

Central role of G protein $G\alpha i2$ and $G\alpha i2^+$ vomeronasal neurons in balancing territorial and infant-directed aggression of male mice

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Aggression is controlled by the olfactory system in many animal species. In male mice, territorial and infant-directed aggression are tightly regulated by the vomeronasal organ (VNO), but how diverse subsets of sensory neurons convey pheromonal information to limbic centers is not yet known. Here, we employ genetic strategies to show that mouse vomeronasal sensory neurons expressing the G protein subunit $G\alpha i2$ regulate male–male and infant-directed aggression through distinct circuit mechanisms. Conditional ablation of $G\alpha i2$ enhances male–male aggression and increases neural activity in the medial amygdala (MeA), bed nucleus of the stria terminalis, and lateral septum. By contrast, conditional $G\alpha i2$ ablation causes reduced infant-directed aggression and decreased activity in MeA neurons during male–infant interactions. Strikingly, these mice also display enhanced parental behavior and elevated neural activity in the medial preoptic area, whereas sexual behavior remains normal. These results identify $G\alpha i2$ as the primary G protein α -subunit mediating the detection of volatile chemosignals in the apical layer of the VNO, and they show that $G\alpha i2^+$ VSNs and the brain circuits activated by these neurons play a central role in orchestrating and balancing territorial and infant-directed aggression of male mice through bidirectional activation and inhibition of different targets in the limbic system.

olfactory | GCamp6f | V1R receptor | infant-directed aggression | territorial aggression

Aggression is an innate social behavior most commonly displayed in males, typically directed to other males of the same species (1) or to another male's offspring (2). Such behaviors are important for resource competition, establishment of group hierarchies, and access to sexual partners. For example, pup-directed aggression resulting in infanticide ultimately induces endocrine changes in females, which makes them quickly receptive to a male newcomer (3) and thus increases reproductive success. In rodents, the role of the olfactory system is critical for initiating aggression. Pheromonal cues present in secretions from adult males or pups are detected by distinct subsets of sensory neurons in the vomeronasal organ (VNO) (4–7) to initiate neural signals that, in turn, trigger aggressive behavior. However, many of the cellular and molecular mechanisms underlying such aggression-promoting signaling remain unknown.

The mouse VNO contains two major populations of vomeronasal sensory neurons (VSNs): VSNs of the apical layer of the vomeronasal sensory epithelium (VNE) express the G protein $G\alpha i2$ and members of the V1R family of vomeronasal G protein-coupled receptors, whereas VSNs of the basal layer express $G\alpha o$ and members of the V2R receptor family (8–14). $G\alpha o$ -expressing (i.e., $G\alpha o^+$) cells have been implicated in male–male aggression by detecting urine-derived high molecular weight (HMW) pheromones, particularly MUP proteins, and ESP1 peptide, both of which are capable of inducing aggression (15–19). Conditional ablation of

$G\alpha o$ eliminates VSN transduction of MUPs and ESP1 as well as male–male aggression (16, 20, 21). However, organic low molecular weight (LMW) molecules recognized by $G\alpha i2$ VSNs can also induce aggression (22). Furthermore, mice carrying a global deletion of $G\alpha i2$ are less aggressive (23), suggesting that both VSN populations may interact to generate aggressive behavior. Thus, whether each VNO subsystem activates independent aggression circuits or whether the two subsystems function in a cooperative and integrative manner to generate territorial aggression is not yet clear.

Infanticidal behavior, in which an adult attacks and kills an alien pup, is observed in virgin adult males and is highly dependent on the VNO. Genetic deletion of the transient receptor potential channel $Trpc2$, the primary sensory ion channel of VSNs, or surgical VNO ablation strongly reduce aggression toward pups (24, 25). Pup odors in virgin males preferentially activate a region of the accessory olfactory bulb (OB; AOB) innervated by $G\alpha i2$ neurons (25), but how molecularly defined VSN subsets influence pup-directed aggression remains unclear. Several regions in the limbic brain are activated during infanticide and male–male aggression, including the medial amygdala (MeA), the bed nucleus of the stria terminalis (BNST),

Significance

Male mice detect pheromones that trigger aggressive behavior toward other males or another male's pups. We found that a subpopulation of chemosensory neurons in the vomeronasal organ organizes and balances both types of aggression by reducing or enhancing each behavioral output. These neurons use a signaling cascade that requires the G protein $G\alpha i2$ in the detection of volatile pheromones and steroid derivatives. This subset of sensory neurons conveys pheromonal information to limbic centers in the brain through independent mechanisms, targeting different groups of neurons during male–male or infant-directed aggression. How the mouse olfactory system detects and processes pheromones that trigger different forms of aggression should aid in the identification of neural networks mediating male–male vs. infant-directed social aggression.

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Data deposition: The datasets generated and/or analyzed during the present study are available in the Data Inra Dataverse portal (<https://data.inra.fr/>).

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and the ventromedial hypothalamus (VMH) (25, 26). Current understanding of these neuronal substrates is insufficient to explain whether infanticide and male–male aggression are initiated by the same or different subsets of VSNs. Furthermore, it is not known whether the same or different groups of neurons from these common limbic structures are activated during male–male or infant-directed aggression. One possibility is that neuronal circuits originating from $G\alpha i2^+$ VSNs may independently coordinate infant-directed and male–male aggression.

Because the *Gnai2* gene, which encodes $G\alpha i2$, is ubiquitously expressed in the developing brain and cortex (27, 28), analysis of VNO-dependent behaviors in mice carrying a global $G\alpha i2$ deletion (28) is impeded. Furthermore, no functional recordings in single VSNs lacking $G\alpha i2$ have been performed. To overcome these limitations, we have generated mice harboring a conditional deletion of $G\alpha i2$ in the olfactory system. These mice show a striking reduction in the sensory response to LMW organic molecules, demonstrating that $G\alpha i2$ is an obligate requirement for normal signaling of apical VSNs. Furthermore, territorial aggression is enhanced in these mutant mice, whereas infant-directed aggression is strongly diminished. Together with c-Fos mapping in aggression-controlling brain centers, our study establishes a critical role of $G\alpha i2$, the VSNs that express this G protein, and the circuits derived from $G\alpha i2^+$ VSNs in orchestrating and balancing territorial and infant-directed aggression of male mice.

