. 1H). We exposed three pups to Cartpt-Cre: Ai9 -FGE mice for four days, and as the days passed, the proportion of mice showing aggressive behavior decreased, while the number of parental individuals increased (Fig. 1I); mice showing aggressive and parental respectively on day four were perfused with PFA 90 min after the end of the behavioral test. The results of the immunohistochemical analysis showed a significant increase of c-Fos positive Cartpt-neurons in the aggressive and parental groups compared to the control group but no difference between the aggressive and parental groups (Fig. 1J, K).

Sensitivity to GABAergic synaptic inputs from the Me to the cMPOA are suppressed by mating experience and cohabitation with a late gestational female

We infused an AAV vector to express blue light-sensitive channelrhodopsin, ChR2(H134R) in Me^{Cartpt} neurons (Fig. 2A). After incubation periods, we performed whole-cell patch clamp recordings from cMPOA neurons in slices prepared from these mice. Application of blue light to brain slices, including

the cMPOA, depolarized the synaptic terminals derived from Me^{Cartpt} neurons and induced both excitatory and inhibitory synaptic currents in cMPOA neurons; as expected, control group mice expressing only eYFP did not show light-evoked synaptic responses (Fig. 2B-D). We evaluated social experience-dependent synaptic changes at both excitatory and inhibitory pathways. At the recording potential (−60 mV), glutamatergic and GABAergic ionotropic receptor currents should flow in the opposite direction. Thus, glutamatergic and GABAergic predominance can be distinguished by the net change in membrane current. Because of the abundance of GABAergic neurons in the MePD[13], including retrogradely labeled cMPOA projecting MePD neurons (Fig. S2), we chose an experimental protocol that emphasized the EPSC amplitude. The driving force for EPSC and IPSC, calculated by subtraction of the recording potential (−60 mV) and reversal potential (−1 mV for EPSC, −87 mV for IPSC calculated by Nernst equation), was about 59 mV and 27 mV, respectively. Under this experimental protocol, we counted cMPOA neurons expressing predominantly blue light-induced EPSCs or IPSCs by the net membrane current change. Whereas 83.3% of cMPOA neurons were IPSC-dominant in virgin male mice, only 21.4% were IPSC-dominant in FGE males (Fig. 2F). In addition, we observed that intracellular perfusion of a membrane-impermeable G-protein signaling blocker GDPβS into the cMPOA neurons reversed the ratio of IPSC- dominant neurons in FGE males to the level of virgin males. The data presented suggest that experiencing mating and cohousing with a pregnant female changes the excitatory/inhibitory (E-I) balance at synaptic transmission from Me^{Cartpt} into the cMPOA. Whereas application of tetrodotoxin (TTX) blocked light-induced synaptic current, an additional application of 4-aminopyridine rescued, suggesting the monosynaptic projection at the Me^{Cartpt}-cMPOA pathway (Fig. 2F).

Such changes in E-I balance could be caused by an increased excitatory or a decreased inhibitory synaptic function. We analyzed spontaneous postsynaptic currents in the cMPOA and found changes in the frequency of spontaneous inhibitory postsynaptic currents (sIPSCs) but no differences in amplitude. A comparison of relative frequencies showed a trend towards less frequent intervals of sIPSC in the paternal and FGE groups than in virgin (Fig. 2H-K). No differences were found in spontaneous excitatory postsynaptic currents (sEPSCs, Fig. S3A-E).

Next, we applied electrical stimulation on the fiber inputs including those from Cart-positive Me to the cMPOA. Similar to FGE mice, paternal mice showed a significant level of decreased eIPSP amplitude in the cMPOA compared with the virgin mice (Fig. 2L). In addition, intracellular infusion of GDPβS reversed eIPSP amplitude in the paternal group. Average evoked excitatory postsynaptic potentials (eEPSPs) amplitudes did not differ between the groups (Fig. S3F). We also addressed the effects of pregnant female exposure alone (i.e., without the experience of copulation and delivery) on virgin males (virgin male with late gestation; VMLG group, Fig. S4A) or sexual experience without staying until late gestation of female partner (male with mating experience; MME, Fig. S4D). As a result, eIPSP amplitude in the cMPOA in VMLG and MME mice was not changed (Fig. S4B and S4E), suggesting that either mating experience or cohabitation with a late gestational female was not enough to reduce eIPSP amplitude in the cMPOA. There were no significant differences in the passive

155 membrane properties of cMPOA neurons among the groups (Table S1). In behavioral test, most mice
156 showed aggression on the first day in both groups; in the VMLG group, this did not change throughout
157 the four days, whereas in the MME group, some mice showed parental behavior as the experimental
158 days passed.

159 To address the recorded cell type in the cMPOA, we prepared cell samples using the same
160 experimental methods as patch clamp recordings were manually collected using a glass pipette. RNA-
161 seq analysis was performed to evaluate mRNA expression levels. Six samples were combined and
162 represented as data for one mouse. Table S2 lists the differentially expressed genes (DEGs) in cMPOA
163 neurons among virgin (V), FGE (F), and paternal (P) mice. Further, we evaluated the expression levels
164 of 21 representative genes previously reported in activated MPOA neurons during social behavior[21]
165 to explore the recorded neuron's cell type in this study and found no difference in their expression
166 levels among the groups. Among all samples, the expression level of *Galanin* (*Gal*) was the highest
167 (Fig. 2M). We visualized *Galanin* mRNA-positive neurons with Alexa647 using *in situ* hybridization
168 chain reaction (HCR). We observed a banded *Galanin*-expressing region extending ventrally from the
169 posterior part of the anterior commissure (AC) and covering the cMPOA region (Fig. 2N). Also, the cell
170 types of the recorded neurons in our experimental protocol were addressed by co-staining of post hoc *in situ*
171 hybridization and visualization of biocytin by reacting it with streptavidin conjugated to fluorescein
172 isothiocyanate (FITC). We observed that 85.0% (34 in 40 cells) of the recorded neurons were positive
173 for *Galanin* mRNA co-staining (Fig. 2O, P). When the average evoked inhibitory postsynaptic
174 potential amplitude was compared in the neuron confirmed as *Galanin*-positive, the FGE group
175 showed significantly smaller than the virgin group (Fig. 2Q), as seen in Fig. 2L. These meticulous
176 findings suggest that mating and cohabitation with a female before pup delivery induces synapse
177 plastic changes in the cMPOA of male mice, which densely includes *Galanin*-positive neurons.
178

179 **Optogenetic inhibition of Me-to-cMPOA inputs changes the spontaneous synaptic activity**

180 Next, we attempted to silence synapses of Me^{Cartpt} terminals in the cMPOA to examine
181 whether inhibition of these inputs modulates neural and/or synaptic activity. For this, we infused an
182 AAV vector encoding vertebrate long-wavelength opsin (vLWO)[22,23] bilaterally into the Me of virgin
183 Cartpt-Cre mice to suppress Me^{Cartpt} inputs (Fig. 3A). To confirm the inhibitory effects of vLWO, we
184 performed whole-cell patch clamp recordings from Me^{Cartpt} neurons expressing vLWO-eGFP.
185 Application of green light hyperpolarized Me^{Cartpt} neurons (Fig. 3B and 3C) but did not in the control
186 group (Fig. 3D and 3E).

187 Next, we infused an AAV vector encoding ChR2 and vLWO into the Me of virgin Cartpt-Cre
188 mice to confirm the inhibitory effects of vLWO at the synaptic terminal (Fig. 3F and 3G). After more
189 than four weeks, brain slices were prepared and recorded from cMPOA neurons. A green light could
190 affect ChR2, and therefore, instead of using green light as above, the red light was used to stimulate
191 the vLWO. The amplitude of blue light-induced IPSC was significantly reduced by vLWO activation
192 (Fig. 3H and 3I). Furthermore, the suppressed synaptic inputs from the Me^{Cartpt} to the MPOA could

193 result in reduced direct synaptic transmission and in more frequent inhibitory synaptic currents by
194 disinhibition of surrounding interneurons. To address this hypothesis, we observed spontaneous
195 IPSCs (sIPSC) in each cMPOA neuron before and after inhibiting inputs from the Me^{Cartpt} via vLWO
196 activation (Fig. 3J-L). Within 25 recorded neurons, sIPSC frequency was increased by more than 10%
197 in 13 neurons and reduced by more than 10% in 1 neuron. The average frequency of the sIPSC in
198 cMPOA was significantly increased (Fig. 3L). The application of TTX blocked the effects of vLWO
199 activation (Fig. 3M and 3N). These data suggest that inhibition of the Me^{Cartpt} inputs to the cMPOA
200 could modify the activity of each neuron in the cMPOA by acting on an inter-neuronal network.
201
202 **In vivo optogenetic inhibition of Me-cMPOA inputs suppresses infanticidal behavior**
203 Next, we aimed to address the causal relationship between synapse plastic changes in the
204 cMPOA and behavioral changes. To address the behavioral causality of the impaired Me-cMPOA
205 inputs, we infused an AAV vector encoding vLWO into the Me of virgin Cartpt-Cre mice, and two optic
206 fibers were bilaterally implanted above the cMPOA for optogenetic stimulation. While the green light
207 was delivered to the cMPOA, three pups were exposed (Fig. 4A). The proportion of vLWO-expressing
208 mice that did not show infanticidal behavior was more significant than in the control group. As a
209 reference to previous reports, we scored each behavioral pattern as follows; infanticide within 3 min
210 = 0, infanticide between 3-30 min = 1, neither infanticide nor parenting (non parenting) = 2, one or
211 two pups retrieved to the nest = 3, all three pups retrieved to the nest = 4. About this relative
212 frequency of behavioral patterns, we found statistically significant differences between the vLWO and
213 the control group (Fig. 4B). After a four-day test with a green light application, subject mice were
214 exposed to pups again without the green light application. As a result, a similar proportion of subject
215 mice as day four did not infanticide again. The latency to first sniffing did not differ significantly
216 between the vLWO group and control group (Fig. 4C). Latency and probability of each mouse
217 committing infanticide throughout test days were shown in the survival curve (Fig. 4D). Because we
218 detected altered GABAergic neurotransmission in the cMPOA of FGE and paternal mice, we tested
219 the effects of inhibition of the Me input to cMPOA in vGAT-IRES-Cre mice. As a result, similar trends
220 to the case of Carpt-Cre mice were observed in vGAT-IRES-Cre mice with statistically significant
221 differences (Fig. 4E-I). These data suggest that inhibition of the Me inputs to the cMPOA disrupts
222 aggression of virgin male mice toward pup without minimal effect on investigation motivation.
223
224 **Paternal experience enhances inhibitory transmission in the BSTrh through a postsynaptic**
225 **mechanism**
226 We have demonstrated that the decreased inhibition of MPOA by Me input upon experiences with
227 female is a crucial event for suppressing infanticide in the FGE. However, about half of FGE mice
228 still show infanticidal behavior, whereas almost all paternal mice do not show infanticidal behavior[8].
229 Next, we examined the synaptic change in paternal mice upon experiences with the pup.
230 The downstream structure of the MPOA, the rhomboid nucleus of the bed nucleus of the stria

terminalis (BSTrh), is activated by infanticidal behavior and negatively regulated by cMPOA[11]. To address the impact of social experiences on the BSTrh synaptic property, we measured the changes in the excitatory−inhibitory (E/I) ratio of the virgin, FGE, and paternal groups in a manner similar to our previous studies[24]. The average amplitude of IPSPs evoked by electrical stimulation of the stria terminalis (Fig. 6A) was enhanced in the BSTrh of the paternal group compared to FGE and virgin groups (Fig. 6B). However, the average eEPSP amplitudes did not differ significantly between these groups (Fig. 6C). These data suggest that, in the paternal mice, increased inhibition in the BSTrh critically occurs following experiences with pups, called pup sensitization.

We hypothesized that the cMPOA plays a critical role in increasing inhibition in the BSTrh. To evaluate this hypothesis, we specifically lesioned the MPOA. To this end, we bilaterally injected NMDA into the cMPOA in virgin and paternal mice (Fig. 6D and S5) and, 3 to 9 days later, performed whole-cell recordings from BSTrh. In the BSTrh of ipsilaterally lesioned paternal mice, the average eIPSP amplitude was significantly smaller than in unlesioned paternal mice (Fig. 6E). These data strongly suggest that the increased inhibitory input to the BSTrh is mediated by the cMPOA in mice showing paternal behavior. It should be noted that cMPOA fiber inputs into BSTrh were not likely stimulated to evoke synaptic responses in the current protocol because cMPOA lesion unchanged eIPSP amplitude in virgin mice (Fig. 6F).

We next addressed whether this increased inhibition onto the BSTrh occurs through a pre- or post-synaptic mechanism. There were no significant differences in passive membrane properties among the three groups (Table S3). We carried out a patch-clamp analysis on BSTrh of paternal group mice. We found out that while inclusion of the GDPβS in the pipette does reduce the amplitude of eIPSPs to the level of the virgin group (Fig. 6G), eEPSP did not show apparent changes (Fig. 6H). These data suggest that the increased eIPSP amplitude in the BSTrh occurs mainly by the postsynaptic mechanisms. We also analyzed the paired-pulse ratios to compare the release probability from presynaptic terminal and found out that the ratio of eEPSCs and eIPSCs did not differ between paternal and virgin groups (Fig. 6I). Altogether, we conclude that the cMPOA in the paternal mice mediates plastic changes at GABA synapses in the BSTrh mainly by the postsynaptic mechanisms, and these sequential events are centrally involved in the fundamental switch in the paternal behaviors of the father animals.

