Serotonin sensing by microglia conditions the proper development of neuronal circuits and of social and adaptive skills

Anne Roumier (anne.roumier@inserm.fr)
Institut du Fer à Moulin, INSERM U1270, Sorbonne Université https://orcid.org/0000-0002-1369-9231
Giulia Albertini
Ivana D'Andrea
Mélanie Druart
New York University Langone Health
Catherine Béchade
Nayadoleni Nieves_Riveira
Fanny Etienne
Corentin Le Magueresse
INSERM and Sorbonne Université https://orcid.org/0000-0001-8418-4991
Alexandra Rebsam
Nicolas Heck
Luc Maroteaux

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Abstract

The proper maturation of emotional and sensory circuits requires a fine tuning of serotonin (5-HT) level during early postnatal development. Consistently, dysfunctions of the serotonergic system have been associated with neurodevelopmental psychiatric diseases, including autism spectrum disorders (ASD). However, the mechanisms underlying the developmental effects of 5-HT remain partially unknown, one obstacle being the action of 5-HT on different cell types.

Here, we focused on microglia, which play a role in brain wiring refinement, and we investigated whether the control of these cells by 5-HT is relevant for neurodevelopment and spontaneous behaviors. Since the main 5-HT sensor in microglia is the 5-HT_{2B} receptor subtype, we prevented 5-HT signaling specifically in microglia by conditionally invalidating *Htr2b* gene in these cells. We observed that abrogating the serotonergic control of microglia during postnatal development impacts the phagolysosomal compartment of these cells and their proximity to dendritic spines, and perturbs neuronal circuits maturation. Furthermore, this early ablation of microglial 5-HT_{2B} receptors leads to adult hyperactivity in a novel environment and behavioral defects in sociability and flexibility. Importantly, we show that these behavioral alterations result from a developmental effect, since they are not observed when microglial *Htr2b* invalidation is induced later, at P30 onward.

Thus, a primary alteration of 5-HT sensing in microglia, during a critical time window between birth and P30, is sufficient to impair social and flexibility skills. This link between 5-HT and microglia may explain the association between serotonergic dysfunctions and behavioral traits like impaired sociability and inadaptability to novelty, which are prominent in psychiatric disorders such as ASD.

Introduction

Neurodevelopmental psychiatric disorders such as autism spectrum disorders (ASD) are characterized by alterations of spontaneous behaviors and personality traits, like social interactions and adaptability to novelty. Despite their high prevalence - roughly one percent of the total population for ASD -, preventive, diagnosis and therapeutic actions for these disorders are still limited by lack of understanding of their underlying pathophysiology. Among potential risk factors for neurodevelopmental psychiatric disorders are events or mutations that affect the immune system and notably the brain resident macrophages, microglia, which participate to neuronal migration, synapse formation and elimination[1]. An imbalance of the neuromodulator serotonin (5-HT) has also been incriminated[2–4]. Indeed, hyperserotonemia was one of the first biomarkers identified for autism[5] and is observed in 25% of ASD patients with current criteria[6]. Furthermore, 5-HT has developmental roles[7–9], and in mice, increasing or decreasing 5-HT availability during development, through genetic or pharmacological means, alters emotional and sensory neuronal circuits maturation, and has long-term effects on anxiety and sociability in adulthood[7–9]

The mechanisms underlying the implication of 5-HT in the etiology of neurodevelopmental disorders remain partly elusive due to the potential action of 5-HT on different cell types. Notably, besides neurons,

which express a large array of serotonergic receptors, microglia express the 5-HT receptor subtype 2B (5-HT_{2B}) throughout postnatal life[10–12] and we have shown that 5-HT triggers a 5-HT_{2B}-dependent directional motility of microglial processes[10,13]. In addition, *Htr2b*$^{-/-}$ mice, fully invalidated for the gene encoding 5-HT_{2B} receptors, show defects in the maturation of the retinal circuit in the thalamus[10], a developmental process of synapse elimination requiring both microglia and 5-HT[9,14–16], and a wide spectrum of behavioral alterations[17]. However, the interpretation of *Htr2b*$^{-/-}$ mice phenotype is limited by the fact that *Htr2b* gene is expressed not only by microglia but also by subsets of serotonergic and dopaminergic neurons[18,19]. Considering the prominent role of microglia in sculpting brain circuits, and their ability to respond to 5-HT, we tested here the hypothesis that impaired 5-HT sensing specifically in microglia is sufficient to alter the refinement of postnatal circuits, and thereby to induce alterations in spontaneous behaviors relevant to neurodevelopmental psychiatric disorders.

To this aim, using the tamoxifen-inducible creERT2/LoxP system, we invalidated *Htr2b* gene specifically in the microglia/macrophage lineage, either just after birth, or after four weeks of postnatal development, a time point hereafter referred to as “P30”. Our results show that impairing 5-HT signaling in microglia since birth perturbs microglial development and the refinement of neuronal circuits, and leads to hyperactivity in a novel environment, poor sociability and limited behavioral flexibility. Importantly, such behavioral alterations are not induced by ablation of the microglial 5-HT_{2B} receptors after P30, demonstrating a developmental role of the serotonergic regulation of microglia for these spontaneous behaviors. Altogether, our results support the idea that 5-HT, via the 5-HT_{2B} receptor, controls microglia and some of their well-established effects on brain development, and that an early alteration of this serotonergic control can contribute to the etiology of neurodevelopmental disorders characterized by sociability and flexibility defects, such as ASD.

Results

1. Absence of 5-HT_{2B} receptors in neonatal microglia decreases their lysosome content, alters their morphology, and impacts the synapse-microglia proximity in the developing brain.

During the first weeks of postnatal development, microglia proliferate and undergo morphological and functional maturation, with modifications in their phagocytic activity[20,21]. A precise timing of these changes is necessary for microglia to properly regulate brain circuits formation through the induction of dendritic filopodia formation[22], engulfment of presynaptic elements[14,23,24], or promotion of spine maturation[25], but the determinants of this maturation are unknown. To investigate whether microglia development was affected by lack of serotonergic sensing, we triggered an early postnatal ablation of microglial 5-HT_{2B} receptors by administrating tamoxifen to *Cx3cr1*$^{creERT2/+}$;*Htr2b*$^{fl/fl}$ pups between postnatal day (P)1 and P5[12]. We then characterized microglia in these mice, named hereafter cKO$^{Htr2b-\mu glia}{}_{TXFbirth}$, at P15, in comparison with microglia in control cWT$_{TXFbirth}$ mice of the same age, i.e. *Cx3cr1*$^{creERT2/+}$;*Htr2b*$^{+/+}$ mice similarly treated with tamoxifen at birth (timeline in Fig. 1a). Data from

males and females were pooled except for parameters when a sex-dependent effect was observed (e.g. for morphology, see hereafter). First, we checked the microglial (Iba1$^+$ cells) density and did not detect effect of the genotype in any of the brain regions we analyzed (hippocampus, cortex, dorsal lateral geniculate nucleus (dLGN) of the thalamus) (**Fig. S1a-b**). Then, as developing microglia normally exhibit high phagocytic activity, which has been linked to synaptic pruning and refinement of brain connectivity[23,26,27], we measured the percentage of microglial (Iba1$^+$) volume occupied by the macrophage phagolysosomal marker CD68. This revealed that the lysosomal content was strongly reduced (– 40%) in hippocampal microglia of P15 cKO$^{Htr2b-\mu glia}{}_{TXFbirth}$ compared to cWT$_{TXFbirth}$ mice (Fig. 1b-c). During postnatal development, microglia also undergo a transition from amoeboid to ramified [20,21], in a sex-dependent manner[28]. We thus performed three-dimensional (3D) reconstructions of individual microglia in the hippocampus (*Cornu Ammonis* (CA) 1) at P15 (examples in Fig. 1d) to assess their morphology. In male mice, 3D Sholl analysis showed a reduced complexity of microglial processes in cKO$^{Htr2b-\mu glia}{}_{TXFbirth}$ compared to cWT$_{TXFbirth}$ (Fig. 1e), as well as a significant decrease in total length of processes and the number of processes terminal points (Fig. 1f-g). Noteworthy, these differences were not detected in females (Fig. 1h-j), indicating a sex-dependent effect of 5-HT$_{2B}$-mediated signaling on microglia morphology.