Results

Conditional Deletion of $G\alpha i2$ in VSNs. We used the Cre-loxP system to create mice with a tissue-specific and time-dependent deletion of $G\alpha i2$. Mice carrying a floxed allele of *Gnai2* (*Gnai2^{flx/flx}*) (29) were crossed with OMP-Cre mice (30, 31), in which the coding region for olfactory marker protein (OMP) is replaced by that of Cre recombinase. Conditional $G\alpha i2$ mutants (*cGai2^{-/-}*) were heterozygous for Cre (*Gnai2^{flx/flx}Omp^{cre/+}*); mice heterozygous for both alleles (*Gnai2^{flx/+}Omp^{cre/+}*) served as controls (*cGai2^{+/+}*). All experiments were performed with adult male mice (8–12 wk old).

We used immunohistochemistry (IHC) to examine the VNE in *cGai2^{+/+}* and *cGai2^{-/-}* males. $G\alpha i2$ immunoreactivity was absent in the VNE of *cGai2^{-/-}* mice, confirming the loss of $G\alpha i2$ protein expression (Fig. 1A). Staining was positive for markers of basal (V2R2, family C V2Rs), apical (PDE4A, phosphodiesterase

4A), or both (OMP) VSN populations in control and mutant mice (Fig. 1A and *SI Appendix*, Fig. S1A), showing that general tissue structure remained intact. By using RT-PCR with whole VNO cDNA from *cGai2^{+/+}* or *cGai2^{-/-}* males, we identified transcripts for several *V1r* receptors and two *V2r* receptors, *Tpc2* and *Plcb2*, in both genotypes (*SI Appendix*, Fig. S1B), indicating that expression of transduction molecules also remained intact. Quantitative RT-PCR analyses showed that relative expression of *Gnai2* in the VNO of *cGai2^{-/-}* males was reduced by 1.86 fold ($P < 0.001$), whereas *Gnao* expression increased by 1.47 fold ($P < 0.01$; Fig. 1B). *Gnai2* expression in the main olfactory epithelium (MOE) of control vs. mutant mice was not significantly different (Fig. 1B).

Previous work indicated a role for G protein α -subunits in the survival of VSNs (16, 23, 32). We analyzed PDE4A immunoreactivity, specific for the apical $G\alpha i2$ -expressing zone (33), and the volume of apical and basal VNE layers in *cGai2^{+/+}* and *cGai2^{-/-}* mice. The volume of the apical layer was reduced by 1.41 fold whereas that of the basal layer increased 1.35-fold in *cGai2^{-/-}* mice ($P < 0.001$; Fig. 1C). Cell density remained unchanged (*SI Appendix*, Fig. S1C), indicating that the volume reduction of the apical layer likely resulted from a decrease in the number of VSNs. A reduced volume was also detected in whole AOB of *cGai2^{-/-}* mice as shown by IHC for OMP (13% reduction; $P < 0.001$; *SI Appendix*, Fig. S1D). By using IHC for $G\alpha o$, we found a reduced glomerular layer in the rostral AOB (31% reduction; $P < 0.001$), the primary target of $G\alpha i2^+$ VSNs (*SI Appendix*, Fig. S1D). The general structure of MOE and glomerular layer of the main OB (MOB) remained unchanged in *cGai2^{-/-}* mice (*SI Appendix*, Fig. S1E). Thus, conditional $G\alpha i2$ deletion caused a selective loss of apical PDE4A-expressing VSNs and rostral AOB glomerular volume. We confirmed that general olfactory performance remained normal in *cGai2^{-/-}* males by performing several behavioral tests. There was no significant difference between *cGai2^{-/-}* and *cGai2^{+/+}* males in a food-finding test (*SI Appendix*, Fig. S1F). Likewise, novel odor investigation of female urine and odor discrimination of normal male urine vs. castrated male urine using a habituation–dishabituation paradigm (20, 31) revealed no significant differences between the two genotypes (*SI Appendix*, Fig. S1G). Thus, *cGai2^{-/-}* mice do not display any obvious defects with respect to main olfactory system function.