Effects of pup sensitization on the inhibitory synapse in the cMPOA and in the BSTrh through a postsynaptic mechanism

Repeated exposure of pups to rodents, even male mice, elicits parental behavior [25,26]. These results inspired us to investigate synaptic function in male mice that have never mated but engage in parenting behavior. We previously reported that the majority of virgin male C57Bl6J mice before sexual maturation showed retrieval of pups to their nest[24]. Here, virgin male mice at postnatal day 28 experienced pup exposure four times per week and repeated three, six, and eight weeks. No attacks on pups were observed during this period. At 12 weeks old, we tested the behavioral pattern in

response to pup exposure (Fig. 6A). As a result, consecutive pup exposures did not result in infanticide on pups beyond sexual maturity; instead, each mouse exhibited pup retrieval to the nest. The proportion of pup-sensitized mice showing infanticide increased in proportion to the length of the gap between the end of pup exposure and the behavioral test (Fig. 6B).

Next, we examined the inhibitory synaptic change in pup-sensitized mice upon experience with the pup for eight weeks. The amplitude of eIPSPs in the cMPOA in pup-sensitized males was similar to that of control males without experience of sensation (Fig. 6C). On the other hand, the amplitude of eIPSPs in the BSTrh in pup ed male were potentiated compared with control males (Fig. 6D) as seen in paternal mice (Fig. 5B). These data suggest that the experiences with pup sensitization encode inhibitory synapse in the BSTrh.

Discussion

The results showed that multi-step plastic synapse changes correlate with the transition from infanticidal to parental behavior in male mice (Fig. S6). The synapses from Me^{Cartpt} neurons in the cMPOA were altered by interactions with females (Fig. 2). Optogenetic inhibition of the Me^{Cartpt} -cMPOA pathway resulted in impaired aggression of virgin male mice (Fig. 4), suggesting plastic change in Me^{Cartpt} -cMPOA synapses is the potential trigger for the behavioral transition from virgin to FGE. In addition, the shift from FGE to paternal was accompanied by an increased BSTrh inhibition (Fig 5). These plastic changes caused the change of E/I balance, which correlated positively with the neuronal activity of the cMPOA and BSTrh when virgin or paternal males were contacted with pups.

The Me has been implicated in various social behaviors, including social investigation, mating, and aggression[8,12,27-30]. In males, the functional association between the Me and the MPOA is critical for mating behavior[31,32]. The Me comprises several subdivisions with neural activity patterns, distinct projections and cell types[28,33,34], including the MePD, a sexually dimorphic nucleus crucial for aggressive behaviors[12,28,35,36]. In the present study, we focused on Cartpt, which has been reported to be enriched in two of the 16 clusters of the Me [20]. Cartpt-positive neurons were more responsive to pups than to neutral objects (Fig. 1J, K). The one-way ANOVA test also found significant differences in the total number of cFos-positive (non-specific) neurons per unit area ($F(2, 8) = 4.912$, $P=0.0406$). However, no differences were detected among the groups in the post hoc test. These data support the importance of investigating the contribution of the Me^{Cartpt}-MPOA pathway in the neural mechanisms of social behavior.

Each subpopulation of Me neurons might specifically control some cMPOA neurons and the associated behavioral pattern. Our targeted cMPOA area are mainly composed by *Galanin*-positive neurons (Fig 2M-O), consistent with the previous reports that the activation of *Galanin*-positive MPOA neuron cause inhibition of aggressive behavior toward pup[12,14]. The MPOA contributes to several types of intrinsic behaviors, activating the MPOA neurons according to different patterns[11,14,28-30,37-39]. However, the mechanisms underlying the expression of one appropriate

behavior remain unknown. Suppressing the accessory olfactory signals mediating the Me, presumably changes neural activity patterns in the cMPOA. This hypothesis is supported by the results that temporal disinhibition of the Me－cMPOA pathway modifies behavioral patterns and increases cMPOA inter-neuronal network activity, as reflected by the increased frequency of sIPSCs (Fig. 3). In addition to the Me, other inputs into the cMPOA would drive several inter-neuronal network activity patterns to achieve the multi-functional MPOA and behavioral choices.

In the present study, we show for the first time that social experience with females, including mating, alters the E-I balance in synaptic transmission in the cMPOA in male mice. Changes in GABAergic neurotransmission were observed in sIPSCs and electrical stimulation-induced postsynaptic potentials of FGE and paternal group (Fig. 2L), but not in glutamatergic neurotransmission (Fig. S3). Me^{Cartpt} neurons contain more GABAergic neurons, supporting the possibility of altered GABAergic synaptic function in the cMPOA, the projection site from Me^{Cartpt}. In addition, changes in the probability of neurotransmitter release from the presynaptic side and receptor sensitivity and expression levels are known to cause changes in the E-I balance. Me^{Cartpt}: Ai9 neurons showed more cFos positive neurons against pups than in neutral objects, but no significant differences between the infanticide and parental groups (Fig. 1K). In the electrophysiological analysis, GDPβS infusion into the recording cMPOA neurons reversed the E-I balance in FGE mice to the level of virgin (Fig. 2C). Thus, it is suggested that changes in $GABA_A$ receptor in the cMPOA neurons cause the E-I balance changes in the Me^{Cartpt}-cMPOA pathway. However, these hypotheses do not match the reduced sIPSC frequency in FGE mice (Fig. 2G-K); the hypothesis that only some GABA synapses within a single cMPOA neuron are drastically altered may explain the results. It is also necessary to take into account complex mechanisms, such as changes in activity occurring in neurons throughout the MPOA associated with synaptic changes that alter the pattern of intercellular communication, rather than merely input from the Me^{Cartpt}. The details require further investigation. How does the experience with female mice bring about these changes? As neither behavior nor synaptic function was altered in the VMLG model (Fig S4), we consider it unlikely that the experience with a pregnant female could direct the brain function and behavior of virgin male mice towards the parental side. Similarly, no inhibitory synaptic changes in the cMPOA were observed in male mice that did not experience mating but came to express parental behavior through pup sensitization (Fig. 6). These data suggest that the synaptic changes in the cMPOA that we detected encode the experience of mating and cohabitation with females but not pup. On the other hand, it was previously reported that the number of males showing infanticide decreased about two weeks after ejaculation without cohabitation with the female partner[7,40]. The behavior of males toward pups appears to be controlled by factors triggered by ejaculation, which remain effective for several subsequent weeks, thus preventing infanticide of the male's own offspring. Several groups have reported that prolactin has the effect of promoting paternal behavior [41,42]. However, the possibility that mating-induced prolactin concentration increases may influence subsequent paternal expression has been negatively described in studies using the D_2 receptor agonist bromocriptine. Post-mating neurotransmission in the brain

area related to paternal expression may be altered over time by multiple hormones/neurotransmitters and changes in receptor sensitivity, as has been discussed [43]. Synaptic functional changes that occur on the way to express fatherhood, such as those found in the present study, may provide clues to elicit new developments in clarifying paternal expression. In this study, the MME model, which experienced mating but separated from female mice, showed parental behavior after several days of pup exposure, although most of them showed infanticide on the first experimental day. Also, the MME model differed from the FGE and paternal groups in the amplitude of eIPSP (Fig S4). The experiences of mating and the social isolation period of 2 weeks after mating might affect synaptic function in the cMPOA and behavioral patterns related to aggression and pup sensitization.

Interestingly, unlike the synaptic changes in the Me^{Cartpt} - cMPOA pathways of FGE mice, an inhibitory shift was observed in the BSTrh E/I balance induced by the caring experience (Fig. 5, 6). What is the biological significance of the increased BSTrh inhibition? Like the previous report[11], we observed that BSTrh inactivation by hM4Di significantly delayed infanticidal behavior in virgin male mice without parental behavior initiation (Fig. S7). This suggests that BSTrh does not block parental behavior directly. On the other hand, considering the reduced latency for the pup retrieval as the experimental days progressed in FGE and paternal mice (Fig. S8), BSTrh plastic changes could contribute to pup sensitization, which underlies the onset of pup caring. The cMPOA lesions reversed the increased BSTrh inhibition in paternal mice to the level of virgin mice, suggesting that the inhibitory transmission of BSTrh was controlled by cMPOA (Fig. 6D and 6E). The following facts support this: (1) cMPOA neurons project into the BSTrh, and (2) unilateral lesion of the cMPOA increases the number of c-Fos positive neurons in the ipsilateral BSTrh of mice exposed to pups[11]. Because increased BSTrh inhibition in paternal mice is sensitive to intracellular GDPβS infusion (Fig. 6G), some neurotransmitter or peptide metabotropic receptors may influence BSTrh during and/or after pup sensitization. The cMPOA neurons activated during parental behavior contain many neurotransmitters, including Galanin, neurotensin, and tachykinin2[10,24]. Moreover, the anterior commissural nucleus, adjacent to the cMPOA, contains the third largest population of magnocellular oxytocin neurons. Therefore, cMPOA neurons or adjacent neurons may directly and persistently control GABAA receptor activity in the BSTrh of paternal mice via metabotropic receptors.

The results of this study show that mating and cohabitation with females and pup sensitization are processed in various parts of the brain, resulting in aggressive male mice going into parenting. Converging data suggest that the cMPOA neurons contribute to infanticide inhibition and parental behavior by modifying the inter-neuronal network and projecting it downstream, including BSTrh. Uncovering the relevant MPOA subgroup for each function requires the analysis of neural circuits. Understanding the modulatory mechanism of synaptic plasticity in the cMPOA and BSTrh may provide evidence for possible interventions in parental stress and subsequent child maltreatment.

Author contributions

TA conceived the study with support from KOK. TA, TS and MM designed the experiments. TA, KI,

383 and KS conducted the behavioral experiments. TA and KI performed stereotaxic surgeries. TA, YT,
384 KI, KS, YH, SM, YT, and SS performed histological experiments. TA and HU performed whole-cell
385 patch clamp recordings. TM, TS and SH developed the AAV virus expressing vLWO. TA and HO
386 prepared sample for RNA sequence and YS, MS and KS analyzed data. TA wrote the manuscript with
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403

404 **STAR Methods**

405 Animals

406 The Animal Experiment Committee of the RIKEN Brain Science Institute and Institutional Animal
407 Care and Use Committee at Hokkaido University approved all animal experiments, which were
408 conducted in compliance with the National Institute of Health guidelines for the care and use of
409 laboratory animals.

410 Animal maintenance and male exposure to different levels of mating and paternal experience

411 Most C57BL/6J male mice were bred at the RIKEN Brain Science Institute and Graduate School of
412 Pharmaceutical Sciences, Hokkaido University unless specially described. For the BDA (Thermo
413 Fisher Scientific) tracer injection into Me (Fig. 1A-C and S1), we utilized C57BL/6J male mice from
414 Japan SLC. Cartpt-Cre mice (Jackson Laboratory, stock number 009615), vGAT-IRES-Cre mice
415 (Jackson Laboratory, stock number 016962) and Ai9 (Jackson Laboratory, stock number 007909) were
416 bred at the Graduate School of Pharmaceutical Sciences, Hokkaido University. We backcrossed vGAT-
417 IRES-Cre mice with C57BL/6J mice at least five generations after arrival from Jackson Laboratory.
418 Mice were housed in individually ventilated cages and provided ad libitum access to water and food
419 and maintained under a 12-h light/dark cycle in cages lined with TEK Fresh Standard bedding
420 (Envigo). Mice were weaned at postnatal day 28 (P28). All mutant heterogenic mice were co-housed
421 with wild-type mice until the experiments. To produce paternal group mice, a virgin male mouse was
422 housed with a female for mating. After delivery, the male stayed with pups for 3 days. All paternal
423 group males experienced one delivery and were used for experiments within 20 days after the birth
424 of pups. If pups did not survive for more than 3 days, the male was not included in the paternal group
425 for experiments. Other virgin male mice were mated and co-housed with a female only until late
426 gestation but not delivery, termed 'fathers in gestation experience' (FGE) mice.

427

428 Stereotaxic surgery

429 BDA (1.25 μg/ dissolved in 12.5 nL 0.1 M phosphate buffer), N-methyl-D-aspartic acid (NMDA, Sigma-
430 Aldrich, 20 mg/ml in saline), and AAV5-EF1α-DIO-hChR2(H134R)-eYFP (6.6×10^{12} genome copies/ml,
431 provided by Vector Core at the University of North Carolina (UNC) at Chapel Hill, UNC vector core),
432 AAV5-EF1α-DIO-eYFP (5.6×10^{12} genome copies/ml, UNC vector core), AAV10-EF1α-DIO-vLWO-
433 eGFP-5HT1A (3.7×10^{13} or 1.8×10^{13} genome copies/ml, UNC vector core), AAV10-EF1α-DIO-eYFP
434 (1.2×10^{14} or 3.7×10^{13} genome copies/ml, UNC vector core), rAAV2-EF1a-DO_DIO-tdTomato_EGFP-
435 WPRE (more than 7.0×10^{12} vg/ml, Addgene), AAV2-hSyn-HA-IRES-eGFP (3.3×10^{12} genome
436 copies/ml, UNC vector core), and AAV2-hSyn-HA-hM4Di(Gi)-IRES-mCitrine (5.6×10^{12} genome
437 copies/ml, UNC vector core) (100–400 nL/hemisphere), were administered under anesthesia. Briefly,
438 2–3-month-old male mice were anesthetized by intraperitoneal (i.p.) sodium pentobarbital (30 mg/kg)
439 or the mixture of medetomidine hydrochloride (0.3mg/kg), midazolam (4mg/kg), butorphanol tartrate
440 (5 mg/kg)[44], and local subcutaneous (s.c.) lidocaine hydrochloride. The skull was exposed and holes
441 drilled for stereotaxic injection. Glass capillaries of ~50 μm tip diameter were filled with oil and