Physical contacts between microglia and dendritic spines participate to the sculpting of postnatal neuronal networks[22]. We thus analyzed the structural association of microglial processes with hippocampal dendritic spines. To do so, we performed DiI and P2Y12 receptor labeling to simultaneously visualize CA1 apical dendrites and microglia, and we measured the percentage of dendritic spines with microglial processes located within 0.3 µm of the spine head (scheme in Fig. 1k and representative images in Fig. 1l). By this approach, we determined that the proportion of spines in close proximity to microglia was reduced (– 30%) in cKO$^{Htr2b-\mu glia}{}_{TXFbirth}$ mice (Fig. 1m). Of note, the probability for a spine to have a microglial process in its surroundings increases with its head diameter, and thus spine head size can be a confounding factor, but we verified that the proportion of spines apposed to a microglial process was reduced in cKO$^{Htr2b-\mu glia}{}_{TXFbirth}$ mice whatever the spine head size (**Fig. S1c**). As this effect was observed despite unchanged microglia density, and both in males and females whereas the latter have a normal microglia morphology, it may indicate an intrinsic reduced ability of microglia to structurally interact with spines in the absence of 5-HT$_{2B}$ receptor signaling.

In summary, ablation of 5-HT$_{2B}$ receptor in microglia since birth perturbs microglial maturation and the contacts between dendritic spines and microglial processes during early postnatal development.

2. Absence of 5-HT $_{2B}$ receptors in microglia since birth impairs synaptic and axonal refinement in the developing hippocampus, cortex and thalamus, respectively.

The first weeks of postnatal development are marked by intense synapse formation and pruning of connectivity, which preclude the establishment of mature neuronal circuits. Having identified functional and structural defects in P15 microglia when their 5-HT sensing was disturbed, we investigated whether

this may have impacted connectivity at the same age (timeline Fig. 2a). We focused on hippocampus, cortex and thalamus, i.e. regions where microglia have been involved in developmental axonal or synaptic refinement[14, 24–27,29]. Data from males and females were pooled after checking for the absence of sex-dependent effect. In the hippocampus, we first used Golgi staining to analyze the morphology and density of protrusions, i.e. spines and filopodia-like spines, on the dendrites of CA1 pyramidal neurons (Fig. 2b-e). We observed that the density (Fig. 2c) and the length (Fig. 2d) of dendritic protrusions were increased in of $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ compared to $cWT_{TXFbirth}$ mice. Accordingly, the distribution of protrusion types, as defined in[30], was significantly altered in $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice (Fig. 2e). Of note, no differences in the spine head diameter was observed (**Fig. S1d**), further confirming no spine head-related bias in the spine-microglia proximity phenotype mentioned previously. Interestingly, similar alterations in protrusions density, length and types distribution were observed in the prefrontal cortex (L2/L3 principal neurons) (**Fig. S2a-e**). Second, to confirm functionally the existence of synaptic alterations in the hippocampus, we performed whole-cell recording of CA1 pyramidal neurons on acute brain slices. Indeed, hippocampal neurons from $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ P15 mice displayed higher mEPSC frequency compared to controls, despite no changes in amplitude (Fig. 2f-h). Thus, the early impairment of 5-HT sensing in microglia induces structural and functional synaptic alterations in the hippocampus and cortex, which are consistent with impaired synaptic pruning and/or maturation.

Another region undergoing prominent refinement soon after birth is the dLGN of the thalamus[14,23,24], where eye-specific segregation of retinal projections requires both appropriate 5-HT levels[31] and functional microglia[14]. We previously demonstrated that the maturation of this visual circuit is impaired in *Htr2b* full knock-out mice[10]. Here, the conditional knock-out model allowed us to test if the axonal refinement in the dLGN was dependent on the microglial $5\text{-}HT_{2B}$ receptor. We observed that ipsilateral and contralateral retinal inputs were actually significantly less segregated, i.e. more overlapped, in $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ than in $cWT_{TXFbirth}$ mice at P17-18 (Fig. 2i-j), a time point when segregation is normally achieved. Such defective axonal refinement was confirmed by the fact that ipsilateral projections in $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice were scattered over a greater dLGN area than in $cWT_{TXFbirth}$ mice (**Fig. S2f-h**).

Overall, our results in different brain areas demonstrate that impairment of 5-HT sensing in microglia since birth affects synaptic pruning, axonal refinement and thus brain wiring in the first weeks of postnatal development.

3. Absence of $5\text{-}HT_{2B}$ receptors in microglia since birth impacts activity of mice in a novel environment, sociability and flexibility.

Alterations of brain development can be compensated with age or on the contrary lead to persistent behavioral deficits. To assess long-lasting consequences of interrupting $5\text{-}HT_{2B}$ receptor-mediated signaling in microglia since birth, we profiled the behavior of adult (or, for one test, juvenile) $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice in three domains commonly altered in neurodevelopmental psychiatric

disorders: (i) behavior in a novel environment; (ii) social skills; (iii) flexibility. All behavioral experiments were performed and analyzed separately on males (Fig. 3) and females (Fig. 4).

Significant alterations were observed in males (timeline in Fig. 3a**)**. Indeed, when adult $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ male mice were exposed to a novel environment, they responded with significantly increased locomotion (Fig. 3b) compared to $cWT_{TXFbirth}$ mice. This effect seemed to be due to the novelty of the environment rather than hyperactivity *per se*, being more prominent at the beginning of the test. Moreover, when placed in an unfamiliar cylinder, male $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice spent significantly more time self-grooming than $cWT_{TXFbirth}$ mice (Fig. 3c), suggesting an increased propensity to repetitive stereotypic behavior under unknown and stressful conditions. To identify early deficits in social behavior, we performed the maternal homing test (Fig. 3d-f) on juvenile mice. In the first configuration of the test (Fig. 3d, **upper pannel**), juvenile $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ male mice spent significantly more time in the corner with home cage bedding than with fresh bedding (Fig. 3e), demonstrating an intact ability to recognize familiar olfactory cues. However, in the second configuration where we introduced two mesh tubes, one empty and one containing the juvenile's mother (Fig. 3d, **lower pannel**), the time spent in the corner containing the latter tube was significantly reduced, and the time spent in the corner containing the empty tube was increased, in $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice compared to $cWT_{TXFbirth}$ (Fig. 3f). The social deficit observed in $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ juvenile mice toward their mother persisted in adulthood toward unfamiliar mice. Indeed, in a neutral territory, $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ adult male mice spent less time interacting with an unfamiliar (wild-type) juvenile compared to $cWT_{TXFbirth}$ (Fig. 3g). We further explored the social skills of male mice by investigating their social flexibility. To this aim, we recorded the spontaneous social behavior in home cage of male mice housed with a familiar cage mate, during two consecutive days, using the change of litter bedding after day 1 to challenge the social hierarchy (Fig. 3h)[32]. $cWT_{TXFbirth}$ mice adapted their behavior in response to this challenge, as expected: on day 2, they showed less social investigation than on day 1 when social hierarchies were defined (Fig. 3i). By contrast, $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice behaved independently of the environmental challenge, spending similar time interacting with the conspecific on day 1 and on day 2 (Fig. 3i), and overall less time than the cWT, in accordance with their sociability deficit (assessed in Fig. 3d-g). The difference in social flexibility between cWT and $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice was also illustrated by the increased aggressive behavior of cWT on day 2, while $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice displayed an abnormal aggressive behavior overall (Fig. 3j). These results confirm a strong social impairment and reveal traits of social inflexibility in $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice. To understand if the impairment in flexibility could be generalized beyond the social domain, we assessed cognitive flexibility with a reversal learning test (Fig. 3k-l). During the acquisition phase, $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ male mice learned to choose the correct arm of the Y-maze, containing a food reward, as rapidly as the $cWT_{TXFbirth}$ mice. By contrast, in the reversal phase of the test, $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ male mice failed to learn the new position of the correct arm (Fig. 3l), which indicates that early invalidation of 5-HT_{2B} receptors in microglia decreases not only social but also cognitive flexibility.