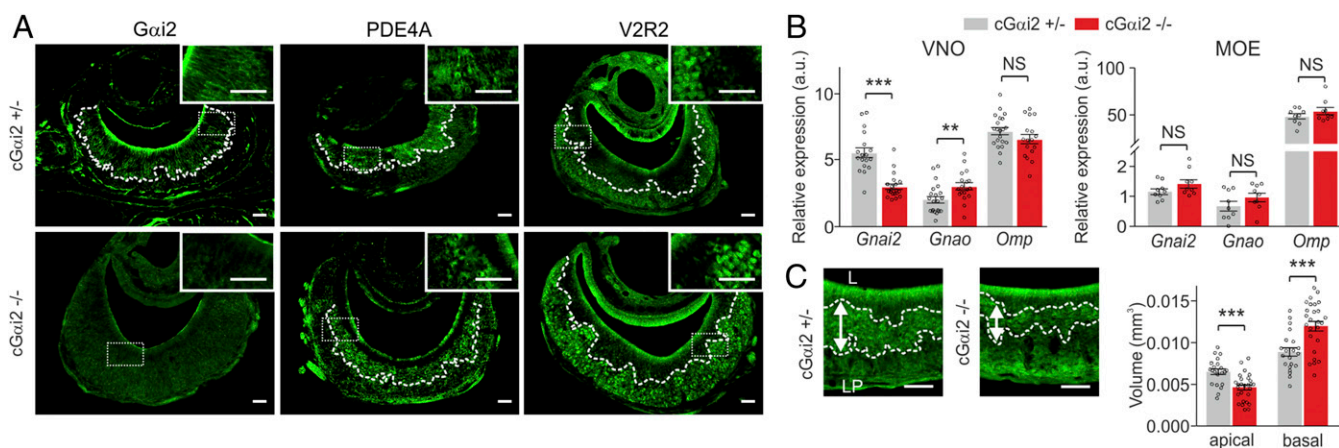


Fig. 1. Expression of marker proteins in the VNO of *cGai2^{+/+}* and *cGai2^{-/-}* mice. (A) Loss of $G\alpha i2$ immunoreactivity in *cGai2^{-/-}* VNO. Antibodies specific for PDE4A (apical layer) or V2R2 (basal layer) indicate that the laminar VNO organization persists in the absence of $G\alpha i2$. (Scale bars, 50 μ m.) (B) Relative expression (normalized to *Hprt1*) of *Gnai2*, *Gnao*, and *Omp* genes in VNO (Left) and MOE (Right). *Gnai2* expression decreased and *Gnao* expression increased, whereas *Omp* expression did not change, in *cGai2^{-/-}* VNO [$**P < 0.01$ and $***P < 0.001$; nonsignificant (NS), $P = 0.21$, Mann–Whitney *U* test; *cGai2^{+/+}*, $n = 20$; *cGai2^{-/-}*, $n = 18$]. No difference in gene expression in the MOE between the two genotypes was observed (NS, $P = 0.22$ – 0.53 , Mann–Whitney *U* test). (C) Analysis of apical and basal VNO layer volume distinguished by PDE4A immunostaining indicates a significant reduction in the apical VNO layer [*t* test, $t(46) = 3.975$; $***P < 0.001$] and an increase in basal VNO layer [*t* test, $t(46) = 3.929$; $***P < 0.001$] of *cGai2^{-/-}* ($n = 27$) vs. *cGai2^{+/+}* mice ($n = 21$). L, lumen; LP, lamina propria. Data are expressed as means $\pm$ SEM. (Scale bars, 50 μ m.)

required for VSN sensory transduction in the apical VNE layer and plays a central role in detecting small organic molecules and steroid derivatives.

Normal Male Sexual Behavior in *Gai2* Mutants. *Trpc2*^{-/-} male mice exhibit pronounced alterations in sexual behavior, including elevated mounting and courtship behaviors toward other males (41, 42). To determine whether *Gai2* is also required for male sexual behavior, we first measured serum testosterone levels and the weight of sexual organs (testes, preputial glands, seminal vesicles), but found no significant differences between *cGai2*^{-/-} and *cGai2*^{+/-} males (*SI Appendix*, Fig. S3 *A* and *B*). We next analyzed sexual behaviors toward females in sexually naïve *cGai2*^{-/-} and *cGai2*^{+/-} males (*SI Appendix*, Fig. S3 *D–G*). *cGai2*^{-/-} and *cGai2*^{+/-} males displayed the same level of preference for estrous female urine volatiles and nonvolatiles (*SI Appendix*, Fig. S3C). We also scored the number of animals mounting an intruder (female, male, or castrated male) and the mounting episodes (*SI Appendix*, Fig. S3D). *cGai2*^{-/-} and *cGai2*^{+/-} males showed robust mounting and a short latency to mount females, but very rarely displayed sexual behavior toward male or castrated male intruders. Next, we scored the latency to mount female intruders and to ejaculate, and the total mating time (*SI Appendix*, Fig. S3 *E* and *F*). Latency to ejaculate and total mating time of *cGai2*^{-/-} males were statistically indistinguishable from those of *cGai2*^{+/-} males ($P = 0.21–0.89$). We further assessed male courtship behavior by measuring ultrasonic vocalizations at high frequencies (30–110 kHz) emitted by resident males. *cGai2*^{-/-} and *cGai2*^{+/-} males produced high numbers of vocalizations in response to female intruders, whereas few vocalizations were produced during male–male investigation, and there was no significant difference between genotypes (*SI Appendix*, Fig. S3G). Together, these findings reveal that *cGai2*^{-/-} males display normal sexual behaviors and sexual motivation.

Territorial Aggression Is Enhanced in *Gai2* Mutant Males. Conditional deletion of *Gao* in VSNs eliminated male–male aggression (16). This effect could result from cooperation of *Gao* and *Gai2* subsystems, or the *Gai2* subsystem could operate relatively independently, being dispensable for aggression and/or controlling a parallel aggression circuit. To distinguish between these hypotheses, we compared territorial aggression of adult *cGai2*^{-/-} male mice vs. age-matched *cGai2*^{+/-} males in the resident–intruder paradigm (15, 16) (Fig. 3A).

Surprisingly, the number of animals attacking an adult male intruder was significantly higher in *cGai2*^{-/-} (25 of 27 mice; 93%) vs. *cGai2*^{+/-} residents (15 of 23 mice; 65%; $P < 0.05$; Fig. 3A), but there was no difference in the intruder investigation time for each genotype (*SI Appendix*, Fig. S4A). Total attack duration in three consecutive 10-min trials was high in *cGai2*^{-/-} and *cGai2*^{+/-} males (130 and 78 s, respectively; $P < 0.05$), showing that *Gai2* is dispensable for the display of aggression. By contrast, castrated male intruders consistently induced less aggression in control *cGai2*^{+/-} male residents (37 s; 50% reduction; $P < 0.05$; Fig. 3A), whereas attack duration to castrated males was approximately threefold higher in *cGai2*^{-/-} residents (129 s; $P < 0.01$) and did not differ from the level of aggression to intact male intruders ($P = 0.8$). Thus, there was no loss of territorial aggression in *cGai2*^{-/-} male residents.

Previous work has shown that the HMW (>10 kDa) and LMW (< 10 kDa; includes small peptides) fractions of urine from adult male mice can induce aggression in male residents (15, 16). Therefore, we tested whether *cGai2*^{-/-} VSNs are capable of detecting these two fractions. We used Ca^{2+} imaging in *cGai2*^{-/-}, *cGai2*^{+/-}, and *Trpc2*^{-/-} VSNs to record responses to whole urine and the HMW and LMW fractions (Fig. 3B). All fractions induced large responses in *cGai2*^{+/-} VSNs: 592 of 4,698 cells

screened (12%) responded to urine, 250 of 4,698 to LMW fractions (5%), and 402 of 5,577 (7%) to HMW fractions. In *cGai2*^{-/-}, urine responses were reduced by half (215 of 3,366 activated cells; 6%; $P < 0.001$) and LMW fraction responses by approximately 60% (74 of 3,366; 2%; $P < 0.001$), whereas HMW responses were identical or even slightly elevated (551 of 5,797; 9%; $P = 0.2$; Fig. 3B). We identified activated cells by combining Ca^{2+} imaging with post hoc immunostaining (*SI Appendix*, Fig. S2B) (15, 16) using antibodies against PDE4A and *Gao* (Fig. 3C). The vast majority of cells activated by HMW were *Gao*⁺ in *cGai2*^{-/-} and control VSNs. LMW fraction and castrated male urine activated *Gao*⁺ and PDE4A⁺ control VSNs, but nearly all *cGai2*^{-/-} activated cells were negative for PDE4A (Fig. 3C and *SI Appendix*, Fig. S4B). Together, these results indicate that activation of the *Gao*⁺ VSN subpopulation is sufficient to induce intermale aggression, irrespective of whether this aggression is promoted by HMW or LMW urine fractions or castrated male urine.