442 backfilled with the test drug or AAV vector. Injection was targeted by referring to the Mouse Brain
443 Atlas of Flanklin & Paxinos (2007) coordinates for the Me (AP −1.5 mm, ML 2.1 mm, DV −5.4 mm
444 and AP −1.2 mm, ML 1.9 mm, DV −5.6 mm), cMPOA (AP 0.1 mm, ML 0.55 mm, DV −5.1 mm), and
445 BSTrh (AP −0.1 mm, ML 1.2 mm, DV −4.2 mm). After injection, the skin was closed with a nylon
446 suture. Mice were kept in single housing 3−4 days for recovery. Mice injected with AAV vectors were
447 then maintained under group housing for more than 4 weeks to allow for expression of vector genes.
448 One week before behavioral testing, optic fibers were implanted into the targeted area as described
449 below.
450
451 Histological analysis
452 Mice were anesthetized by sodium pentobarbital (50 mg/kg, i.p.) and transcardially perfused with 4%
453 paraformaldehyde (PFA) dissolved in phosphate buffered saline (PBS, pH 7.4). Brains were removed
454 from the skull and post-fixed overnight in PFA at 4 °C, followed by incubation in PBS/20% sucrose for
455 1 day and PBS/30% sucrose for 1−2 days. Brains were then embedded in O.C.T. Compound (Sakura
456 Finetek) at −80 °C and sectioned at 40 μm using a Cryostat (Leica Biosystems) unless otherwise
457 indicated. Some brains were used to prepare sections for electrophysiological analysis. In the case of
458 BSTrh recording after MPOA lesion, serial slices including MPOA were sectioned at 80 μm in cutting
459 solution (see below) using a Leica VT1200 Semiautomatic Vibrating Blade Microtome (Leica). These
460 slices and the slices including BSTrh used for electrophysiological analysis were fixed in 4% PFA and
461 immunostained.
462 For fluorescent immunohistochemical staining, brain slices were incubated in PBS
463 containing 0.1% Triton X-100 (PBST) for more than 15 min and then in 0.4% Block Ace (Dainihon-
464 Seiyaku) for an hour. Slices were then incubated at 4 °C overnight in Block Ace solution containing
465 primary antibody. After several rinses in PBST, slices were incubated in PBST containing secondary
466 antibody at room temperature. Table S4 shows antibody list.
467 To stain the BDA anterograde tracer, sections were incubated with Alexa 568-conjugated
468 streptavidin (1:500, Thermo Fisher Scientific) for 2 hours. After washout of the secondary antibody
469 or streptavidin, slices were mounted on glass slides with VECTASHIELD Mounting Medium (Vector
470 Laboratories). For 3, 3-diaminobenzidine (DAB) staining, immunolabeled slices were incubated in 0.1
471 M glycine for 10 min, 0.5% H_2O_2 for 30 min, and VECTASTAIN ABC reagent (Vector Laboratories)
472 overnight at 4 °C. After rinsing several times with PBST, the slices were incubated with Vector DAB
473 Substrate (Vector Laboratories) including nickel chloride for about 5 min. The stained slices were
474 mounted on gelatin-coated glass slides and dried. After nissl staining, slides were treated with
475 Softmount (Wako). Labeling of *Galanin* positive neurons followed modified protocol of *in situ*
476 hybridization chain reaction (HCR) using short hairpin DNAs[45,46] using probes listed in Table S5.
477 Fixed brain section re-sliced at 75 μm after patch clamp recording with internal solution containing
478 1% biocytin (Sigma) and 100 nU RNase inhibitor (Promega), or 30 μm brain section fixed by 4% PFA
479 were soaked in methanol for 10 minutes. After washing with PBST, the sections were prehybridized

480 for 10 min at 37°C in a hybridization buffer containing 10% dextran sulfate, 1× standard saline citrate
481 (SSC), 0.1% Tween 20, 50 μg/ml heparin, 1× Denhardt's solution. The sections were moved to another
482 hybridization solution containing a mixture of 20 nM split-initiator probes, and incubated overnight
483 at 37°C. For *in situ* HCR, 3 μM hairpin DNA solutions were separately snap-cooled before use. The
484 sections were incubated in amplification buffer (10% dextran sulfate in 5× SSCT) with 60 nM hairpin
485 DNA pairs for 2 hours at 25°C. Then, the samples were washed with PBST three times at room
486 temperature.
487 Immunofluorescence images were captured using an incident-light fluorescence microscope
488 (Leica DM6000B, Leica), confocal laser-scanning microscope (FV-10, Olympus), or fluorescence
489 microscope (BZ-X700, Keyence). To allow for comparison among trials, the contrast and brightness of
490 all photographs were adjusted linearly and uniformly using Adobe Photoshop CS5 (Adobe Systems)
491 unless specially described. For the lesion study, sections were immunostained with anti-NeuN
492 antibody to confirm cell death in the target area. The loss of NeuN-immunoreactive cells in the
493 NMDA-injected group was compared with the saline group to judge the lesioned area.
494
495 Electrophysiology
496 Electrophysiological recordings were performed as described previously[24]. The artificial cerebral
497 spinal fluid (ACSF) contained 126 mM NaCl, 2.5 mM KCl, 1.25 mM NaH_2PO_4, 1 mM $MgCl_2$, 2 mM
498 $CaCl_2$, 26 mM $NaHCO_3$, and 10 mM glucose (pH 7.3). For a cutting solution, NaCl in ACSF was
499 replaced with the same concentration of choline chloride. Mice were injected with pentobarbital (30
500 mg/kg, i.p.) followed by transcardiac perfusion of ice-cold cutting solution. The brains were removed,
501 and 230-μm brain slices including the target area prepared in ice-cold choline chloride-based cutting
502 solution using a Leica VT1200 Semiautomatic Vibrating Blade Microtome. Brain slices were stored
503 in warmed ACSF at 32 °C for 20–30 min and then kept at room temperature until recording.
504 For electrophysiological recordings, slices were superfused with 32 °C–34 °C ACSF at 2–4
505 mL/min in a chamber mounted on a microscope. Neurons were identified using a 40× or 60× lens and
506 an infrared camera (IR-1000, DEGE-MTI). Glass electrodes (World Precision Instruments) of 4–9 MΩ
507 resistance were used for whole-cell patch clamp recordings in response to electrical stimulation using
508 ~0.5 MΩ glass electrodes containing ACSF. Recording electrodes were filled with a potassium-based
509 internal solution (132 mM K-gluconate, 3 mM KCl, 10 mM HEPES, 0.5 mM EGTA, 1 mM $MgCl_2$, 12
510 mM Na-phosphocreatine, 4 mM Mg-ATP, 0.5 mM Na-GTP, 0.2-0.3 % biocytin, pH 7.25) and signals
511 were recorded using an Axopatch 700B amplifier (Molecular Devices). Only cells with access
512 resistance <30 MΩ and exhibiting action potentials with >60 mV amplitude evoked by positive current
513 injection were included in the analysis. Whole-cell currents were filtered at 3 kHz. The liquid junction
514 potential (11 mV) was compensated. Stimulating electrodes were placed at the dorsal BSTrh or
515 cMPOA to stimulate stria terminalis. To activate the ChR2-expressing axon terminals, we utilized a
516 LED (465 nm, LEX2-LZ4-B, Brainvision Inc.). To activate the vLWO-expressing neurons, green light
517 generated by a 100 W mercury lamp (U-RFL-T) was applied through a fluorescence band pass filter

518 (520-550 nm) (Olympus). Red light was provided by Fiber-Coupled LED (625 nm, Thorlabs). Evoked
519 synaptic currents and potentials were measured at least three times at the same stimulus intensity
520 and averaged. Responses with action potentials were omitted from the analysis. We recorded evoked
521 excitatory postsynaptic potentials (eEPSPs) and eEPSCs at a holding potential of −85 mV in the
522 presence of 100 μM picrotoxin. eIPSPs were recorded at −65 mV and eIPSCs at −60 mV in the presence
523 of 20 μM CNQX and 20 μM MK-801. In experiments using optogenetic suppression using vLWO, slices
524 were also perfused with 25 μM 9-cis-retinal, 0.1% dimethyl sulfoxide, 0.025% (±)- α-tocopherol and
525 0.2% bovine serum albumin.
526
527 Behavioral test
528 The tests of paternal behavior toward pups were performed as described previously[24]. Mice were
529 housed individually in cages containing new purified paper bedding (Alpha-Dri, Shepherd Specialty
530 Papers) and a cotton square (Nestlet, Ancare). After 1–2 days, three pups aged 1–6 days were placed
531 into the cage corner avoiding the nest. Tests were performed once each day for 30 min on 4 successive
532 days during the daytime unless otherwise indicated. The endpoint of the aggressive behavior toward
533 pups to terminate the experiments was 2-s screams or visible wounds on the pup skin. Wounded pups
534 were immediately euthanized. The paternal behavioral score was evaluated according to previous
535 reports as follows: 4 = all pups were retrieved, 3 = 1 or 2 pups were retrieved, 2 = no pup was retrieved,
536 1 = at least one pup was attacked >3 min after placement in the test cage, and 0 = at least one pup
537 was attacked within 3 min after placement in the test cage.
538 For c-Fos mapping, the procedure was modified from a previous study[8]. Briefly, mice were
539 exposed to a pup protected inside wire-mesh ball (tea balls, 45 mm diameter; Minex Metal, Tsubame,
540 Japan) with about 10 holes (5 mm diameter) placed in a cage corner avoiding the nest for 30 min.
541 Ninety minutes later, the adult male was anesthetized with pentobarbital (50 mg/kg, i.p.) and
542 transcardially perfused with 4% PFA/PBS for brain isolation as described above. The c-Fos
543 immunoreactive cells were counted automatically by Image J software (National Institutes of Health,
544 Bethesda, MD, USA).
545
546 Optogenetic and chemogenetic manipulation of neural activity in vivo
547 Zirconia ferrules optical fibers (Thorlabs) of 200 μm diameter core (NA = 0.37) were cut and polished
548 for >70% coefficient of transmission. These constructs were bilaterally implanted into the mouse brain
549 area 1-mm above the target area and fixed with dental cement. After the mouse had recovered from
550 the surgery (one week later), the optic fibers were connected via Ceramic Split Mating with 1×2
551 Branching Fiber-optic Patch Cords-Glass (0.37 NA, Doric Lenses) to a diode laser (450 nm or 532 nm,
552 Changchun New Industries Optoelectronics Tec.) through a FC/PC connector. Averaged light power
553 at the tips between the bilateral fiber tips was set to 30−40 mW (450 nm) or 10−12 mW (532 nm).
554 Light pulses were controlled by TTL Pulse Generators (Doric Lenses). After connecting the fibers,
555 experimental mice were allowed free actiTon for 15 min. During the last minute of the behavioral test,

556 mice received constant light on for 20 s without light pulses followed by a 10-s off period. This
557 photostimulation protocol was continued throughout the 30-min behavioral experiment. After the
558 behavioral experiments, animals were perfused with 4% PFA to prepare the brain slices. Only animals
559 with bilateral expression of fluorescence labeled fiber and the bilateral optic fibers above targeted
560 area between 0.3-1.0 mm from the targeted area were included for the data analysis. For the
561 chemogentic silencing, we infused CNO (2.0 mg / kg, i.p.) and observed the behavioral pattern 30-35
562 min later. After the behavioral experiments, we immunostained the brain slices with anti-GFP. Only
563 animals with bilateral expression of fluorescent signal in the targeted area were included for the data
564 analysis.
565
566 RNA-seq analysis
567 Mouse brain slices were prepared using essentially the same procedures for electrophysiological
568 experiments. Six cMPOA neurons were manually collected by using 1 ~ 2 MΩ glass electrodes
569 containing ACSF and suspended in cell lysis buffer (0.5% Triton-X100, 0.5 U/μL RNase inhibitor, 5
570 ng/μL yeast rRNA). The cell samples were immediately frozen and stored at −80°C until starting
571 reverse transcription. Reverse transcription and cDNA library preparation were performed using the
572 Smart-seq2 method[47] with some modifications. Briefly, 12 μM $dT_{30}VN$ primer (5'-
573 AAGCAGTGGTATCAACGCAGAGTACT$_{30}$VN-3) were added into microtubes containing cell lysates
574 (final concentration, 1 μM); then, samples were heat-denatured at 70 °C for 3 min, followed by
575 immediate incubation on ice. Next, samples were mixed with a reverse transcription reaction solution
576 containing locked nucleic acid (LNA)-template switching oligo primer (5'-
577 AAGCAGTGGTATCAACGCAGAGTACrGrG+G-3', rG; riboguanosines, +G; LNA-modified guanosine,
578 final concentration of 0.6 μM) and reverse transcriptase (SMARTscribe, Clontech, final concentration
579 of 5 U/μL), and incubated at 42°C for 120 min followed by at 70°C for 10 min to terminate the reaction.
580 The resultant cDNA samples were purified using solid phase reversible immobilization (SPRI) beads
581 (AMPure XP, Beckman Coulter). The purified cDNA samples were amplified by PCR using the IS
582 primer (5'-NH_2-AAGCAGTGGTATCAACGCAGAGT-3', final concentration of 0.24 μM) and Tks Gflex
583 DNA polymerase (Takara Bio, final concentration of 0.025 U/μL). The amplified cDNA samples were
584 purified by SPRI beads. The quality and quantity of cDNA sample was confirmed by an Agilent 2100
585 Bioanalyzer using the High sensitivity DNA kit (Agilent Technology, CA, USA).
586 The cDNA samples were then processed to generate indexed libraries for sequencing using a
587 NEBNext Ultra II DNA Library Prep Kit for Illumina (#E7645, New England Biolabs Inc., Ipswich,
588 MA, USA), according to manufacturer's instructions. Then, libraries were sequenced for 50-bp single-
589 end reads using HiSeq 3000 (Illumina, San Diego, CA, USA). Output fastq files were aligned to the
590 mouse genome (GRCm38/mm10) using STAR aligner[48]. Library size normalization was performed
591 using R (v.4.1.0) by calculating transcripts per million (TPM). Genes with <5 TPM in all samples were
592 excluded from the analysis. We selected 22 genes for neuronal cluster-mediated social behavior in the
593 MPOA based on previous reports[21]. However, *Oprd1* was excluded because of its low expression.