Sex differences have been reported in many psychiatric disorders, with notably a higher prevalence of neurodevelopmental disorders in males[33]. We thus assessed whether $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ females presented similar behavioral phenotypes than those observed in mutant males (timeline in Fig. 4a). When placed in a novel environment, adult $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ female mice didn't show hyperlocomotion (Fig. 4b). Nonetheless, as mutant males, $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ females showed enhanced self-grooming in an unfamiliar cylinder compared to cWT (Fig. 4c), suggesting an increased propensity to repetitive stereotypic behavior. We also observed a phenotype for juvenile $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ female mice in the maternal homing test, similar as the one observed in cKO males: despite a normal preference for the nest corner *vs* empty corners (Fig. 4d), the time spent in the corner containing the tube containing their mother was significantly reduced, and the time spent interacting with the empty tube and in the empty corner were increased, compared to $cWT_{TXFbirth}$ females (Fig. 4e). We did not observe defects in social behavior in adult females (Fig. 4f), which might be due to the different nature of social activity between the two sexes at adulthood, male mice being more sensitive to environmental modifications and more prone to increase their repertoire of social explorations to assess social hierarchy[34]. Finally, we assessed cognitive flexibility with the reversal learning test. As observed for mutant males, after a normal acquisition phase, $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ females failed to learn the new position of the correct arm in the reversal phase, in comparison with the $cWT_{TXFbirth}$ females (Fig. 4g**)**. Of note, since most behaviors required intact olfactory capacities, we tested both genotypes in the olfactory habituation/dishabituation test, and we did not detect any difference in their olfactory skills (males: **Fig. S3a**, females: **Fig. S3b**).

Overall, early invalidation of *Htr2b* in microglia leads to severe behavioral alterations in both sexes. The phenotype is however particularly pronounced in males, where it is characterized by increased activity (locomotion, self-grooming) in a novel environment, decreased sociability, and deficits in social and cognitive flexibility. These defects could be linked to the early microglial and synaptic alterations observed in $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ males and females at P15. However, given the importance of 5-HT in adult behavior, and the expression of $5\text{-}HT_{2B}$ receptor gene in microglia throughout life, we performed additional experiments to disentangle the developmental versus adult (acute) effects of 5-HT signaling in microglia on the phenotype observed.

4. Ablation of $5\text{-}HT_{2B}$ receptors in microglia at P30 does not alter spontaneous behaviors.

To test a possible adult/acute role of serotonin to microglia signaling in the behavioral alterations observed in $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ adult mice, we repeated the same behavioral tests on mice where invalidation of microglial *Htr2b* had been induced only after four weeks of postnatal life ("P30"), i.e. once microglia are mature and synaptogenesis and pruning completed[1]. To this aim, $Cx3cr1^{creERT2/+}$;$Htr2b^{fl/fl}$ mice, as well as control $Cx3cr1^{creERT2/+}$;$Htr2b^{+/+}$ mice, were treated with a first dose of tamoxifen between P28 and P30 and a second one 48h later, to generate $cKO^{Htr2b-\mu glia}{}_{TXF-P30}$ and $cWT_{TXF-P30}$ mice, respectively. This protocol was previously shown to be as efficient as the early tamoxifen treatment to induce recombination at the *Htr2b* locus (Fig. S7 in [12]). Behavioral experiments were performed at least

one month after tamoxifen treatment (timeline: Fig. 5a), and males and females were analyzed separately (in Fig. 5 and S4, respectively). In this late ablation condition, after checking normal olfactory skills (males: **Fig. S3c**; females: **Fig. S3d**), we did not detect any deficit in locomotion or self-grooming in a new environment (males: Fig. 5b-c; females: **Fig. S4a-b**), nor in sociability (males: Fig. 5d; females: **Fig. S4c**), or in social (males: Fig. 5e-f) or cognitive flexibility (males: Fig. 5g; females: **Fig. S4d**). This is consistent with the idea that these behavioral domains rely on the establishment of a proper brain connectivity during early postnatal development[35]. Besides, these results indicate that the behavioral defects observed when microglial *Htr2b* is invalidated since birth are directly linked to an impairment of serotonergic signaling to microglia during a postnatal window between birth and P30.

Discussion

In this work, our aim was to investigate if disturbed sensing of 5-HT by microglia affects microglial and neuronal maturation, and can be implicated in behavioral alterations observed in neurodevelopmental psychiatric disorders. Our findings demonstrate that interrupting the serotonergic control of microglia perturbs microglial functions during postnatal development, affects synaptic and axonal refinement throughout the brain at P15-P18, and induces long-lasting behavioral phenotypes in adulthood such as repetitive behavior in a new environment, deficits in sociability and a lack of behavioral flexibility. Importantly, these behavioral alterations, which are reminiscent of core symptoms of neurodevelopmental disorders, are not induced by the ablation of microglial 5-HT_{2B} receptors after P30. This work thus provide evidence that behavioral features (including response to novelty, sociability and flexibility) require the developmental control of 5-HT on microglia.

Microglial 5-HT_{2B} receptor is required in the neonatal period for proper microglial functions and brain wiring. Our data demonstrate that early (i.e. since birth) invalidation of microglial *Htr2b* triggers higher density of dendritic spines and enhanced excitatory neurotransmission in the hippocampus at P15. Synaptic refinement occurs early in postnatal development and relies, notably, on active contacts between microglia and dendritic shafts, promoting spine formation[22,29], and on microglial phagocytosis of presynaptic structures[14,22–24]. Intriguingly, if microglia cannot detect early 5-HT signal through 5-HT_{2B} receptors, they display reduced $CD68^{+}$ phagolysosomal volume at P15, suggesting reduced phagocytic capacity in physiological condition. In addition to the phenotype observed in hippocampal and cortical neurons, presynaptic contralateral and ipsilateral inputs in the dLGN are still intermingled in $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice at P18, suggesting a delay in circuit refinement. In line with their decreased CD68 content, microglia invalidated for *Htr2b* might be less prone to eliminate presynaptic inputs in the dLGN. Additionally, we discovered that a reduced fraction of hippocampal spines is found in close proximity of microglial processes in $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice, suggesting that the absence of 5-HT signal in microglia alters their ability to interact with surrounding neurons. Given that microglia provide a negative feedback control of neuronal activity[36], reduced proximity between microglia and neurons could also contribute to the enhanced excitatory neurotransmission observed in $cKO^{Htr2b-\mu glia}{}_{TXFbirth}$ mice.

Microglial 5-HT $_{2B}$ receptor supports the serotonin-dependent refinement of the visual thalamus during postnatal development. It was previously reported that segregation of retinal projection into eye-specific territories in the dLGN does not occur in monoamine oxidase A knock-out mice (MAOA-KO), which have elevated brain levels of 5-HT, and that these defects can be reversed by inhibiting 5-HT synthesis from P0 to P15. The serotonin transporter (SERT), which is transiently expressed in the dLGN into the ipsilateral retinal projection fields, has been proposed to confer specific neurotransmission properties on a subset of retinal ganglion cells that are important for proper segregation of retinal projections[15]. This was reinforced by the complementary evidence that eye-specific segregation in the dLGN and topographic refinement of ipsilateral axons in the dLGN are impaired in mice lacking vesicular release, in RIM1/2 conditional knock-out mice in SERT-positive neurons[37]. We previously reported that full 5-HT$_{2B}$ receptor deficiency induces anatomical alterations of the ipsilateral projecting area of retinal axons into the dLGN at P30, validating the contribution of this receptor into 5-HT-dependent retinal projection segregation[10]. Here, we demonstrate that presynaptic contralateral and ipsilateral inputs in the dLGN are still intermingled in cKO$^{Htr2b-\mu glia}{}_{TXFbirth}$ mice at P17-18, revealing that part of the 5-HT contribution to this segregation is to control microglia.