Increased Brain Activation to Male Intruder in *Gai2* Mutant Males. To strengthen these results, we mapped in vivo brain activation in nine distinct regions of the central nervous system implicated in aggression (26) by using immunodetection of the immediate early gene *c-Fos*. These analyses included subdivisions of the MeA [posterodorsal MeA (MeApd) and posteroventral MeA (MeApv) divisions] and VMH [dorsomedial VMH (VMHdm) and ventrolateral VMH (VMHvl)], the posteromedial part of the medial division of the BNST (BNSTmpm), medial preoptic area (MPOA), and lateral septum (LS). Nonstimulated *cGai2*^{-/-} and *cGai2*^{+/-} males showed equivalent levels of basal *c-Fos* activity in all nine brain regions (*SI Appendix*, Fig. S4C). Exposure to adult male intruders induced a significant increase in the number of *c-Fos*⁺ nuclei in three of these regions: MeApd, BNSTmpm, and LS (Fig. 3D and E). We did not observe significant differences in some other regions implicated in aggression, such as the VMH (Fig. 3E).

Male–male aggression and male pheromones activate a specific subpopulation of MeA neurons that are GABAergic and positive for the androgen receptor (AR) (43, 44). We used double-label IHC for *c-Fos* and AR, GABA, calbindin (CB), or calretinin (CR) to identify the MeA neurons activated in our experiments. In *cGai2*^{-/-} and *cGai2*^{+/-} males, *c-Fos*⁺ nuclei largely colocalized with AR (Fig. 3F and G) and GABA, but not with CB and CR (*SI Appendix*, Fig. S4D). Moreover, the proportion of *c-Fos*⁺ neurons positive for AR was even larger in *cGai2*^{-/-} males, whereas no change was observed in the absolute number of AR⁺ neurons (Fig. 3G). Therefore, conditional *Gai2* deletion resulted in increased neural activation of a population of GABAergic, AR⁺ neurons in the MeA following exposure to a male intruder.

Infant-Directed Aggression Is Diminished in *Gai2* Mutant Males, but Parental Behavior Is Enhanced. Infanticidal behavior in mice, in which an adult attacks and kills a pup, is observed in virgin adult male mice and depends strongly on a functional VNO (24, 25). We investigated infant-directed behavioral consequences of the *Gai2* deletion. We exposed virgin males to 1–2-d-old pups and found that the number of aggressive animals was drastically reduced, whereas attack latency was significantly increased in *cGai2*^{-/-} males vs. heterozygous controls ($P < 0.01$; Fig. 4A and B). Moreover, two critical measures of parenting behavior—pup grooming and pup retrieval—were significantly increased in *cGai2*^{-/-} males ($P < 0.05$ and $P < 0.01$; Fig. 4B). Thus, the display of pup-directed aggression is strongly decreased, whereas parental behavior is enhanced, in *Gai2* mutant males.

We used *Fos* immunodetection to examine whether the lack of apical/*Gai2*⁺ sensory inputs alters neural activity in aggression-controlling brain centers during infant-directed aggression (Fig.