Heatmaps were drawn using gplots (v.3.1.1). Differentially expressed genes (DEGs) between virgin, FGE, and paternal mice were analyzed using DESeq2 (v.1.32.0). Genes with a false discovery rate-adjusted $p \leq 0.05$ and a $\log_2$ fold change ≥ 2 in either direction were considered DEGs.

Statistical analysis

Group means were compared by Fisher's exact test, the two-tailed t-test, one-way or two-way repeated measures ANOVA followed by a post hoc test as indicated. All statistical tests were two-tailed and conducted with GraphPad Prism software 6 and 9 (GraphPad Software, Inc., La Jolla, CA, USA) or R (v.4.4.0) and ARTool (v.2.2.2). To compare the distribution of behavioral pattern of each mouse during optogenetic manipulation, we performed Aligned Rank Transformation (ART) to handle nonparametric factorial data transformations, and two-way ANOVA analysis. A P-value < 0.05 was deemed statistically significant. Statical data was written in the Fig. legends and Table S6.

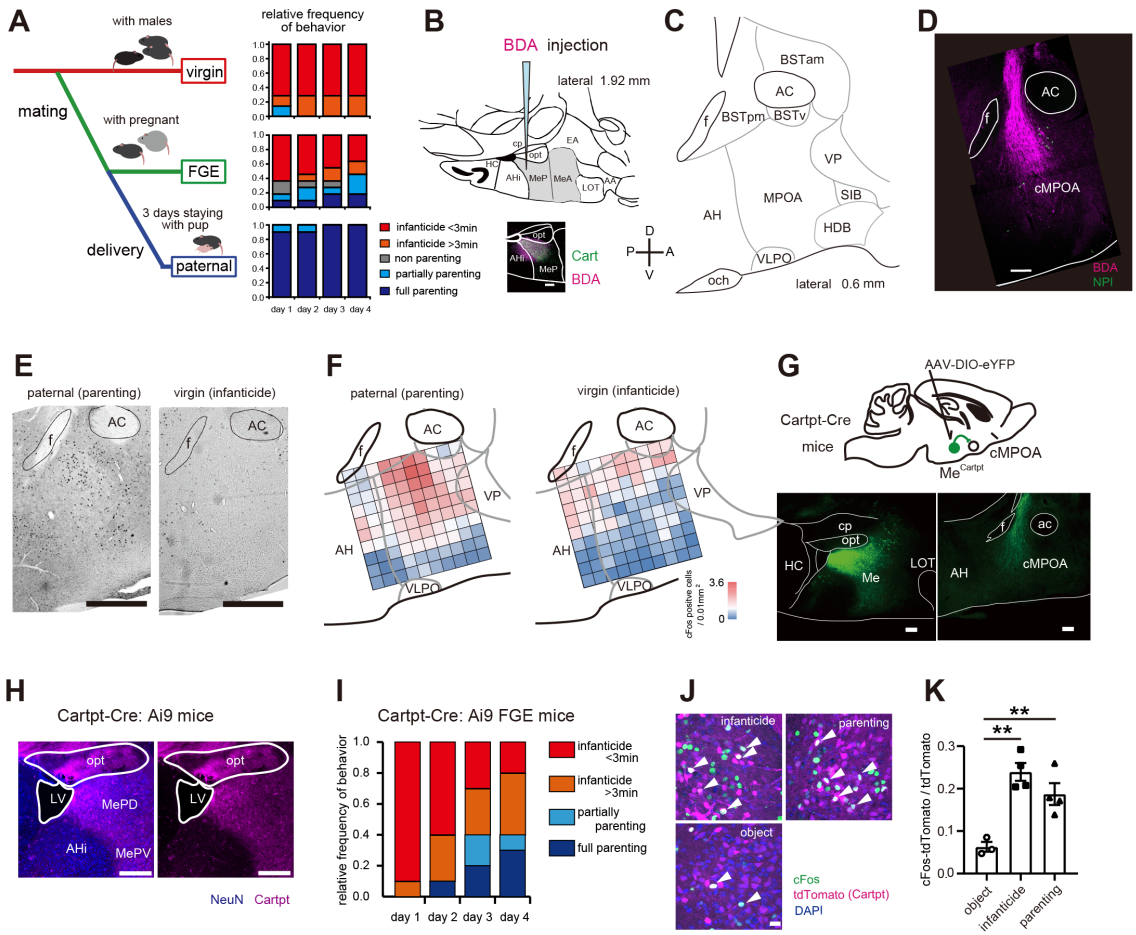
Data availability

All data that support the findings presented in this study are available from the corresponding author upon request. The raw sequences have been deposited in the DNA Data Bank of Japan (DDBJ) under the DDBJ BioProject umbrella with accession number PRJDB8470, and to the DDBJ Read Archive DRA008585 (BioSample ID: SAMD00175991- SAMD00176002).

613 **Figure Legends**

614

615



616

617 Fig. 1 The medial amygdala sends projections to the cMPOA

618 (A) (left) Schematic diagram of "virgin" male mice, intermediate males called "FGE" by mating and

619 cohabitation with partner female, and "paternal" mice, that experienced delivery of partner females

620 and cohabitation with pups for three days. (right) Relative frequencies of behavioral patterns of virgin,

621 FGE, and paternal mice toward pups during four consecutive days of pup exposure.

622 (B) upper, Medial amygdala in the parasagittal section. lower, Representative images of the Me

623 stained with anti-Cart visualized with Alexa 488 and BDA visualized with Alexa 568-conjugated

624 streptavidin (magenta). Scale bar = 200 μm.

625 and behavioral patterns of

626 (C) medial preoptic area (MPOA) in the parasagittal section.

(D) Representative images of the Me injected with the tracer BDA in the MPOA. Parasagittal sections are shown. Fixed sections were visualized with Alexa 568-conjugated streptavidin (magenta). In parallel, fixed sectioned were immunostained with anti-NPI and visualized with Alexa 647 (green). Scale bar = 200 μm.

(E) Image of cFos visualized by DAB staining in the mice showed parenting and infanticide. Scale bar = 500 μm.

(F) Expression distribution of cFos-positive neurons in each region delimited by the 100 μm grid. Red-shifted color indicates a higher density of cFos-positive neurons. paternal (n = 8), virgin (n = 3)

(G) AAV5-EF1α-DIO-eYFP was injected into the Me of Cartpt-Cre mice. Representative images of eYFP emission from Me and MPOA. Me^{Cartpt} neurons sent projection fibers into the MPOA. Scale bar = 200 μm.

(H) Representative images of the MePD in Cartpt-Cre: Ai9 reporter mice. Among MePD neurons immunostained with anti-NeuN antibody visualized with a secondary antibody conjugated to Alexa 647 (blue), 21.2% Cartpt neurons (magenta) were tdTomato positive (1 male, 1 female). Scale bar = 300 μm.

(I) Relative frequencies of behavioral patterns of FGE Cartpt-Cre: Ai9 reporter mice toward pups during four consecutive days of pup exposure.

(J) Representative images of cFos induction in the MePD following pup exposure or neutral object to FGE Cartpt-Cre: Ai9 reporter mice. Fixed sections were stained with anti-cFos and visualized with Alexa 647 (green). Arrowhead indicates the tdTomato- cFos- double-positive neurons. Scale bar = 30 μm.

(K) The ratio of c-Fos-positive neurons out of all tdTomato-positive Me^{Cartpt} neurons following pup or object exposure. object (n = 3), infanticide (n = 4), parenting (n =4). Statistical analysis by one-way ANOVA, $^{**}P < 0.01$.

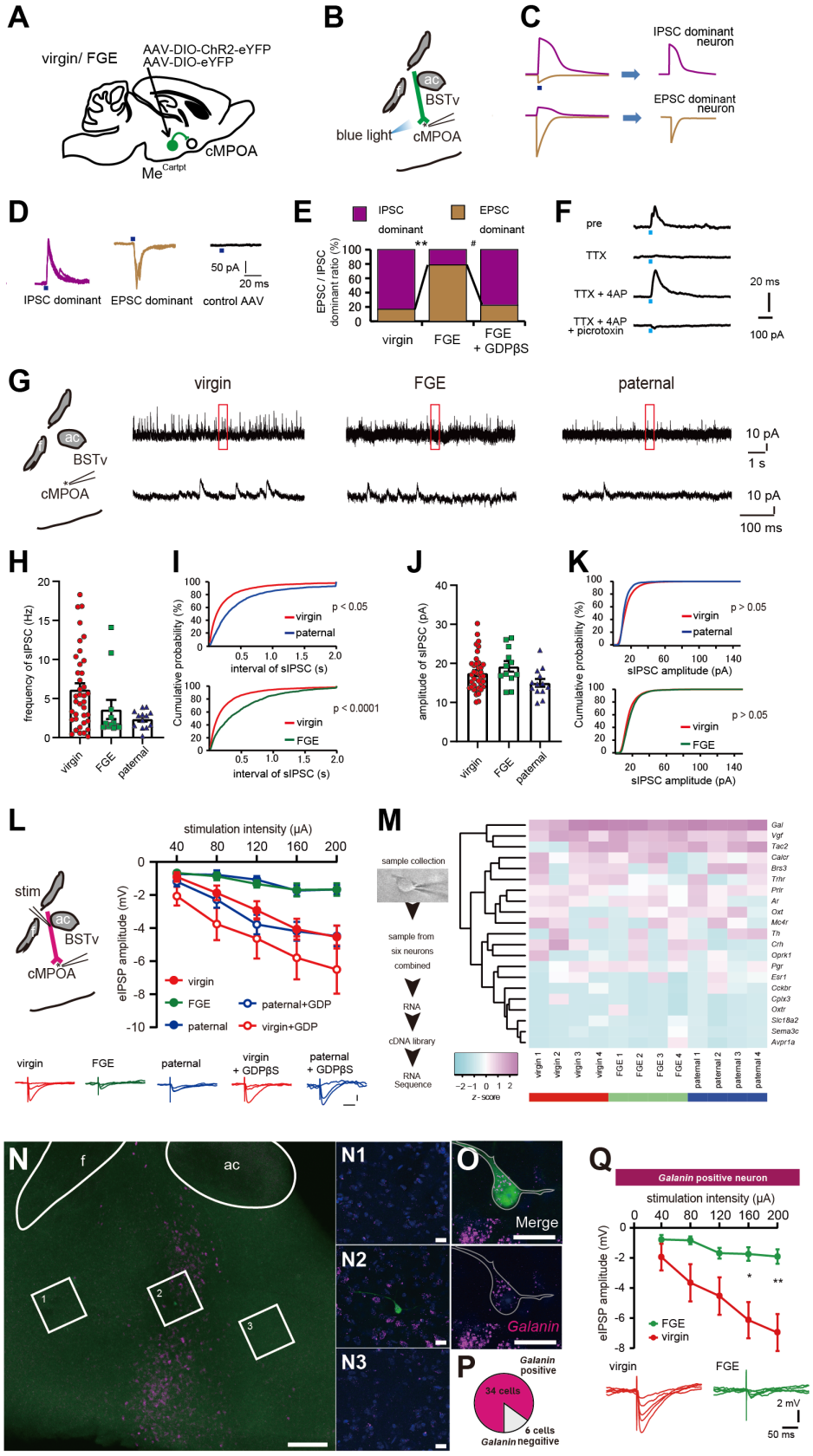

A
virgin/ FGE
AAV-DIO-ChR2-eYFP
AAV-DIO-eYFP
cMPOA
Me Cartpt
B
ac
BSTv
blue light
cMPOA
C
IPSC dominant neuron
EPSC dominant neuron
D
IPSC dominant
EPSC dominant
control AAV
50 pA
20 ms
E
IPSC dominant
EPSC dominant
EPSC / IPSC dominant ratio (%)
virgin
FGE
FGE + GDPβS
F
pre
TTX
TTX + 4AP
TTX + 4AP + picrotoxin
20 ms
100 pA
G
virgin
FGE
paternal
BSTv
cMPOA
10 pA
1 s
10 pA
100 ms
H
frequency of sIPSC (Hz)
virgin
FGE
paternal
I
Cumulative probability (%)
virgin
paternal
p < 0.05
interval of sIPSC (s)
virgin
FGE
p < 0.0001
interval of sIPSC (s)
J
amplitude of sIPSC (pA)
virgin
FGE
paternal
K
Cumulative probability (%)
virgin
paternal
p > 0.05
sIPSC amplitude (pA)
virgin
FGE
p > 0.05
sIPSC amplitude (pA)
L
stim
ac
BSTv
cMPOA
stimulation intensity (μA)
eIPSP amplitude (mV)
virgin
FGE
paternal
paternal+GDP
virgin+GDP
virgin
FGE
paternal
virgin + GDPβS
paternal + GDPβS
M
sample collection
sample from six neurons combined
RNA
cDNA library
RNA Sequence
z-score
Gal
Vgf
Tac2
Galcr
Brs3
Trhr
Prlr
Ar
Oxt
Mc4r
Th
Crh
Oprk1
Pgr
Esr1
Cckbr
Cpxk3
Oxtr
Slc18a2
Sema3c
Avpr1a
virgin 1
virgin 2
virgin 3
virgin 4
FGE 1
FGE 2
FGE 3
FGE 4
paternal 1
paternal 2
paternal 3
paternal 4
N
f
ac
1
2
3
N1
N2
N3
O
Merge
Galanin
P
Galanin positive
34 cells
6 cells
Galanin negative
Q
Galanin positive neuron
stimulation intensity (μA)
eIPSP amplitude (mV)
FGE
virgin
virgin
FGE
2 mV
50 ms

Fig. 2 Synapse plastic changes in the cMPOA neuron that occur in the process leading to paternal expression

(A) AAV5-EF1α-DIO-eYFP or AAV5-EF1α-DIO-ChR2-eYFP was injected into the Me of Cartpt-Cre mice. After the expression of eYFP with/without ChR2, whole-cell patch clamp recordings were performed from cMPOA neurons in parasagittal sections of virgin and FGE mouse brains.