Microglial 5-HT $_{2B}$ receptor is required during the neonatal period, but not later, for adult social behavior and cognitive flexibility. We previously reported defects in social interactions in *Htr2b*$^{-/-}$ male mice[17]. Hereby, we observed that, if microglial 5-HT$_{2B}$ receptors are absent since birth, both male and female mice later display a plethora of behavioral abnormalities resembling key symptoms of neurodevelopmental psychiatric disorders, notably abnormal response to novelty, and decreased sociability and adaptability. Intriguingly, these behavioral alterations were not induced by the absence of these receptors after P30. This suggests that 5-HT acts as a global modulator of microglia during the critical time-window of postnatal development between birth and P30, which is required for the establishment of specific behavioral domains.

Sex-dependent effects of the invalidation of microglial 5-HT $_{2B}$ receptors. Microglia exhibit sexually dimorphic transcriptomic and morphological differences along postnatal development and adulthood[28,38–40]. Since neurodevelopmental and psychiatric disorders show a marked sexual dimorphism, it is plausible that sex-dependent microglial functions contribute to the different prevalence of these diseases among males and females. As well, a PET scan study demonstrated that women's brains show lower 5-HT activity[41], possibly reflecting a sex-dependent contribution of 5-HT to psychiatric disorders. We therefore paid attention to possible sex-dependent effects of microglial 5-HT$_{2B}$ receptors invalidation, and observed indeed that early invalidation of microglial *Htr2b* induces a significant alteration of the microglial morphology (reduced complexity of the ramifications) in male mice only. However, the other effects of the early invalidation of microglial 5-HT$_{2B}$ receptors (impairment of microglial CD68 content, synaptic refinement, behavior), were observed in both sexes, which highlights the universal importance of 5-HT sensing by microglia during postnatal development.

Mechanisms linking activation of microglia through 5-HT $_{2B}$ receptors and downstream effects. A still open, question concerns the intracellular signaling effectors of 5-HT in microglia. Both 5-HT and ATP/ADP, activating P2Y12 receptors, induce directional motility of microglial processes[10,13,42]. Moreover, pharmacologic or genetic P2Y12 receptors disruption in adolescent mice induces a reduction in microglial ramification[43], similar to what we observed in males mice invalidated for *Htr2b*. It is thus possible that G_i-coupled P2Y12- and G_q-coupled 5-HT$_{2B}$ receptor-mediated signals are interconnected, either physically, as GPCR heterodimers[44], or functionally. This latter possibility would remind of a mechanism existing in platelets, where aggregation is induced either by ADP[45] or 5-HT[46] through activation of P2Y12 or 5-HT$_{2A}$ – which is structurally very close to 5-HT$_{2B}$ – receptors, respectively, and inhibited by P2Y12 or 5-HT$_{2A}$ receptor antagonists[47,48]. Our results also raise the question of how the stimulation of microglia by 5-HT impacts on synapses and neurons. Our findings suggest that during development, reduced microglial phagocytic capacity and proximity with spines in the absence of 5-HT signaling in microglia is responsible for the altered refinement and thus the behavioral impairments. However, additional mechanisms might be involved, such as decreased somatic contacts or altered secretion of factors affecting spine plasticity.

In summary, our data strongly support that 5-HT acts as an upstream global modulator of microglial functions during early postnatal development, and that a lack of serotonergic control of microglia affects brain connectivity refinement and thereby a variety of behaviors that are altered in neurodevelopmental disorders. Given the number of exogenous factors known to change 5-HT levels during postnatal development, such as physical abuse, maternal separation and maternal inflammation, stress, antidepressants, and their correlation to neurodevelopmental disorders, our findings further emphasize the need of optimal brain levels of 5-HT for proper brain development and function throughout life. Besides, as the serotonergic system is targeted by an array of pharmacological compounds, this newly identified pathway of microglia regulation might open new therapeutic avenues for early intervention in neurodevelopmental disorders.

Materials And Methods

Animals

Animal experiments were carried out according to the national guidelines on animal experimentation and were approved by the Ethical Committee for Animal Experiments of the Sorbonne University, Charles Darwin C2EA – 05 (authorization N°APAFIS#28230-2020111619109364 v4, and 01170.02). All efforts were made to minimize animal suffering. Results are described in accordance with the ARRIVE guidelines for reports in animal research[49]. To obtain targeted invalidation of *Htr2b* gene in microglia, we crossed the *Cx3cr1*^{creERT2} line (MGI Cat# 5528845, RRID:MGI:5528845), which express a tamoxifen-activable cre recombinase under the control of the endogenous *Cx3cr1* promoter, and the *Htr2b*^{flox} line (*Htr2b*^{tm2Lum}/*Htr2b*^{tm2Lum}, *IMSR Cat# EM:05939*, RRID:IMSR_EM:05939), where loxP sites are inserted around the first coding exon of *Htr2b* gene, allowing invalidation of the gene when the recombinase is

activated by tamoxifen as previously described[12,50,51]. All lines were backcrossed on 129S2 background for more than 10 generations. *Cx3cr1*$^{creERT2/+}$;*Htr2b*$^{fl/fl}$ mice were used to obtain the conditional invalidation (see below the protocol to activate the creERT2 recombinase with tamoxifen). *Cx3cr1*$^{creERT2/+}$;*Htr2b*$^{+/+}$ mice, similarly treated with tamoxifen, were used as control mice. P15, P25 or P80-120 male and female animals were used for the experiments (experimental design summarized in Table 1). As indicated along the Results, Figures and Legends, data from males and females are presented separately for microglia morphology and for behavioral experiments, and pooled when no sex-dependent effect was apparent. All mice were group-housed (2–5 mice per cage) in a 12/12 h light/dark cycle with free access to food and water. Temperature and relative humidity were maintained at 21 ± 1°C and between 30% and 60%, respectively.

Table 1

Tamoxifen administration and experimental design

Time of invalidation of *Htr2b* in microglia	**Age at the time of the analysis**	**Sex**	**Analyses performed**
"Early" invalidation (tamoxifen P1-P5), i.e. “TXFbirth” subscript	P15	Males and females	Immunohistochemistry to study microglia, DiI/P2Y12 receptor labeling, Golgi staining, patch clamp recordings (*ex vivo*)
	P15-P18	Males and females	Anterograde labeling (P15) and analysis (P18) of retinogeniculate projections (*ex vivo*)
	P25 (maternal homing test), P80-P120	Males and females	Behavioral assessment
"Late" invalidation (tamoxifen P28-P32), i.e. “TXF-P30” subscript	P80-P120	Males and females	Behavioral assessment

Tamoxifen administration

To study the consequences of invalidation of microglial *Htr2b* at different time points, we used the following experimental approaches. First, to invalidate the *Htr2b* gene since birth (“early” invalidation), we performed intragastric administrations of 50 µg of tamoxifen (Sigma-Aldrich, T5648) per day for 3 days between P1 and P5 as previously described[52]. In a second approach, to invalidate the *Htr2b* gene since P30 (“late” invalidation), tamoxifen was administrated twice between P28 and P32, at 48 h interval, via oral gavage (each gavage corresponding to 0.2 mg tamoxifen.g^{-1} body weight), as previously

described[50]. Of note, we previously validated the efficacy of our protocols to activate creERT2 recombinase by determining by qPCR the level of *Htr2b* recombination in the microglial fraction of mice that received early or late tamoxifen administration, demonstrating a similar decrease (> 85%, Figure S7C in [12]). Moreover, we waited at least 1 month after tamoxifen treatment to allow the full renewal of peripheral Cx3cr1^{+} cells[50,53–56].