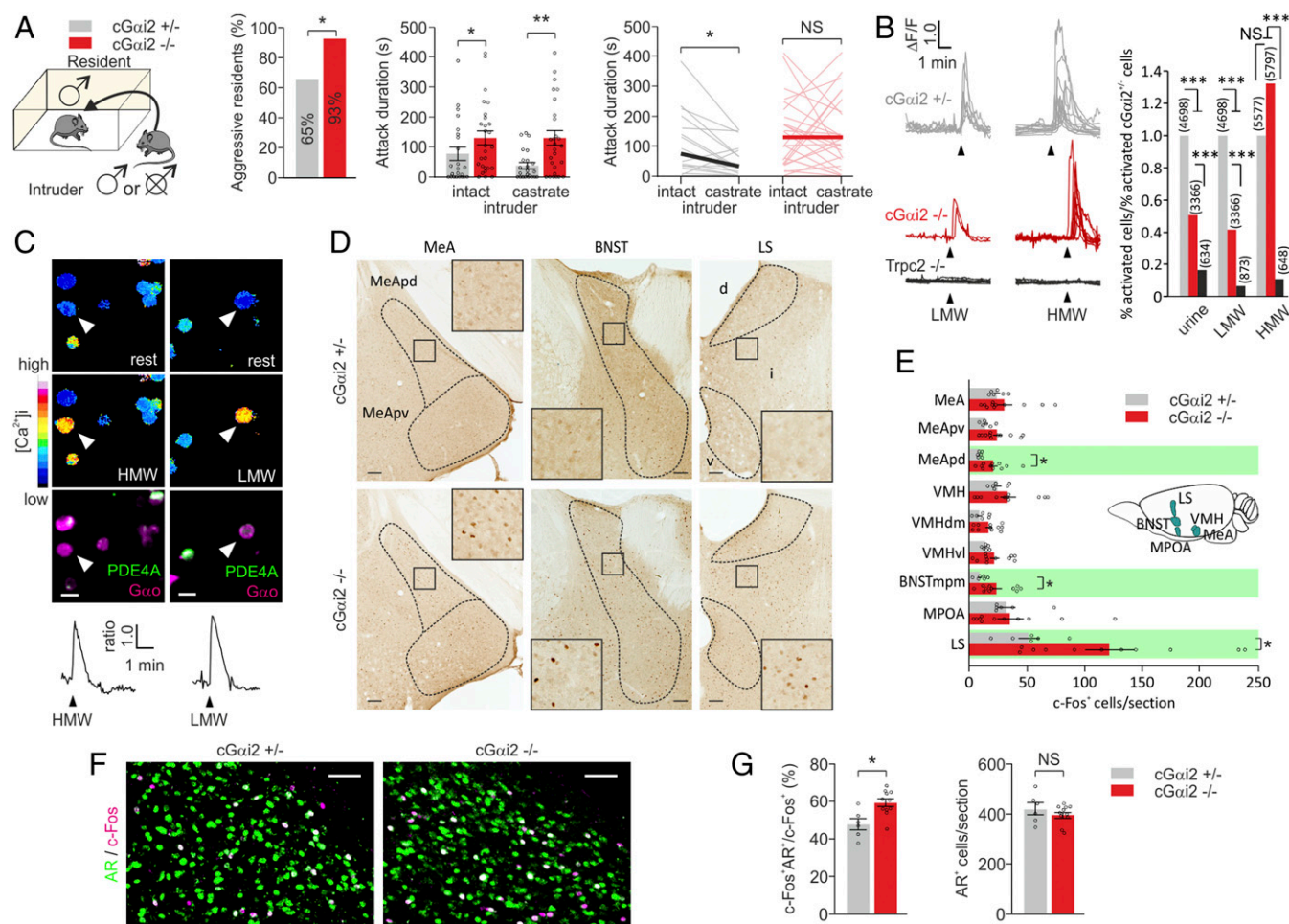


Fig. 3. Loss of *Gai2* enhances territorial aggression and increases activity in aggression-controlling brain centers. (A) Territorial aggression is enhanced in sexually experienced *cGai2*^{-/-} resident males exposed to intact and castrated intruders in the resident–intruder assay. Fifteen of 23 *cGai2*^{+/+} mice (65%) and 25 of 27 (93%) *cGai2*^{-/-} resident males were aggressive at least once during three consecutive resident–intruder trials to intact and castrated male intruders ($*P < 0.05$, Fisher's exact test). Cumulative attack duration was higher in *cGai2*^{-/-} residents ($**P < 0.01$ and $*P < 0.05$, Mann–Whitney *U* test). Comparison of *cGai2*^{+/+} residents' behavior toward gonadally intact vs. castrated intruders indicates the normal reduction in aggression toward a castrate ($*P < 0.05$, Wilcoxon test). This behavior is lost in the *cGai2*^{-/-} residents [nonsignificant (NS), $P = 0.8$, Wilcoxon test]. (B) Examples of Ca^{2+} transients (Left) imaged in dissociated VSNs of *cGai2*^{+/+}, *cGai2*^{-/-}, and *Trpc2*^{-/-} mice stimulated with LMW (1:100) and HMW (1:100) fractions. Analysis of responding cells over total *cGai2*^{+/+} responding cells (Right) reveals reduced responsiveness to urine (1:100) and LMW fraction in *cGai2*^{-/-} cells and a loss in *Trpc2*^{-/-} cells ($***P < 0.001$; NS, $P = 0.2$, Fisher's exact test). Number of cells analyzed is indicated above each bar. Each stimulus was tested in 3–20 mice. (C) Fura-2 ratio imaging and post hoc IHC of *cGai2*^{-/-} cells indicate that cells activated by LMW and HMW fractions are *Gao*⁺ and *PDE4A*⁻. Time points of Ca^{2+} images show resting or peak fluorescence levels to stimulation with HMW or LMW fractions. Representative Ca^{2+} transients shown for imaged cells (white arrowheads) are indicated for each condition. (Scale bar, 10 μm .) (D) Examples of c-Fos activation in MeA, BNST, and LS of *cGai2*^{+/+} and *cGai2*^{-/-} male mice exposed to intact male intruder for 10 min. Dashed lines indicate the border of brain areas. Boxes are shown at higher magnification in the *Inset*. (Scale bars, 100 μm .) (E) Quantification of c-Fos⁺ cells per section in *cGai2*^{+/+} ($n = 6$) and *cGai2*^{-/-} residents ($n = 11$) after exposure to an intact intruder reveals an increase in c-Fos expression in MeApd, BNSTmpm, and LS of *cGai2*^{-/-} mice (marked in green; $*P < 0.05$; NS, $P = 0.15$ – 0.99 , Mann–Whitney *U* test). (F) *Gai2* deletion resulted in increased c-Fos activation of a population of GABAergic, AR⁺ neurons in the MeApd following a 10-min exposure to an intact male intruder. (G) Percentage of c-Fos⁺ neurons expressing AR (Left) and number of AR⁺ cells per section (Right) in the MeApd after a 10-min exposure to an intact male intruder ($*P < 0.05$; NS, $P = 0.46$, Mann–Whitney *U* test). (Scale bars, 50 μm .) d, dorsal LS; i, intermediate LS; v, ventral LS. Data are expressed as means $\pm$ SEM.

4 C and D). We compared the density of c-Fos⁺ nuclei of *cGai2*^{-/-} males vs. *cGai2*^{+/+} males following pup exposure. In the granular layer of the anterior AOB, c-Fos⁺ cell density was significantly lower in parental *cGai2*^{-/-} males vs. aggressive *cGai2*^{+/+} male mice ($P < 0.001$; Fig. 4 C and D), consistent with reduced sensory input from the apical VNO in these mutants. Aggressive *cGai2*^{+/+} males also showed more c-Fos⁺ cells in the MeApv and MeApd compared with *cGai2*^{-/-} males, suggesting that *Gai2*-dependent sensory inputs elicit MeA activation and infant-directed aggression. We also investigated the MPOA of the hypothalamus, a key region in the control of parenting behaviors (45). We observed specific activation during pup interactions in *cGai2*^{-/-} males, but this activation was absent in

aggressive *cGai2*^{+/+} controls (Fig. 4 C and D). Importantly, our c-Fos mapping revealed significantly higher activation in the medial preoptic nucleus (MPO), the central region of MPOA, of *cGai2*^{-/-} males compared with parental controls ($P < 0.05$; Fig. 4 C and D). Thus, *Gai2*-dependent VNO inputs seem to inhibit MPOA activation and subsequent parental behavior.

To identify the activated neurons in the MeA during pup-directed aggression and determine whether they belong to the same AR⁺, GABAergic neurons activated during male–male aggression, we performed double-label IHC for c-Fos and AR. There was little overlap between c-Fos⁺ and AR⁺ nuclei in aggressive *cGai2*^{+/+} males (Fig. 4E). c-Fos⁺ nuclei also did not colocalize with CB⁺ or CR⁺ cells in the MeA (SI Appendix, Fig. S5).