(B) Schematic image of the recording from the cMPOA neuron in a parasagittal section. Input fibers from Me^{Cartpt} expressed ChR2 were stimulated by blue light application.

(C) Diagram of dominant responses of IPSC and EPSC in the opposite current direction as that of GABAergic and glutamatergic ionotropic receptors.

(D) Representative traces of blue light-evoked IPSCs and EPSCs in IPSC- and EPSC-dominant cMPOA neurons. When Me^{Cartpt} neurons were injected with the control AAV virus, no responses to optical activation were observed in cMPOA neurons.

(E) Relative frequencies of excitatory- and inhibitory-dominant cMPOA neurons in virgin mice (n = 12 cells; 4 animals), FGE mice (n = 14 cells; 3 animals), and FGE mice with GDPβS (1 mM) in the pipette solution (n = 9 cells; 2 animals). A significant difference in of excitatory- to inhibitory-dominant cMPOA neurons ratio between virgin and FGE group mice was observed (Fisher's exact probability test, **P = 0.0048). A significant difference in the ratio of excitatory- and inhibitory-dominant cMPOA neurons between FGE mice and FGE mice with GDPβS (1 mM) in the pipette solution (FGE + GDPβS group) was also observed (Fisher's exact probability test, #P = 0.0131).

(F) Representative traces of blue light-evoked IPSCs in IPSC-dominant cMPOA neurons. The application of TTX blocked light-evoked IPSC. Additional application of 4AP recovered IPSC, which was sensitive to picrotoxin.

(G) left, Schematic image of the recording from cMPOA neuron in a parasagittal section. right, Representative traces of sIPSC in cMPOA from virgin, FGE and paternal mice.

(H) Frequency of sIPSC in the cMPOA neuron of virgin (n =38 from 11 animals), FGE (n = 12 from 4 animals), and paternal mice (n = 14 from 6 animals). Statistical analysis by Kruskal-Wallis test, *P = 0.0207,

(I) Cumulative probability plots of the inter-event interval of the sIPSCs. Statistical analysis by Kolmogorov-Smirnov test, P < 0.0001 (virgin vs FGE), P = 0.0227 (virgin vs paternal),

(J) Amplitude of sIPSC in the cMPOA neuron of virgin (n =38 from 11 animals), FGE (n = 12 from 4 animals). Statistical analysis by One way ANOVA, P = 0.0666.

(K) Cumulative probability plots of the amplitude of the sIPSCs. Statistical analysis by Kolmogorov-Smirnov test, P>0.05

(L) left, Schematic image of the recording from the cMPOA neuron in a parasagittal section. Input fibers from MePD were electrically stimulated. right, Input–output curves of stimulus-evoked IPSPs from virgin (n = 18 cells; 6 animals), FGE (n = 14 cells; 4 animals), paternal (n =8 cells; 3 animals), virgin with GDPβS (1 mM) in the pipette solution (n = 13 cells; 4 animals), paternal with GDPβS (n

691 = 16 cells; 4 animals). Statistical analysis by two-way RM ANOVA, P = 0.0016.
692 (M) left, summary of experimental procedure. right, RNA-seq identification of candidate gene
693 expressed in the cMPOA neurons. Heatmap showing a *z*-scored TPM of selected genes for neuronal
694 cluster-mediated social behavior in the MPOA[21]. virgin n = 4 (n = 4), FGE (n = 4), and paternal (n =
695 4).
696 (N) Representative images of the MPOA. *Galanin* mRNA Alexa 647 -conjugated hairpin DNA (#S23)
697 (magenta), streptavidin conjugated with FITC (green) and DAPI (blue). (N1-N3) magnified images
698 corresponding area in (N), Scale bar = 200 μm for (N, left) and 20 μm for (N1-N3)
699 (O) Representative images of cMPOA neurons after whole-cell patch-clamp recording. Biocytin was
700 infused from recording pipette. Fixed sections visualized with Alexa 488-conjugated streptavidin
701 (green) and *in situ* HCR for *Galanin* mRNA Alexa 647 -conjugated hairpin DNA (#S23) (magenta).
702 Scale bar = 20 μm.
703 (P) Ratio of *Galanin* positive cMPOA neurons targeted for whole-cell patch-clamp recording.
704 (Q) Input–output curves of stimulus-evoked IPSPs from the *Galanin* positive cMPOA of virgin mice
705 (n = 12 cells; 7 animals) and FGE mice (n = 7 cells; 5 animals). Values are presented as the mean ±
706 standard error. (bottom) Representative traces used to construct input–output curves (40, 80, 120,
707 160, and 200 μA stimuli). Statistical analysis by two-way RM ANOVA, P = 0.0397, Holm-Sidak post
708 hoc test, *P < 0.05, **P < 0.01 vs. virgin group.
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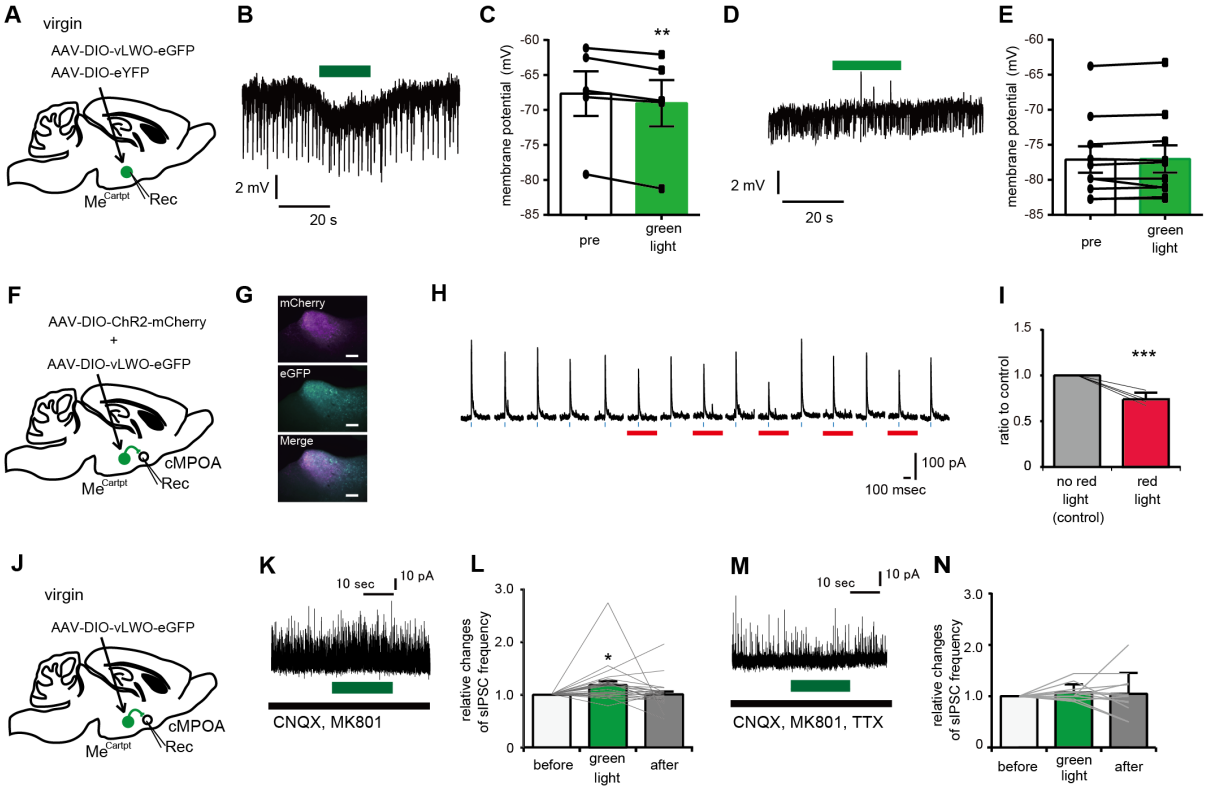

Fig. 3 The modulation of Me inputs into the cMPOA

(A) AAV10-EF1α-DIO-vLWO-eGFP or AAV10-EF1α-DIO-eYFP were injected into the Me of Cartpt-Cre mice and whole-cell recordings were obtained from fluorescent-labeled Me neurons.

(B) Representative resting membrane potential traces recorded from a Me^{Cartpt} neuron expressing vLWO. Green light was applied for 20 s (green bar).

(C) Effects of green light application on the resting membrane potential in the Me^{Cartpt} neurons expressing vLWO. The data are shown as the averaged potentials between −6 s and −1 s before the onset of green light application (pre-green light) and between 5 s and 10 s after the onset of green light application (green light). Lines represent the data obtained from individual neurons (n = 5), and bars represent the averaged data obtained from five neurons. Statistical analysis by two-tailed paired t-test, **P = 0.0017, compared with pre-green light application.

(D) Representative resting membrane potential traces recorded from a Me^{Cartpt} neuron expressing control eYFP. Green light was applied for 20 s (green bar). Five animals were excluded due to exclusion criteria.

(E) Effects of green light application on the resting membrane potential in the Me^{Cartpt} neurons expressing control eYFP. Lines represent the data obtained from individual neurons (n = 10), and bars represent the averaged data obtained from nine neurons. Statistical analysis by two-tailed paired t-test, P = 0.6308, compared with pre-green light application.

730 (F) AAV5-DIO-ChR2(H134R)-mCherry and AAV10-EF1α-DIO-vLWO-eGFP-5HT1A was injected into
731 the Me of Cartpt-Cre mice and whole-cell recordings were obtained from cMPOA neurons.
732 (G) Representative images of the Me expressing eGFP and mCherry. Scale bar = 200 μm.
733 (H) Representative traces of blue light-evoked IPSCs in the cMPOA neurons. Red bar indicates red
734 light application (2 s).
735 (I) Effects of red-light application on the blue light-evoked postsynaptic currents in the cMPOA
736 neurons. Lines represent the data obtained from individual neurons (n = 4), and bars represent the
737 averaged data obtained. Statistical analysis by two-tailed paired t-test ***P = 0.0007, compared with
738 pre-red light application.
739 (J) AAV10-EF1α-DIO-vLWO-eGFP was injected into the Me of Cartpt-Cre mice and whole-cell
740 recordings were obtained from cMPOA neurons.
741 (K) Representative trace of green light-induced modulation of sIPSCs in the cMPOA neurons. Green
742 light was applied for 20 s.
743 (L) Effects of green light application on the frequency of sIPSC in the cMPOA neurons. Lines represent
744 the data obtained from individual neurons (n = 25), and bars represent the averaged data. Statistical
745 analysis by repeated measures ANOVA, P = 0.0396, followed by Dunnett's multiple comparisons post
746 hoc test *P = 0.0332 compared with pre-green light application. One data showed large sIPSC
747 frequency. It was judged as an outlier in Grubbs' test. Without this data point, the same repeated
748 measure ANOVA analysis resulted in F (1.733, 39.87) = 4.149, P=0.0279, indicating that the
749 conclusion remains when leaving out this outlier.
750 (M) Representative trace of sIPSCs in the cMPOA neurons in the presence of TTX (1 μM).
751 (N) Application of TTX blocked the green light induced changes of IPSCs frequency. Lines represent
752 the data obtained from individual neurons (n = 12), and bars represent the averaged data. Statistical
753 analysis by repeated measures ANOVA, P = 0.6561 followed by Dunnett's multiple comparisons post
754 hoc test *P = 0.2338 compared with pre-green light application.
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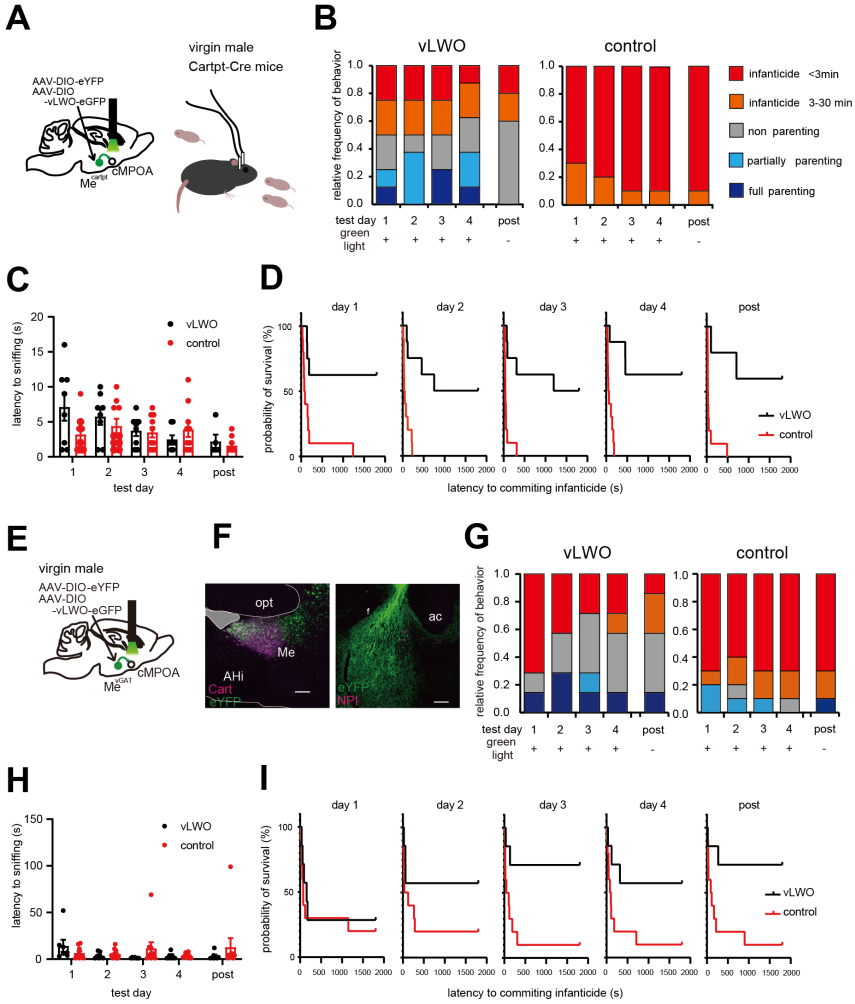

Fig. 4 Optogenetic manipulation of the Me^{Cartpt}–cMPOA input suppressed infanticidal behavior of virgin male mice

(A) AAV10-EF1α-DIO-vLWO-eGFP-5HT1A or AAV10-EF1α-DIO-eYFP was injected into the Me of Cartpt-Cre mice.