Immunohistochemistry

Mice were deeply sedated (pentobarbital, 140 mg.kg^{-1} i.p.) and transcardially perfused with 4% formaldehyde in 0.1 M phosphate buffered saline (PBS). Brains were harvested and immersed in the same fixative for 24 h at 4°C. Afterwards, they were transferred to a PBS solution with 0.01% sodium azide until being cut. 50 µm-thick coronal slices were cut using a vibratome (Leica). Brain slices covering the regions of interest were selected following the mouse brain atlas of Franklin and Paxinos[57]. Brain slices were washed one time in PBS, then incubated in permeabilizing and blocking solution (0.25% gelatin and 0.1% triton in PB) for 30 min. Primary antibodies, rabbit anti-Iba1 (0.0013 µg.µL^{-1}, Wako 019-19741), rat anti-CD68 (0.002 µg.µL^{-1}, AbD Serotec MCA1957), and rat anti-P2Y12 receptor (0.5 µg.µL^{-}1, Biolegend 848002) were diluted in PGT buffer (0.125% gelatin and 0.1% triton in PB). Samples were incubated for 24 h at 4°C with gentle agitation. After rinsing three times with PGT 0.125% buffer, secondary fluorochrome-conjugated antibodies were added to PGT buffer for 3h at room temperature. To quantify Iba1^{+} cells density, we used a donkey anti-rabbit Cy3 (0.002 µg.µL^{-1}, Jackson Laboratories 711-165-152); to colocalize Iba1/CD68 and to assess Iba1^{+} cells morphology, we used donkey anti-rabbit 488 (0.002 µg.µL^{-1}, Invitrogen A21206) and donkey anti-rat Cy3 (0.002 µg.µL^{-1}, Millipore AP189C). After rinsing three times with PGT 0.125% buffer and once with PBS, sections were mounted in Mowiol containing DAPI (0.005 µg.µL^{-1}, Sigma).

Image acquisition and analysis

For quantification of Iba1^{+} cell density, images were acquired with a Leica DM6000 epifluorescence microscope equipped with a CCD camera (CoolSNAP EZ, Teledyne Photometrics). Density of Iba1^{+} cells was quantified on 20x images collected in several regions (identified anatomically), including CA1, CA3 and dentate gyrus (DG) of the dorsal hippocampus, retrosplenial cortex (Ctx) and dLGN. For each region, one image per hemisphere was taken from four to six separate brain sections to obtain an average value for that mouse. Images were smooth processed and binarized, and Iba1^{+} cells were identified and counted using the Analyze particle plugin for ImageJ, setting the minimum detectable size at 40 µm^{2}.

For 3D reconstruction of entire microglial cells and analysis of microglial lysosome content, confocal fluorescent images were acquired on an upright confocal microscope (Leica TCS SP5), using a 40x/1.25–0.75 oil (11506253) objective with 2X electronic magnification (188.92 nm pixel size) and lasers set at 488 and 561 nm for excitation of FITC and Cy3, respectively. Stacks were acquired using a 0.5 µm z-interval. Image stacks were imported into ImageJ for processing as previously described[58,59]. Briefly, to edit the channel window containing Iba1^{+} cells, an Unsharp Mask filter was used to further

increase contrast using a pixel radius of 3 and mask weight of 0.6, a despeckle step was performed to remove salt-and-pepper noise and outlier pixels were removed with the Remove Outliers function (pixel radius 2; threshold 50). Image stacks were then imported into Imaris Software (Bitplane). Individual microglia were reconstructed in 3D using the filament tracer module and measures of the process length, terminal points, as well as 3D-Sholl analysis were performed to assess their morphology. For analysis of $CD68^+$ intracellular compartment, surface module was used to reconstruct the volume of individual Iba1 + cells and of CD68-labeled lysosomes, and then the percent of microglia volume occupied by CD68 was assessed as previously described[58]. The experimenter carrying out the acquisition and analysis of images was blind to the mice genotype.

DiI labeling of dendritic spines and analysis of microglial proximity

Deeply sedated mice (pentobarbital, 140 $mg.kg^{-1}$ i.p.) were transcardially perfused with 2% formaldehyde in PBS. Whole brains were removed, immersed in the same fixative for 1 h, transferred to a solution consisting of PBS with 0.01% sodium azide until being cut, and sectioned at 100 µm thickness on a vibratome (Leica). Two sections per mouse were selected in the region corresponding to 1.82 mm caudal to bregma in the mouse brain atlas of Franklin and Paxinos[57]. DiI labeling of dendritic spine and spine analysis were performed as previously described[60]. Briefly, DiI beads (1,10-dioctadecyl-3,3,30,30-tetramethylindocarbocyanine perchlorate; Molecular Probes, Eugene, OR) were delivered to the slices using a helium gas pressure (100–150 psi) through the gene gun device (BioRad). A 3 µm pore size filter (Isopore polycarbonate, Millipore) was inserted between the gene gun and the slice to select single beads. Slices were kept in PBS at room temperature for at least 2 h to allow DiI diffusion in neurons, then incubated in permeabilizing solution (0.1% triton in phosphate buffer, PB) for 5 min, followed by blocking solution (0.25% gelatin and 0.01% triton in PB) for 45 min. Rat anti-P2Y12 receptor (0.5 $µg.µL^{-1}$, Biolegend 848002) was diluted in a solution of 0.125% gelatin and 0.01% triton in PB and samples were incubated for 72 h at 4°C with gentle agitation. After rinsing three times with 0.125% gelatin and 0.01% triton in PB, donkey anti-rat 488 (0.0013 $µg.µL^{-1}$, Invitrogen A21208) was added to the buffer for 3h at room temperature. Slices were mounted in Mowiol containing DAPI (0.005 $µg.µL^{-1}$, Sigma). Image stacks of apical dendritic segments in CA1 were taken using a confocal laser scanning microscope (SP5, Leica) equipped with a 63x/1.4 NA objective (oil immersion, Leica) with a pinhole aperture set to 1 Airy unit, pixel size of 60 nm and z-step of 200 nm. The excitation wavelength and emission range were 488 and 500–550 nm for Alexa 488 (i.e. P2Y12 receptor) and 561 and 570–620 for DiI. Deconvolution with experimental point spread function from fluorescent beads using a maximum likelihood estimation algorithm was performed with Huygens software (Scientific Volume Imaging). One hundred fifty iterations were applied in classical mode, background intensity was averaged from the voxels with lowest intensity, and signal to noise ratio values were set to a value of 20. For each mouse, 10 dendritic segments of 20–50 µm in length were analyzed. Dendritic spines were analyzed with Neuronstudio software[61] (version 9.92; http://research.mssm.edu/cnic/tools.html). Images from the P2Y12 receptor channel were preprocessed in order to enhance the contrast, using an Unsharp Mask filter using a pixel radius of 3 and mask weight of 0.6, a despeckle step was performed to remove salt-and-pepper noise and

outlier pixels were removed with the Remove Outliers function (pixel radius 2; threshold 50). To analyze the interaction between microglial processes and dendritic spines, we measured the percentage of dendritic spines having microglial processes located within 0.3 µm surrounding the spine head using Fiji-ImageJ software. To assess the presence of microglial processes, for each spine, its 3D coordinates and head diameter measured with Neuronstudio were used to draw a sphere on the image using the DrawShape function of the plugin 3DImageSuite. A second sphere centered on the spine coordinates with a diameter extended by 0.3 µm was then drawn. The volume space in between the two spheres was converted into a Region of Interest. The mean intensity inside the 3D ring volume was assessed in the channel corresponding to Alexa 488 (i.e. P2Y12 receptor), and compared to that of the background. If the mean intensity was more than ten times than that of the background, it was considered that the spine had microglial processes in proximity.