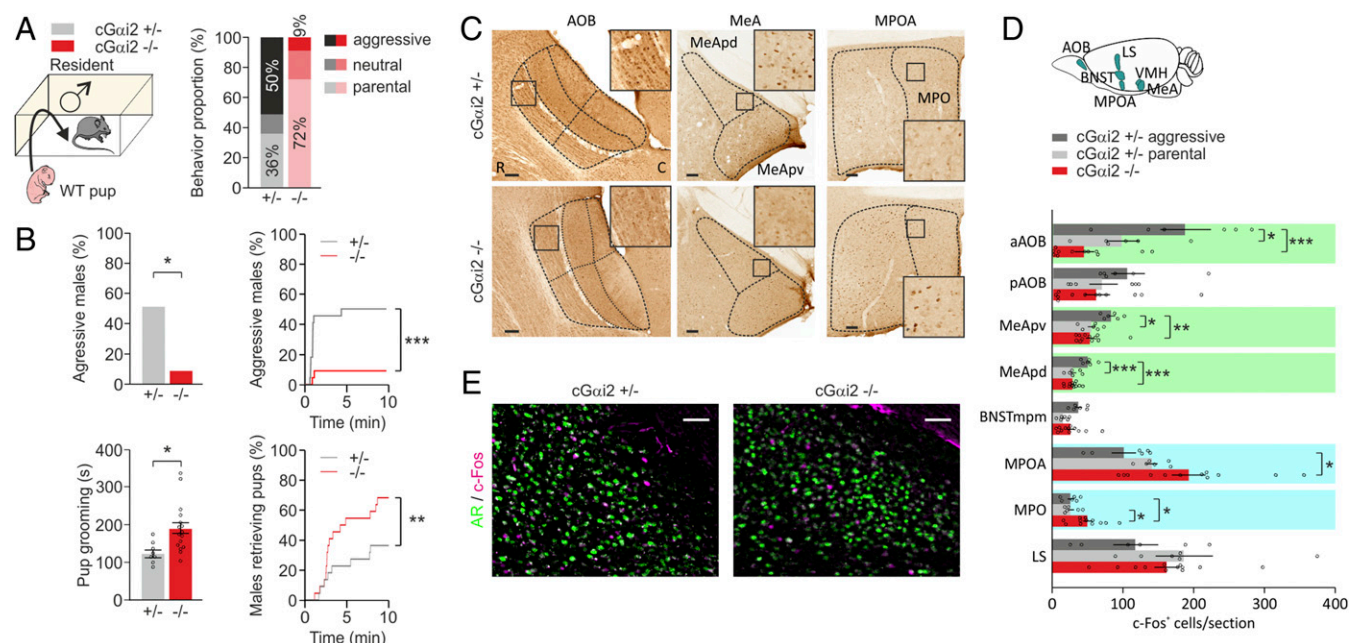


Fig. 4. $cGai2^{-/-}$ male mice show diminished infant-directed aggression but enhanced parental behavior. (A) Comparison of pup-directed behavior of adult $cGai2^{+/+}$ vs. $cGai2^{-/-}$ male residents. Pups (WT) were used at postnatal days 1–2. Males attacked (aggressive), ignored (neutral), or retrieved neonates to the nest (parental behavior). $cGai2^{-/-}$ males were predominantly parental (72%), whereas $cGai2^{+/+}$ males attacked the pups (50%; $n = 22$ for each genotype). (B) Percentages of aggressive males ($*P < 0.05$, Fisher's exact test) and their latency to attack the neonates ($***P < 0.001$, Kolmogorov–Smirnov test), pup grooming times of the $cGai2^{+/+}$ ($n = 8$) and $cGai2^{-/-}$ residents ($n = 16$) that showed the behavior [t test: $t(22) = 2.73$, $*P < 0.05$], and percentage of males retrieving pups ($***P < 0.01$, Kolmogorov–Smirnov test). (C) Examples of c-Fos activation in AOB, MeA, and MPOA of $cGai2^{+/+}$ and $cGai2^{-/-}$ males exposed to an alien pup for 10 min. Dashed lines indicate brain areas where c-Fos+ cells were counted. Boxes are shown at higher magnification in the Inset. C, caudal; R, rostral. (Scale bars, 100 μ m.) (D) Quantification of c-Fos+ cells per section of aggressive $cGai2^{+/+}$ ($n = 6$), parental $cGai2^{+/+}$ ($n = 6$), and $cGai2^{-/-}$ residents ($n = 12$) after exposure to an alien pup reveals increased c-Fos activation in aAOB, MeApd, and MeApv of aggressive $cGai2^{+/+}$ males [aAOB, $F(2,21) = 10.72$, $P < 0.001$; MeApd, $F(2,21) = 13.98$, $P < 0.001$; MeApv, $F(2,21) = 6.075$, $P < 0.001$, ANOVA; $*P < 0.05$, $**P < 0.01$, $***P < 0.001$, Tukey test; green]. Enhanced activation is observed in the MPOA (MPO) of $cGai2^{-/-}$ males [MPOA, $F(2,21) = 5.236$, $P < 0.05$; MPO, $F(2,21) = 4.377$, $P < 0.05$, ANOVA; $*P < 0.05$, Tukey test; blue]. No significant differences are observed in other regions analyzed ($P = 0.06–0.81$, ANOVA). (E) Conditional $Gai2$ deletion does not cause c-Fos activation of a population of GABAergic, AR+ neurons in the MeApd following a 10-min exposure to neonates. (Scale bar, 50 μ m.) aAOB, anterior AOB; pAOB, posterior AOB. Data are expressed as means $\pm$ SEM.

Therefore, the MeA neurons activated during pup-directed aggression are distinct from those activated during male–male aggression. Together, these results provide strong support for a model in which $Gai2^{+}$ VSNs control infant-directed aggression by activation of specific aggression nodes that, in turn, inhibit parental-specific circuits.

Discussion

Our results show that the $Gai2^{+}$ population of VSNs controls important aspects of male–male and infant-directed aggression. We identify $Gai2$ as the primary G protein α -subunit mediating the detection of small organic chemosignals by apical VSNs, most likely being responsible for activation of $Trpc2$ and subsequent Ca^{2+} entry downstream of $V1R$ activation. $Gai2$ is an abundant G protein expressed in major cognitive centers such as the cortex and is important for its development, and complete loss or reduction of $Gai2$ signaling can result in defective social interaction, increased anxiety, and intellectual disability (27). Therefore, a global $Gai2$ mutation may impede investigations of complex VNO-dependent social behaviors. Indeed, our results differ from a report that used global $Gai2$ -KO mice that exhibited reduced male–male aggression (23). The conditional, olfactory-restricted KO model developed here ablated $Gai2$ only in *Omp*-expressing cells, indicating that the observed behavioral deficits depend on the olfactory system. *Omp* is highly expressed in mature sensory neurons of MOE and VNO (46). Although $Gai2$ is also expressed in some sensory neurons of the MOE (47), $Gai2$ does not seem to participate in known sensory signaling events (48). Our conditional KO mice showed no obvious defects

in MOE or MOB morphology and odor-guided behaviors depending on a functional MOE, indicating that the behavioral phenotypes we observe are largely mediated by VNO function.