(B) Relative frequencies of paternal/infanticidal behaviors toward pups during manipulation of the Me^{Cartpt}-to-cMPOA input by vLWO activation. Significant difference in the ratio showing infanticidal behavior between mice expressing vLWO-eGFP (n = 8, n =5 for post) or eYFP only (n = 10). Analysis of Variance of Aligned Rank Transformed Data, F (1.236, 13.60) = 63.27, P < 0.0001.

(C) Latencies to first sniffing were compared between vLWO and control group mice. Statistical analysis by two-way RM ANOVA, F (1, 16) = 1.642, P = 0.2183.

(D) Survival curve to indicate the probability of committing infanticide on each experimental day. vLWO-eGFP (n = 8, n =5 for post) or eYFP only (n = 10).

(E) AAV10-EF1α-DIO-vLWO-eGFP-5HT1A or AAV10-EF1α-DIO-eYFP was injected into the Me of vGAT-IRES-Cre mice.

(F) Representative images of eYFP expressed in the Me of vGAT-IRES-Cre mice (green). Sections were immunostained with anti-Cart and visualized with a secondary antibody conjugated to Alexa 594 (magenta). All scale bar = 200 μm.

(G) Relative frequencies of paternal/infanticidal behaviors during vLWO activation at the Me^{vGAT} input into cMPOA. Significant difference in the ratio showing infanticidal behavior between mice expressing vLWO-eGFP (n = 8, n =5 for post) or eYFP only (n = 10). Analysis of Variance of Aligned Rank Transformed Data, F (1.236, 13.60) = 5.2140, P = 0.026

(H) Latencies to first sniffing were compared between vLWO and control group mice. Statistical analysis by two-way RM ANOVA, F (1, 16) = 1.642, P = 0.2183.

(I) Survival curve to indicate the probability of committing infanticide on each experimental day. vLWO-eGFP (n = 8, n =5 for post) or eYFP only (n = 10).

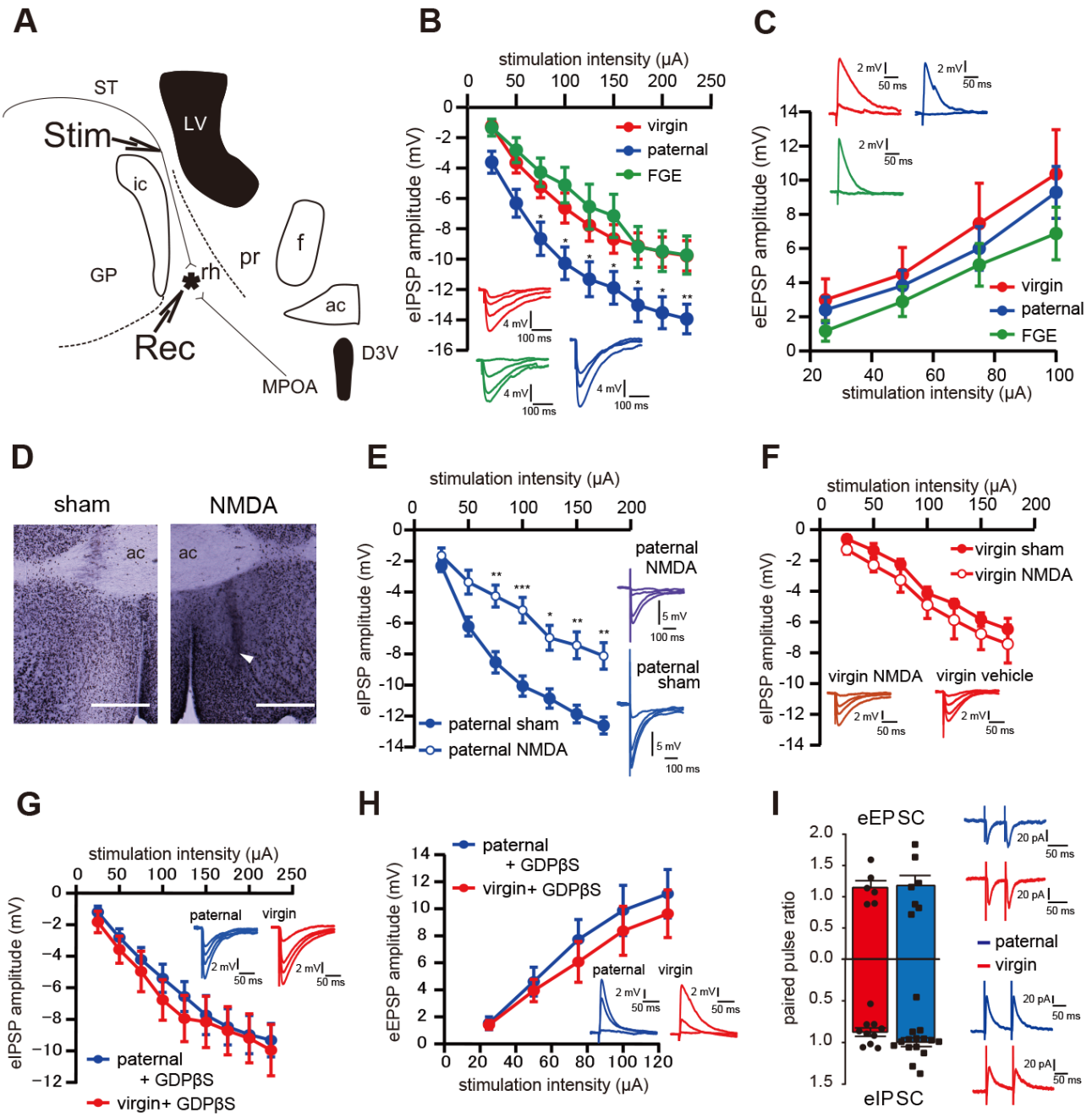

Fig. 5 Inhibitory synaptic inputs into the BSTrh were potentiated in paternal group mice

(A) Whole-cell patch clamp recordings were performed on BSTrh neurons (Rec). To observe the evoked synaptic responses, electrical stimulation was delivered through a stimulating electrode (Stim). rh, rhomboid nucleus; pr, principal nucleus; LV, lateral ventricle; ic, internal capsule; f, fornix; D3V, dorsal third ventricle; GP, globus pallidus; ac, anterior commissure; ST, stria terminalis

(B) Input–output curves of stimulus-evoked IPSPs from virgin mice (n = 16 cells; 10 animals), paternal mice (n = 17 cells; 11 animals), and FGE mice (n = 10 cells; 5 animals). Values are presented as the mean ± standard error. (inset) Representative traces used to construct input–output curves (50, 100, 150, and 200 μA stimuli). Statistical analysis by two-way RM ANOVA, P = 0.0083, followed by

Holm-Sidak post hoc test, *P < 0.05, **P < 0.01 vs. virgin group.

(C) Input–output curves of stimulus-evoked EPSPs from virgin mice (n = 9 cells; 6 animals), paternal mice (n = 15 cells; 6 animals), and FGE mice (n = 6 cells; 3 animals). Values are presented as the mean ± standard error. (inset) Representative traces used to construct input–output curves (25 and 100 μA stimuli). Statistical analysis by two-way RM ANOVA, P > 0.05.

(D) Photographs of the MPOA from sham-operated and NMDA-lesioned mice. Sections were immunostained with anti-NeuN and visualized with DAB. Arrowhead indicates the ventral edge of lesioned area. Scale bar = 500 μm.

(E) Input–output curves of stimulus-evoked IPSPs from paternal sham-operated mice (sham; n = 26 from 7 mice, NMDA; n = 15 from 6 mice). Values are presented as the mean ± standard error. (inset) Representative traces used to construct input–output curves (25, 75, 125, and 175 μA stimuli). Statistical analysis by two-way RM ANOVA, P = 0.0032 followed by Holm-Sidak post hoc test, *P < 0.05, **P < 0.01, ***P < 0.001 vs. virgin group.

(F) Input–output curves of stimulus-evoked IPSPs from sham-operated virgin mice (sham; n = 7 cells; 4 animals) and cMPOA-lesioned virgin mice (NMDA; n = 9 cells; 4 animals). Values are presented as the mean ± standard error. (inset) Representative traces used to construct input–output curves (25, 75, 125, and 175 μA stimuli). Statistical analysis by two-way RM ANOVA, P > 0.05.

(G) Input–output curves of stimulus-evoked IPSPs from virgin mice (n = 10 cells; 4 animals) and paternal mice (n = 9 cells; 4 animals) recorded with GDPβS (1 mM) in the pipette solution. Values are presented as mean ± standard error. (inset) Representative traces used to construct input–output curves (50, 100, 150, and 200 μA stimuli). Statistical analysis by two-way RM ANOVA, P > 0.05.

(H) Input–output curves of stimulus-evoked EPSPs from virgin mice (n = 9 cells; 5 animals) and paternal mice (n = 10 cells; 4 animals) recorded with GDPβS (1 mM) in the pipette solution. Values are presented as mean ± standard error. (inset) Representative traces used to construct input–output curves (25, 75 and 125 μA stimuli). Statistical analysis by two-way RM ANOVA, P > 0.05.

(I) (top) Paired-pulse ratio of eEPSCs (inter-stimulation interval = 50 ms) from virgin mice (n = 6 cells; 5 animals) and paternal mice (n = 7 cells; 6 animals). Statistical analysis by two-tailed unpaired t-test: P > 0.05. (bottom) Paired-pulse ratio of eIPSCs (inter-stimulation interval = 100 ms) from virgin mice (n = 10 cells; 9 animals) and paternal mice (n = 15 cells; 10 animals). Statistical analysis by two-tailed unpaired t-test, P > 0.05.

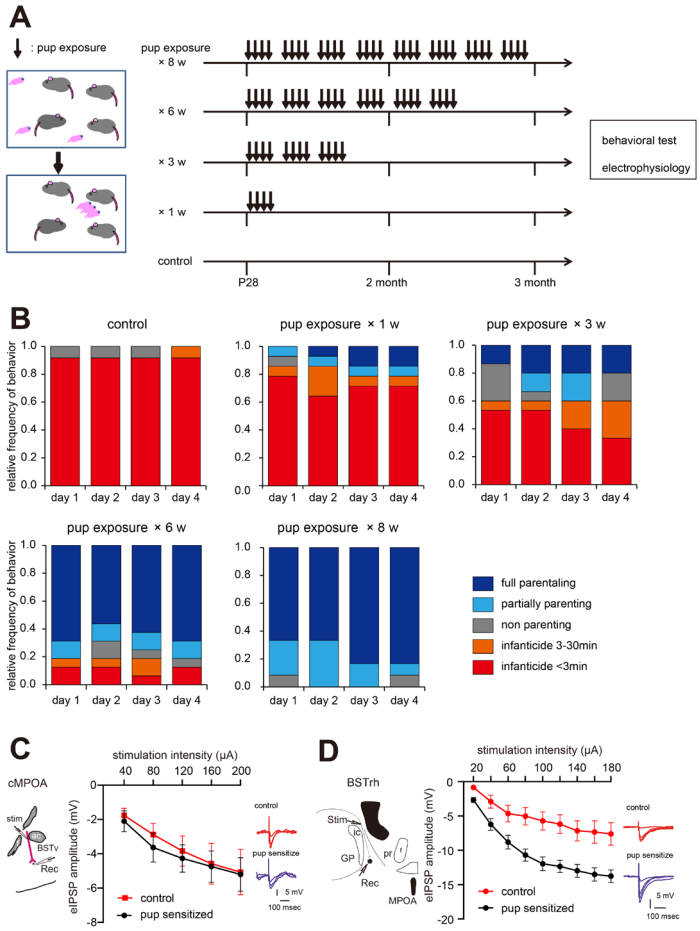

Fig. 6 Inhibitory synaptic inputs into the BSTrh were potentiated in pup-sensitized mice

(A) Schematic diagram of continuous pup exposure. Four male mice at postnatal day 28 for the first time were exposed to three pups for 30-60 min, four times per week. After one, three, six, and eight weeks of this protocol, mice were used for the experiment.

(B) Relative frequencies of paternal/infanticidal behaviors of one, three, six, and eight-week pup exposed and control mice.

(C) left, a schematic image of the recording from the cMPOA neuron in a parasagittal section. Input fibers from MePD were electrically stimulated. middle, Input–output curves of stimulus-evoked IPSPs in the cMPOA from pup-sensitized mice (n = 15 cells; 4 animals) and control mice (n = 9 cells; 3 animals). Statistical analysis by two-way RM ANOVA, P = 0.7579, right, representative trace (40, 120, 200 μA stimuli)

(D) left, a Schematic image of the recording from the BSTth neuron in a parasagittal section. Stria terminalis was electrically stimulated. middle, Input–output curves of stimulus-evoked IPSPs in the BSTth from pup-sensitized mice (n = 16 cells; 4 animals) and control mice (n = 9 cells; 5 animals). Statistical analysis by two-way RM ANOVA, P = 0.0016, right, representative trace (20, 60, 100, 140 μA stimuli)

Values are presented as the mean ± standard error.