Golgi staining and spine analysis

Fresh brains were processed following the Golgi-Cox method as described before[62,63]. Briefly, mice were deeply sedated (pentobarbital, 140 $mg.kg^{-1}$ i.p.) and brains were harvested, briefly rinsed in NaCl, and incubated in the dark in filtered dye solution (10 $g.L^{-1}$ $K_2Cr_2O_7$, 10 $g.L^{-1}$ $HgCl_2$ and 8 $g.L^{-1}$ K_2CrO_4) for 15–16 days. Impregnated brains were then washed 3 × 2 min in distilled water (dH_2O) and transferred to a tissue-protectant solution (30% sucrose in dH_2O) for 24 h. Afterwards, brains were rinsed 3 x 2 min in dH_2O and incubated 30 min in 90% EtOH (v/v). Two hundred µm-thick coronal sections were cut in 70% EtOH on a vibratome (Leica) and washed in dH_2O for 5 min. Next, sections containing the dorsal hippocampus (6 sections per mouse) or medial prefrontal cortex (6 sections per mouse) were reduced in 16% ammonia solution for 1 h, washed in dH_2O for 2 min and fixated in 10 $g.L^{-1}$ $Na_2S_2O_3$ for 7 min. After a final wash in dH_2O, sections were mounted on superfrost slides and allowed to dry at room temperature for 1–2 h. The dehydration steps proceeded as following: 3 min in 50% EtOH, 3 min in 70% EtOH, 3 min in 80% EtOH and 3 min in 100% EtOH, 2 × 5 min in a 2:1 isopropanol:EtOH mixture, 5 min in pure isopropanol and 2 × 5 min in xylol. Neurons were first identified with a light microscope (Leica 6000) under low magnification (×20). At least three neurons per mouse were selected according to the following criteria: (1) consistent and dark impregnation along the entire extent of all the dendrites; (2) presence of fourth-order branches for both apical and basal dendrites, (3) presence of untruncated dendrites, (4) soma entirely within the thickness of the section, and (5) relative isolation from neighboring impregnated neurons. Bright-field images of z-stacks of apical dendrites from hippocampal CA1 and L2/L3 pyramidal neurons were then captured with a × 100 oil objective every 0.2 µm using a CoolSNAP EZ CCD Camera (Teledyne Photometrics). Given that protrusions density reached a plateau 45 µm away from the soma, we selected dendritic segments at least 50 µm away from the cell body. Protrusions were counted on secondary branches of apical dendrites. Only protrusions with a clear connection of the head of the protrusion to the shaft of the dendrite were counted. Protrusion density, length and width were analyzed using the Reconstruct software as described by Risher and colleagues[30]. Protrusions were classified based on their morphology into six classes using the following exclusive criteria[30]: filopodia, when the length value > 2 µm; long thin spines, when the length value > 1 µm and ≤2 µm; thin spines, when the

length-to-width ratio (LWR) value > 1; mushroom spines, when the width value > 0.6 µm; stubby spines, when the LWR value ≤ 1; branched spines, when spines showed more than one head (entered manually by the experimenter). All image analyses were done blind.

Patch clamp recordings

Two hundred fifty µm-thick transverse hippocampal slices were prepared from brains of P15 mice. Mice were deeply sedated (pentobarbital, 140 $mg.kg^{-1}$ i.p.) and the brain was quickly removed from the skull, then sectioned with a vibroslicer (HM 650 V, Microm) in ice-cold artificial cerebrospinal fluid (ACSF) containing the following (in $mmol.L^{-1}$): 125 NaCl, 2.5 KCl, 25 glucose, 25 $NaHCO_3$, 1.25 NaH2PO_4, 2 $CaCl_2$, and 1 $MgCl_2$, continuously bubbled with 95% O2-5% CO_2. Slices were incubated in ACSF at 32°C for 20 min and then at room temperature (20–25°C). For patch-clamp recordings, slices were transferred to the recording chamber where they were continuously superfused with ACSF (30–32°C) buffered by continuous bubbling with 95% O_2-5% CO_2. Patch-clamp pipettes (4–6 Mohm resistance) were prepared from borosilicate glass (BF150-86-10; Harvard Apparatus) using a DMZ pipette puller (Zeitz). CA1 pyramidal neurons were visually identified using an upright microscope (Olympus BX51WI). Neurons were voltage-clamped using an EPC10 amplifier (HEKA Elektronik) and the following intracellular solution (in $mmol.L^{-1}$): 120 Cs-methane sulfonate, 10 CsCl, 10 Hepes, 10 Phosphocreatine, 0.2 EGTA, 8 NaCl, 2 ATP-Na_2, 3 QX 314 (pH 7.25, adjusted with CsOH). Miniature excitatory postsynaptic currents (mEPSCs) were recorded in CA1 pyramidal neurons at a holding potential of -65 mV in the presence of Tetrodotoxin (TTX, 0.5 µM, Hello Bio) and SR95531 hydrobromide (Gabazine, 10 µM, Hello Bio). At least 200 s of recording were analyzed for each cell. Series resistance was left uncompensated. Input resistance was monitored by voltage steps of − 10 mV before and after mEPSC recordings. Experiments were discarded if the series resistance changed by more than 20% during the recording. Data acquisition was performed using Patchmaster software (Heka Elektronik). The junction potential (-14.9 mV) was uncorrected. Signals were low pass-filtered at 4 kHz before sampling at 20 kHz. Recordings were filtered offline at 2 kHz using Clampfit (Molecular Devices) and analyzed using MiniAnalysis (Synaptosoft). During patch-clamp recordings and analysis, the investigator was blind to the mouse genotype.

Anterograde labeling of retinogeniculate projections

P15-16 mice were anesthetized with ketamine–xylazine (100 and 10 $mg.kg^{-1}$, respectively, in 0.9% saline). Eyes were intravitreally injected using a glass micropipette with 1–5 µl of 0.2% cholera toxin subunit B (CTB) conjugated to Alexa Fluor 488 or 555 (Invitrogen) diluted in 1% DMSO. After 48 h, mice were deeply sedated (pentobarbital, 140 $mg.kg^{-1}$ i.p.) and perfused transcardially with 4% paraformaldehyde in PBS. Brains were postfixed overnight with the same fixative and sectioned with a vibratome (60 µm). All sections containing the dorsal lateral geniculate nucleus of the thalamus (dLGN) were selected and directly mounted in Mowiol containing DAPI (0.005 $µg.µL^{-1}$, Sigma). 10X epifluorescent images were obtained using a CCD camera (CoolSNAP EZ, Teledyne Photometrics) attached to an upright Leica 6000 microscope.

MetaMorph software (Molecular Devices) was used for quantitative analyses. All image analyses were done blindly to the mice genotypes. Quantification of eye-specific segregation was performed on images of Alexa Fluor 488-labeled contralateral/Alexa Fluor 555-labeled ipsilateral projections, as previously described by Rebsam and colleagues[64]. Briefly, variable thresholds were used for the contralateral projection and a fixed threshold for the ipsilateral projection. After outlining the boundary of the dLGN, we measured the pixel overlap between ipsilateral and contralateral projections at every 10th threshold value for the contralateral image. The proportion of dLGN occupied by ipsilateral axons was measured as a ratio of ipsilateral pixels to the total number of pixels in the dLGN region. Additionally, we quantified the areas occupied by ipsilateral and contralateral retinogeniculate projections and the extent of ipsilateral retinogeniculate projections along the outer-inner axis (O-I axis), perpendicular to the surface of the dLGN, and the dorsomedial-ventrolateral axis (DM-VL axis), parallel to the surface of the dLGN, as previously described by Hayakawa and Kawasaki[65]. The extent of the ipsilateral projection along the O-I and DM-VM axes was measured by tracing a line between the two points delineating the maximal extent of the ipsilateral signal along the chosen axis. The extent of the ipsilateral projection along the dLGN axis is calculated by dividing the length of the ipsilateral projection by the dLGN length and is expressed as a percentage of dLGN length. For quantifying the areas occupied by ipsilateral retinogeniculate projections, thresholds (Ti) were determined as follows: Ti = Mi x 0.165, where Mi was the maximum signal intensity in five consecutive sections, the third of which was the section containing the largest dLGN area. The size of the area whose signal intensities were more than Ti was used as the size of ipsilateral retinogeniculate projections. For quantifying the areas occupied by contralateral retinogeniculate projections, thresholds (Tc) were determined as follows: Tc = Mc x 0.5, where Mc was the average signal intensity of contralateral retinogeniculate projections. The areas whose signal intensities were less than Tc consisted of two kinds of regions: the “gap,” which is the CTB-negative area in the central dLGN, and the regions that are connected with the contours of the dLGN. In order to measure the size of the gap, the latter was excluded.