We found that conditional deletion of $Gai2$ suppresses infanticidal behavior, consistent with a direct role of $Gai2$ in the detection of pup odor. Furthermore, c-Fos mapping showed less activation in downstream brain areas of the $Gai2$ vomeronasal pathway—aAOB and MeA—in $Gai2$ -deficient virgin male mice exposed to pups. Interestingly, $Gai2$ mutant male mice became parental after contact with pups and showed elevated c-Fos in the MPOA, suggesting that this circuit may inhibit proparental MPOA neurons (49). Thus, infanticidal behavior seems to involve the activation of a dedicated circuit, rather than being merely a consequence of the inhibition of parenting behavior.

Our $Gai2$ mutant males displayed high levels of male–male aggression, indicating that the $Gai2$ subpopulation of VSNs is dispensable for triggering this behavior. Therefore, male–male and infant-directed aggression are initiated by different subsets of VSNs, suggesting that distinct accessory olfactory system circuits control the display of these two forms of aggression. Consistent with this, c-Fos analysis revealed the activation of different populations of MeA neurons in the context of each behavior. Many of these cells were positive for AR in the male–male aggression assay but negative for AR in the pup-directed aggression test. Because deletion of Gao in the VNO eliminated male–male aggression (16), Gao^{+} VSNs are probably the key drivers of aggression induced by LMW and HMW urine fractions. The LMW fraction, which includes peptides <10 kDa, is still partially

antibodies (Alexa Fluor 488 goat anti-rabbit, Alexa Fluor 647 goat anti-mouse, 1:500; Invitrogen). Cells were also stained (5 min, RT) with DAPI.

Quantitative RT-PCR. VNOs and MOEs were dissected from *cGai2^{+/+}* and *cGai2^{-/-}* mice. Pools of VNO or MOE from three animals were established from a total of 21 VNOs and 9 MOEs per genotype. RNA in each pool was isolated with PureLink RNA Mini Kit (Invitrogen). cDNA was synthesized from 1 μ g of total RNA by using a Superscript III First-Strand Synthesis System for RT-PCR (Invitrogen). Quantitative PCRs were performed on a CFX96 Touch Real-Time PCR Detection System (Bio-Rad) using SsoAdvanced Universal SYBR green Supermix (Bio-Rad). PCR conditions for all primers were 95 °C for 3 min followed by 39 cycles (95 °C for 10 s, 60 °C for 30 s). PCR specificity was verified by melting curve analysis. Expression of *Hprt-1*, *Omp*, *Gnai2*, and *Gnao* mRNAs were assessed. Each sample was run in triplicate, and data were analyzed with the CFX Manager 3.0 Software (Bio-Rad) normalized to *Hprt-1* expression level to obtain a Δ Ct and expressed as $2^{-\Delta Ct}$. VNO cDNAs were used to assess *V1re6*, *V1re2*, *V1rf3*, *V1rj2*, *Vmn2r1*, *Vmn2r65*, *Trpc2*, and *Plcb2* expression by endpoint PCR with GoTaq G2 Master Mix. Primer sequences are shown in *SI Appendix, Table S2*. PCR conditions for all primers were 95 °C for 3 min, followed by 39 cycles (95 °C for 45 s, 58 °C for 30 s, and 72 °C for 60 s), and 72 °C for 10 min. Products were run on a 1% agarose gel.

Ca²⁺ Imaging. Ca²⁺ imaging of freshly dissociated VSNs was performed as described previously (15, 16). VNO epithelium was detached from the cartilage and minced in PBS solution at 4 °C. The tissue was incubated (20 min at 37 °C) in PBS solution supplemented with papain (0.22 U/mL) and DNase I (10 U/mL; Fermentas), gently extruded in DMEM (Invitrogen) supplemented with 10% FBS, and centrifuged at 100 $\times$ g (5 min). Dissociated cells were plated on coverslips previously coated with concanavalin-A type V (0.5 mg/mL, overnight at 4 °C; Sigma). Cells were used immediately for imaging after loading them with fluo-4/AM or fura-2/AM (5 μ M; Invitrogen) for 60 min. Coverslips containing VSNs were placed in a laminar-flow chamber (Warner Instruments) and constantly perfused at 22 °C with extracellular solution HBSS (Invitrogen) supplemented with 10 mM Hepes (2-[4-(2-hydroxyethyl) piperazin-1-yl]ethanesulfonic acid). Cells were alternately illuminated at 470 nm for fluo-4 or at 340 and 380 nm for fura-2 imaging, and light emitted above 510 nm was recorded by using a Hamamatsu C10600-10B camera installed on an Olympus IX71 microscope. Images were acquired at 0.25 Hz and analyzed by using ImageJ (NIH), including background subtraction, ROI detection, and signal analyses. ROIs were selected manually and always included the whole cell body. Peak signals were calculated from the temporal profiles of image ratio/fluorescent values. Results are based on recordings from at least three mice for each condition and genotype.