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845 **References**

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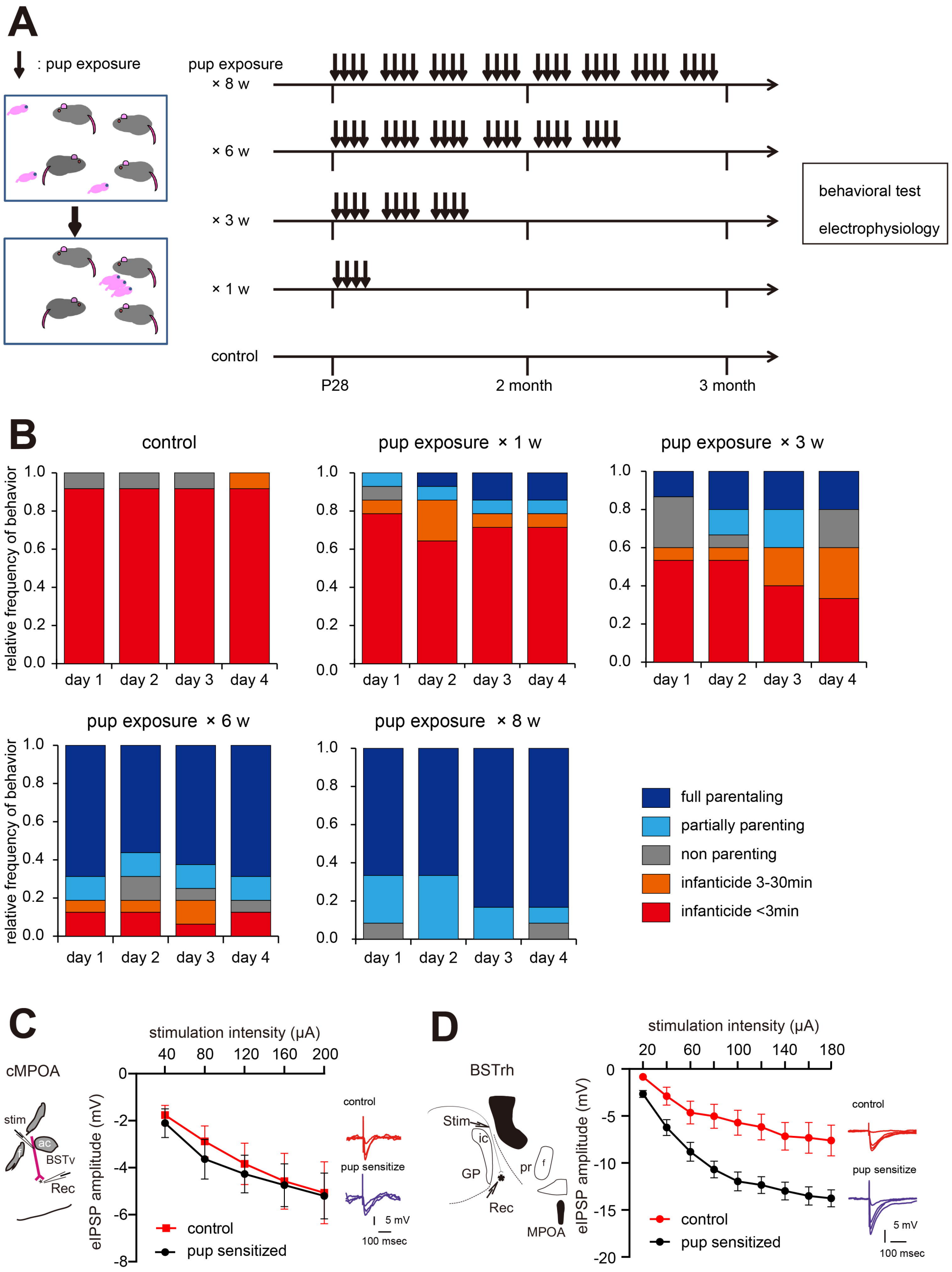
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day 2
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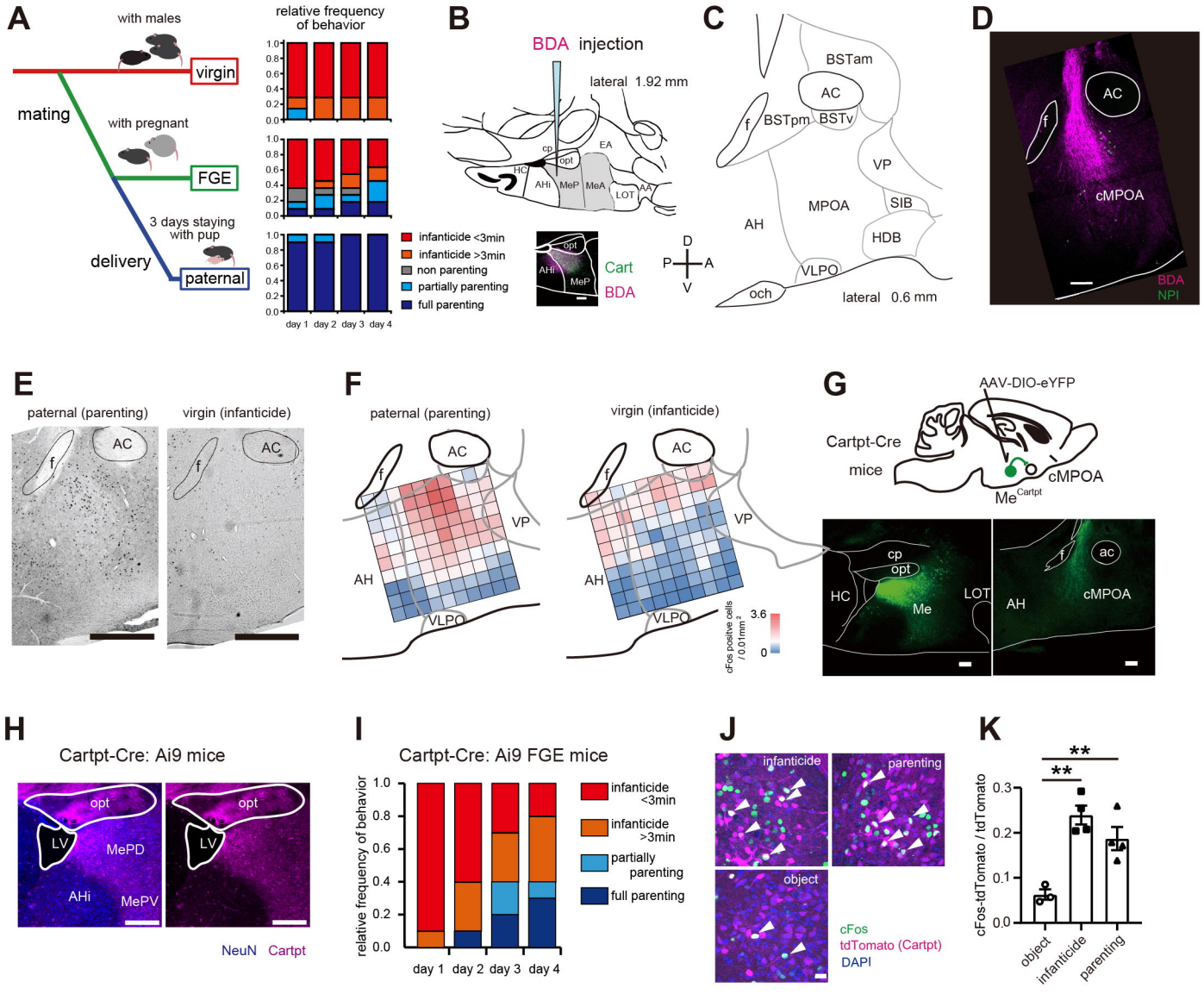
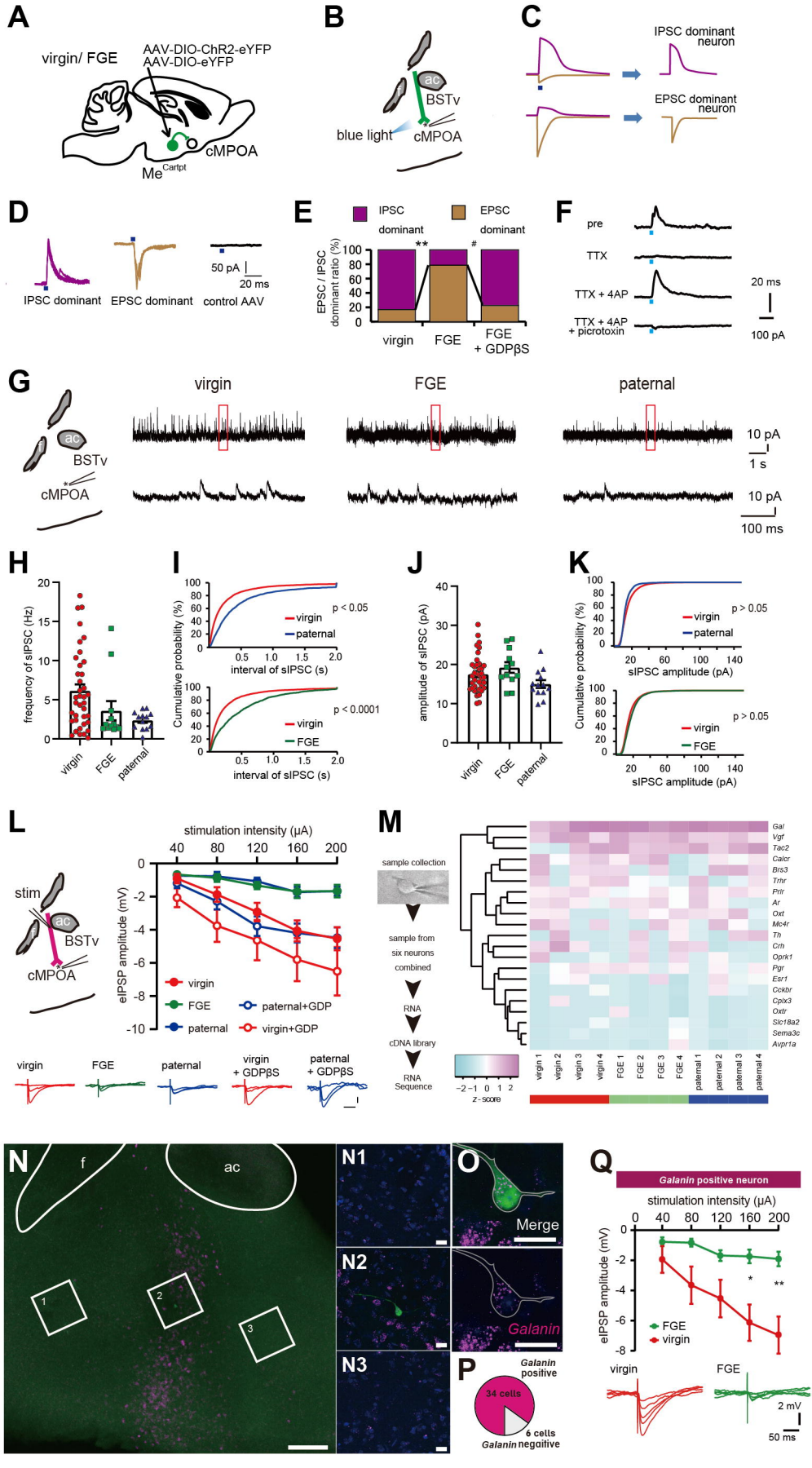
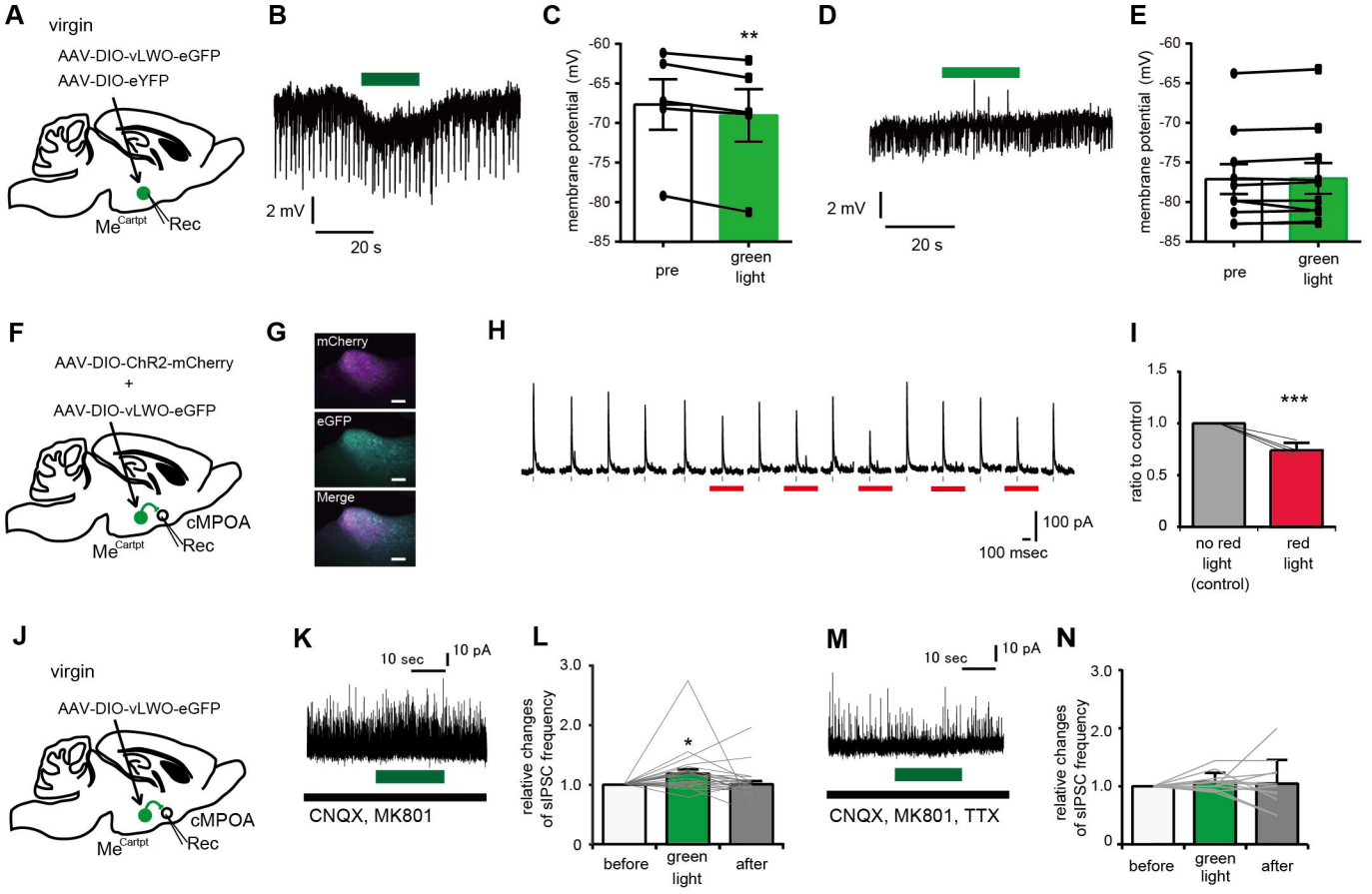
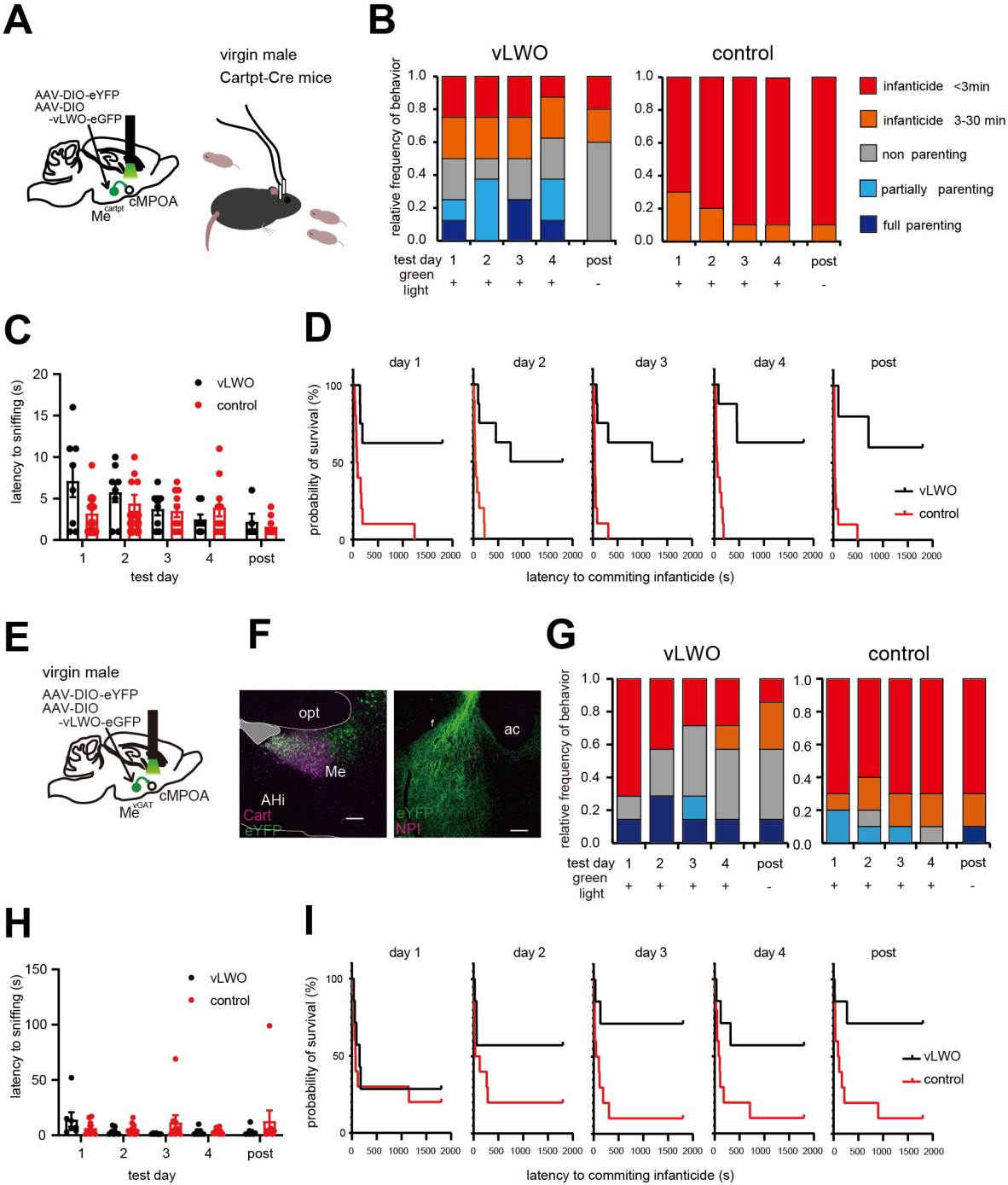
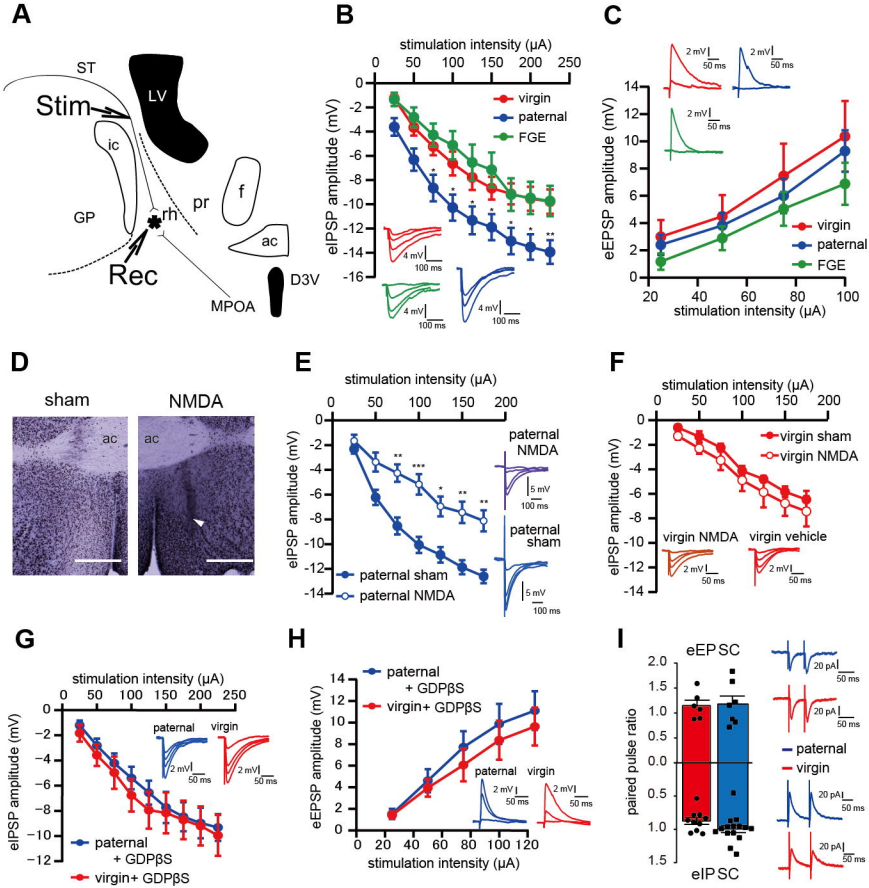
MPOA
stimulation intensity (μA)
eIPSP amplitude (mV)
control
pup sensitized
pup sensitize
5 mV
100 msec