Behavioral assessment

Experiments were carried out in the light phase of the light/dark cycle (between 8:00 a.m. and 8:00 p.m.). For each behavioral test, mice were acclimatized to the testing room for at least 1 hr. Equipment was carefully swabbed with 35% ethanol between each mouse to eliminate odors. Behavioral tests were video-recorded in real-time and analyzed off-line by an experimenter blinded to the experimental groups using the free event recorder JWatcher software (Blumstein & Daniel http://www.jwatcher.ucla.edu/).

Novelty-induced locomotion

Adult mice were individually placed in a cage with the same size of the home-cage containing a thin layer of fresh bedding, and allowed to freely explore for 15 min. Total distance moved and mean velocity were scored during 3 5-min blocks.

Novelty-induced self-grooming

Adult mice were individually placed in a Plexiglas cylindrical arena (20 cm in diameter), and the total time spent performing face, body and/or tail grooming was scored for 5 min as previously described[66].

Homing test

P25 mice were subjected to a maternal homing test as previously described[67]. This test exploits the tendency of mice to maintain body contact with the mother and their siblings and tests olfactory, visual and motor capacities. Mice were separated from the mother for at least 30 min before testing. During habituation, individual juveniles were transferred to a Plexiglas arena (23 × 23 cm, walls 13 cm high) containing fresh bedding with a small amount of soiled nest (not including fecal boli) sprinkled into the opposite corner and allowed to explore for 5 min. Time spent in the starting, nest and neutral corners was measured. Subsequently, the mice were briefly removed to a holding cage while two wire-mesh tubes were placed into the neutral corners, one empty and one containing the animal's mother. Time spent in the four corners was scored.

Social interaction

Each experimental mouse was individually transferred to a novel cage. After 15 min of habituation, an unfamiliar juvenile mouse (7 weeks old) of the same sex and strain, used as a social stimulus, was introduced in the cage for 10 min. The following behavioral patterns were used to define social investigation: anogenital sniff (sniffing the anogenital area of the partner); nose sniff (sniffing the head and the snout region of the partner); body sniff (sniffing any other area of the body of the partner); allogrooming (grooming the partner). The duration of social investigation was measured.

Social flexibility

Social and aggressive behavior in response to a challenge in social hierarchy was recorded according to the paradigm previously described[68,69]. Briefly, mice housed two by two of the same genotype were observed in their home cage, for a single 30 min session on two consecutive days. The cages had not been cleaned for seven days at the time of the observations, to allow impregnation of the bedding with animal's odors. During the first day of observation, no manipulation was performed. On the second day, the cage bedding was changed with clean bedding just before the session of observation. This procedure is known to challenge social hierarchy and to elicit aggressive behavior. The behavioral elements scored for duration were related to social investigation (sniffing and grooming the partner in all body regions indicative of affiliative behavior) or aggressive behavior (active fighting episode of attacks and aggressive grooming, as well as tail rattling and digging behaviors aimed to assess dominant status). Since the data collected was dependent, only one mouse, randomly selected from each cage, has been considered in the analysis. In order to be able to discriminate the two animals during data collection, one of the two experimental subjects was marked with a blue, scentless and nontoxic felt pen seven days before the first day of observation.

Reversal learning

To test memory formation and cognitive flexibility, mice were subjected to a Y-maze task. The apparatus consisted of a transparent, Plexiglas maze composed of 3 test arms forming a Y. The entire procedure took 10 consecutive days: 1 day of habituation, 6 days of acquisition and 3 days of reversal learning. One of the arms was randomly selected as starting arm and, during habituation, mice were individually

located in the maze, free to explore for 30 min. In the acquisition phase, one of the other two was baited with a food reward pellet (Noyes sucrose pellet, 20 mg, Research Diets, Inc., New Brunswick, NJ). The side of the rewarded arm was balanced across mice in order to avoid any side preference. Mice were trained to find the food reward in 10 consecutive trials for 6 days. If the mouse made the correct choice, it was given time to consume the sugar pellet, and then guided back into the start arm for the next trial. Incorrect choices were not rewarded or punished. If the mouse did not make any choice in 3 min, it went back to the home cage and the trial was considered as incorrect. For each successive trial, the reward was always placed in the same arm. Number of errors in arm selection, and number of days to criterion were recorded by an observer, blind to the genotypes. The % of correct choice of one session (i.e., day) is the ratio of the number of correct choices divided by the number of trials (= 10). The criterion for task acquisition, determined for each mouse, was 80% correct responses on three consecutive days. Each mouse that met criterion for acquisition was then further tested using a reversal procedure, in which the reward location was switched to the arm opposite to its previous location for each mouse. Ten trials per day were then performed for reversal learning, using the same methods and criterion as described above. Subjects were food-restricted, maintaining them at 80–85% of their individual body weight calculated under ad libitum feeding conditions, starting 1 week before the beginning of the experiment and throughout the entire procedure.

Olfactory habituation/dishabituation test

The ability to discriminate non-social and social odors was measured using modifications of the olfactory habituation/dishabituation task, as previously described[70]. Subjects were individually tested for time spent sniffing cotton tipped swabs suspended from the cage lid. The olfactory cues were designed to measure familiar and unfamiliar odors, with and without social valence. Sequences of three identical swabs assayed habituation to the same odor, resulting in a progressive decrease in olfactory investigation. Switching to a different odor on the swab assayed dishabituation, i.e. recognition that an odor is new. Five different odors were presented in three consecutive trials of 2 min per trial, with an inter-trial interval of 1 min. The order of swaps was: water (neutral odor), two non-social odors (almond and banana) and two social scents (social 1, unfamiliar mouse of the same sex and different strain, and social 2, unfamiliar mouse of the same strain and opposite sex). In each session trials 50 µL H_2O or 50 µL of a 1:100 dilution of the odor solutions in H_2O were pipetted onto a new cotton applicator directly before the test and sealed in a closed tube until the presentation. Unfamiliar social scents were prepared on the test day by swapping the bottom of a cage with a mouse from a different strain (i.e. C57BL/6J) or opposite sex on a cotton applicator and kept sealed until the presentation. Time spent sniffing the swab was quantitated with a stopwatch by a blinded human observer. Sniffing was scored when the nose was within 2 cm of the cotton swab. Each test session was conducted in a clean mouse cage containing fresh litter.

Statistical analysis

For each figure, the *n* values are summarized at the end of the legend. Statistical analyses were performed using GraphPad Prism 6.01 software (Graph-Pad Software). Males and females were included

and compared to determine if sex impacted our experimental results. All *n* values represent individual animals, unless stated otherwise (i.e. electrophysiology experiments). Notably, in analyses where multiple microglia were assayed per animal, all microglia analyzed for an individual animal were averaged to generate a single value per animal. When appropriate, animals were randomly assigned to conditions. Where possible, conditions were randomized to account for potential ordering effects. To ensure reproducibility, when relevant, experiments were performed at least three times independently. To avoid litter bias in the mouse experiments, experimental groups were composed of animals from different litters randomly distributed. All analyses were conducted with blinding to the experimental condition. Data are presented as scatter dot plot with bar, and the line at the mean ± S.E.M. (standard error of the mean). Comparisons between two groups following a normal distribution were analyzed using two-tailed unpaired t-test with or without Welch's correction, comparisons between two groups not following a normal distribution with Mann-Whitney test. Normality was assessed using the D'Agostino & Pearson omnibus normality test. When we compared cumulative distributions, we used the Kolmogorov-Smirnov test. When more than one variable was evaluated, we employed the two-way ANOVA with or without repeated measures (ANOVA and RM-ANOVA, respectively) with Sidak multiplicity-corrected post hoc comparisons to compare cohorts where appropriate. The statistical tests are reported in the figure legends along with the definition of *n*. For all analyses, $\alpha = 0.05$.