VNO tissue slices were prepared from male *cGai2^{+/+}* GCaMP6f^{+/+} and *cGai2^{-/-}* GCaMP6f^{+/+} mice by using slicing procedures established previously (33, 34, 39). Briefly, mice were euthanized with CO₂, followed by decapitation. VNOs were quickly removed and submerged in oxygenated extracellular solution 1 (95% O₂/5% CO₂) containing (in mM): 120 NaCl, 25 NaHCO₃, 5 KCl, 1 MgSO₄, 1 CaCl₂, and 10 mM glucose (300 mOsm). The vomer bones were removed, the VNO was embedded in 3% low-gelling temperature agarose, and coronal slices (250 μ m) were cut on a vibratome (Microm HM 650 V). VNO tissues slices were imaged by using an upright scanning confocal microscope (LSM 880 Indimio; Zeiss) equipped with a 20 $\times$ 1.0 N.A. Plan-Apochromat water-immersion objective and a standard Argon laser for excitation at a wavelength of 488 nm (GCaMP6f excitation). Emitted fluorescence was collected between 500 and 550 nm. All scanning head settings were kept constant during each experiment. Optical sections were $\sim$ 7 μ m thick. All scanning head settings (i.e., gain, black level, detector aperture, and laser neutral density filter) were kept constant during each experiment. GCaMP6 fluorescence changes are expressed as relative fluorescence changes, i.e., $\Delta F/F_0$ (F_0 was the average of the fluorescence values 10 s before stimulation). Images were acquired at 1 Hz and analyzed by using a combination of Zen (Zeiss), ImageJ (NIH), and Igor (Wavemetrics) software. To identify and mark responding VSNs, ΔF images ($F - F_0$) were overlaid onto transmitted light images (Fig. 2C) by using Adobe Photoshop's difference tool and slightly adjusting the exposure settings. Original ΔF images of ligand-induced VSN responses are shown in *SI Appendix, Fig. S2D*. VNO slices were stimulated successively and in random order by using bath application. The following criteria for stimulus-induced Ca²⁺ responses were applied. (i) A response was defined as a stimulus-dependent deviation of GCaMP6f fluorescence that exceeded twice the SD of the mean of the baseline fluorescence noise. (ii) Cells showing a response to control buffer were excluded from analysis. (iii) A response had to occur within 1 min after stimulus application. In

time-series experiments, ligand application was repeated to confirm the repeatability of a given Ca²⁺ response.

Chemostimulation. Chemostimuli for Ca²⁺ imaging were freshly prepared each day and diluted in extracellular solution to give the following final concentrations: urine and HMW and LMW fractions, 1:100 dilution; 2-heptanone, 10⁻⁸ M (Sigma); 2,5-dimethylpyrazine, 10⁻⁶ M (Sigma); isobutylamine, 10⁻⁷ M (Sigma); isoamylamine, 10⁻⁷ M (Sigma); β -estradiol, 1 μ M (E2, Sigma); 1,3,5 (10)-estratrien-3,17 β -diol disulfate, 1 μ M (E1050; Steraloid or Sigma); 1,3,5 (10)-estratrien-3,17 β -diol 3-sulfate, 1 μ M (E1100; Steraloid or Sigma); 1,3,5(10)-estratrien-3,17 α -diol 3-sulfate, 1 μ M (E0893; Steraloid); A7864, 1 μ M (5-androsten-3 β ,17 β -diol disulfate; Steraloid); sulfated estrogen mix (E mix) E1050, E1100, E0893, and A7864, each 1 μ M; MHC peptide mix SYFPEITHI, SYIPSAEKI, AAPDNRETF, SIINFEKL, 10⁻¹⁰ M each (Genscript); and KCl, 50 mM or 60 mM (slice experiments). Sulfated estrogens were initially prepared in DMSO and further diluted in extracellular solution. C57BL/6 males (8–12 wk old; Janvier) served as urine donors. Animals were sexually naïve and were kept group-housed. Equal volumes of freshly collected urine from at least three animals were pooled. To obtain urine fractions, 0.5 mL of fresh urine was size-fractionated by centrifugation (14,000 $\times$ g for 30 min) by using Microcon (Millipore) or Nanosep (Pall) 10-kDa molecular mass cutoff ultrafiltration columns. The centrifugation supernatant was the LMW fraction, and, to obtain HMW fraction, the retentate was washed with 0.5 mL PBS solution three times and resuspended in 0.5 mL of PBS or oxygenated extracellular solution.

Behavioral Testing. Males were individually housed for 1 wk before testing. Mice were moved to the experimental room 2 h before testing. Assays were conducted 2 h before the start of the dark period.

Resident-intruder male-male aggression assay. Sexually experienced male mice of each genotype (23 *cGai2^{+/+}* and 27 *cGai2^{-/-}*) were tested for territorial aggression. Testing lasted 10 min and began when a sexually inexperienced, gonadally intact, group-housed adult male (i.e., intruder) was placed into the home cage of the test mouse (i.e., resident), whose bedding had not been changed for at least 4 d. Each resident was exposed three times (on consecutive days) to a gonadally intact intruder. After 1 wk, the experiments were repeated with a castrated intruder. Juvenile (postnatal day 18–22) males were castrated under isoflurane general anesthesia and used in adulthood. Residents were not exposed twice to the same intruder. Aggressive behavior was defined as lunging, biting, chasing, tail rattling, wrestling, and kicking. Attack bouts were defined as a succession of aggressive events separated by $<$ 3 s. Cumulative attack duration of three consecutive tests, investigation time of the intruder, and number of mounting episodes were scored.

Pup-directed behaviors. Twenty-two sexually naïve males of each genotype were tested for behavior in the presence of an alien 1–2-d-old neonate (C57BL/6 WT) introduced into the home cage of the test mouse for 10 min. To minimize handling and stress to the pups, one single pup was taken from the nest immediately before the test, avoiding prolonged exposure to cold. If harmed, the pup was immediately removed and killed to minimize suffering and to avoid cannibalizing without previous killing. Mice were categorized as aggressive if they presented aggressive behavior (e.g., biting, killing) toward a pup, as parental if they retrieved a pup into their nest, and as neutral if they were indifferent to a pup. Latencies to attack a pup and pup grooming time were scored.

Statistics. Statistical analyses were performed by using GraphPad Prism 7.0 (GraphPad Software), OriginPro 2016G, and OriginPro 2017G (OriginLab). Assumptions of normality and homogeneity of variance were tested before conducting the following statistical approaches. Student's *t* test was used to measure the significance of the differences between two distributions. In case the results failed the test of normality, a Mann-Whitney *U* test was performed. For paired data comparisons, we used the Wilcoxon signed-ranks test, and, for categorical data, we used the Fisher's exact test. Multiple groups were compared by using a one-way or two-way ANOVA with Tukey's multiple comparison test as a post hoc comparison or Kruskal-Wallis ANOVA for nonnormal distributions. The probability of error level (i.e., α) was chosen to be 0.05. Unless otherwise stated, results are presented as means $\pm$ SEM and documentation of individual data points.

Further details on testosterone measurements, stimulus delivery, and other behavioral tests are provided in *SI Appendix, Materials and Methods*. The datasets generated and/or analyzed during the present study are available from the Data Inra Dataverse portal (<https://data.inra.fr/>).

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