A
with males
virgin
mating
with pregnant
FGE
3 days staying with pup
delivery
paternal
relative frequency of behavior
day 1
day 2
day 3
day 4
infanticide <3min
infanticide >3min
non parenting
partially parenting
full parenting
B
BDA injection
lateral 1.92 mm
cp
opt
EA
HC
AHi
MeP
MeA
LOT
AA
Cart
BDA
D
P
A
V
C
BSTam
AC
BSTpm
BSTv
f
VP
MPOA
SIB
AH
HDB
VLPO
och
lateral 0.6 mm
D
AC
f
cMPOA
BDA
NPI
E
paternal (parenting)
virgin (infanticide)
AC
f
F
paternal (parenting)
virgin (infanticide)
AC
f
VP
AH
VLPO
cFos positive cells / 0.01mm²
3.6
0
G
AAV-DIO-eYFP
Cartpt-Cre mice
cMPOA
Me Cartpt
cp
opt
HC
Me
LOT
ac
AH
cMPOA
H
Cartpt-Cre: Ai9 mice
opt
LV
MePD
AHi
MePV
NeuN
Cartpt
I
Cartpt-Cre: Ai9 FGE mice
relative frequency of behavior
infanticide <3min
infanticide >3min
partially parenting
full parenting
day 1
day 2
day 3
day 4
J
infanticide
parenting
object
cFos
tdTomato (Cartpt)
DAPI
K
cFos-tdTomato / tdTomato
**
**
object
infanticide
parenting


A
virgin/ FGE
AAV-DIO-ChR2-eYFP
AAV-DIO-eYFP
cMPOA
Me Cartpt
B
ac
BSTv
blue light
cMPOA
C
IPSC dominant neuron
EPSC dominant neuron
D
IPSC dominant
EPSC dominant
control AAV
50 pA
20 ms
E
IPSC dominant
EPSC dominant
EPSC / IPSC dominant ratio (%)
virgin
FGE
FGE + GDPβS
F
pre
TTX
TTX + 4AP
TTX + 4AP + picrotoxin
20 ms
100 pA
G
virgin
FGE
paternal
ac
BSTv
cMPOA
10 pA
1 s
100 ms
H
frequency of sIPSC (Hz)
virgin
FGE
paternal
I
Cumulative probability (%)
interval of sIPSC (s)
p < 0.05
p < 0.0001
virgin
paternal
FGE
J
amplitude of sIPSC (pA)
K
sIPSC amplitude (pA)
p > 0.05
L
stimulation intensity (μA)
stim
eIPSP amplitude (mV)
virgin
FGE
paternal
paternal+GDP
virgin+GDP
virgin + GDPβS
paternal + GDPβS
M
sample collection
sample from six neurons combined
RNA
cDNA library
RNA Sequence
z-score
Gal
Vgf
Tac2
Calcr
Brs3
Trhr
Prlr
Ar
Oxt
Mc4r
Th
Crh
Oprk1
Pgr
Esr1
Cckbr
Cplx3
Oxtr
Slc18a2
Sema3c
Avpr1a
virgin 1
virgin 2
virgin 3
virgin 4
FGE 1
FGE 2
FGE 3
FGE 4
paternal 1
paternal 2
paternal 3
paternal 4
N
f
ac
N1
N2
N3
O
Merge
Galanin
P
Galanin positive
34 cells
6 cells
Galanin negative
Q
Galanin positive neuron
stimulation intensity (μA)
eIPSP amplitude (mV)
FGE
virgin
2 mV
50 ms


A
virgin
AAV-DIO-vLWO-eGFP
AAV-DIO-eYFP
Me Cartpt
Rec
B
2 mV
20 s
C
**
membrane potential (mV)
-60
-65
-70
-75
-80
-85
pre
green light
D
2 mV
20 s
E
membrane potential (mV)
-60
-65
-70
-75
-80
-85
pre
green light
F
AAV-DIO-ChR2-mCherry
+
AAV-DIO-vLWO-eGFP
cMPOA
Me Cartpt
Rec
G
mCherry
eGFP
Merge
H
100 pA
100 msec
I
***
ratio to control
1.5
1.0
0.5
0
no red light (control)
red light
J
virgin
AAV-DIO-vLWO-eGFP
cMPOA
Me Cartpt
Rec
K
10 sec
10 pA
CNQX, MK801
L
*
relative changes of sIPSC frequency
3.0
2.0
1.0
0
before
green light
after
M
10 sec
10 pA
CNQX, MK801, TTX
N
relative changes of sIPSC frequency
3.0
2.0
1.0
0
before
green light
after


A
virgin male
Cartpt-Cre mice
AAV-DIO-eYFP
AAV-DIO
-vLWO-eGFP
Me
cartpt
cMPOA
B
vLWO
control
relative frequency of behavior
test day
green light
infanticide <3min
infanticide 3-30 min
non parenting
partially parenting
full parenting
C
latency to sniffing (s)
test day
vLWO
control
D
day 1
day 2
day 3
day 4
post
probability of survival (%)
latency to commiting infanticide (s)
E
virgin male
AAV-DIO-eYFP
AAV-DIO
-vLWO-eGFP
Me
vGAT
cMPOA
F
opt
Me
AHi
Cart
eYFP
ac
eYFP
NPI
G
vLWO
control
relative frequency of behavior
test day
green light
H
latency to sniffing (s)
test day
vLWO
control
I
day 1
day 2
day 3
day 4
post
probability of survival (%)
latency to commiting infanticide (s)


A
ST
LV
Stim
ic
GP
pr
f
rh
ac
Rec
D3V
MPOA
B
stimulation intensity (μA)
eIPSP amplitude (mV)
virgin
paternal
FGE
4 mV
100 ms
C
eEPSP amplitude (mV)
stimulation intensity (μA)
2 mV
50 ms
virgin
paternal
FGE
D
sham
NMDA
ac
E
stimulation intensity (μA)
eIPSP amplitude (mV)
paternal NMDA
paternal sham
5 mV
100 ms
F
stimulation intensity (μA)
eIPSP amplitude (mV)
virgin sham
virgin NMDA
virgin NMDA
virgin vehicle
2 mV
50 ms
G
stimulation intensity (μA)
eIPSP amplitude (mV)
paternal
virgin
2 mV
50 ms
paternal + GDPβS
virgin+ GDPβS
H
paternal + GDPβS
virgin+ GDPβS
eEPSP amplitude (mV)
stimulation intensity (μA)
paternal
virgin
2 mV
50 ms
I
eEPSC
eIPSC
paired pulse ratio
20 pA
50 ms
paternal
virgin