Declarations

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Author contributions

G.A., I.D., L.M. and A.Ro. designed the studies. G.A., I.D, A. Ro and L.M. wrote the manuscript, all authors revised it. G.A., I.D., F.E. and C.B. performed tamoxifen administration. G.A. performed immunofluorescence, image acquisition and analysis, Golgi-Cox staining and spine analyses. N.H. contributed to the design of DiOlistic labeling of dendritic spines, provided reagents and created the ImageJ Macro to analyze microglia/spines proximity. G.A. delivered DiI, performed image acquisition and analysis. C.L.M. contributed to the design and analysis of the electrophysiology experiments and

provided reagents. G.A., M.D. and N.R.N. performed the electrophysiology experiments. A.Re. contributed to the design and analysis of the anterograde labeling of retinogeniculate projections and G.A. performed the intravitreal injections and image acquisition and analysis. I.D. performed behavioral experiments. G.A., I.D. and M.D. performed data analysis.

Competing interests

The authors declare no competing interests.

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Figures

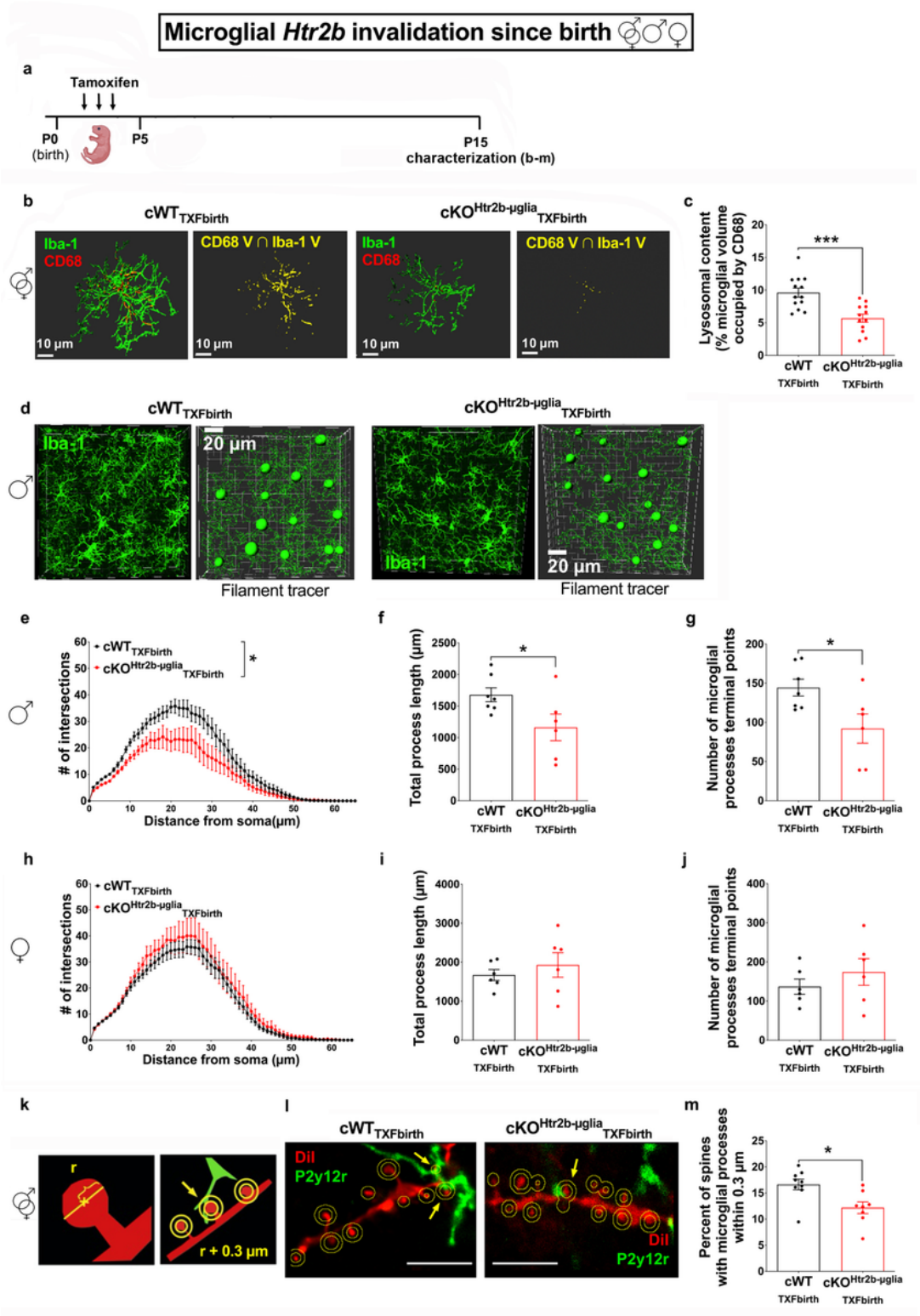

Figure 1

Absence of 5-HT$_{2B}$ receptors in neonatal microglia decreases their lysosome content, alters their morphology, and impacts the synapse-microglia proximity in the developing brain. a, Timeline of tamoxifen treatment for early *Htr2b* invalidation in microglia, and the analyses performed at P15. **b**, Representative images of CA1 microglia with their lysosomal content in cWT$_{TXFbirth}$ and cKO^{Htr2b-}

$^{\mu glia}_{TXFbirth}$ P15 mice. Left panels: immunostaining for Iba1 and the microglial lysosomal protein CD68; right panels: 3D reconstruction of $CD68^+$ lysosomes with $Iba1^+$ cells overlay (in yellow). **c,** The relative microglial cell volume occupied by $CD68^+$ lysosomes is significantly reduced in $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$ mice ($cWT_{TXFbirth}$, *n* = 13 mice, mixed males and females; $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$, *n* = 12 mice, mixed males and females; 8 microglia analyzed and averaged per animal; unpaired t-test with Welsh's correction, p = 0.0003). **(d-g)** Morphological analysis of CA1 microglia in P15 male mice ($cWT_{TXFbirth}$, *n* = 7 male mice; $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$, *n* = 6 male mice; for each mouse, the value represents the average value of 4-8 microglia). **d**, Representative images of microglia ($Iba1^+$ cells, left panels) in CA1 of $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$ P15 male mice, and their 3D reconstructions (right panels) carried out using the filament tracer module by Imaris. **e**, Sholl profiles; note the reduced arborization in microglia from $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$ males compared to $cWT_{TXFbirth}$ (two-way RM-ANOVA: significant main effects of interaction P < 0.0001, $F_{65,715}$ = 2.571, radius P < 0.0001, $F_{65,715}$ = 65.13 and genotype P = 0.0295, $F_{1,11}$ = 6.254). **f**, Total length of microglial processes; note the reduction in $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$ (Mann-Whitney test, p = 0.0350). **g**, Number of microglial processes terminal points; note the reduced number of terminal points in $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$ (Mann-Whitney test, p = 0.0408). **(h-j)** Morphological analysis of CA1 microglia in P15 female mice ($cWT_{TXFbirth}$, *n* = 6 female mice; $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$, *n* = 6 female mice; for each mouse, the value represents the average value of 4-8 microglia). **h**, Similar Sholl profiles of microglia in $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$ female mice. **i**, Similar total length of microglial processes in $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$ female mice. **j**, Similar number of microglial processes terminal points in $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$ female mice. **(k-m)**, Assessment of the association of dendritic spines with microglial processes at P15. **k,** Drawings of the method used for quantification: a spine was counted as associated with a microglial process when microglial P2Y12 receptor (P2Y12r) staining was present at a distance < 0.3 µm. **l,** Representative images of hippocampal dendrites of $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$ mice with some spines surrounded (arrows) by microglial processes ($P2Y12r^+$) in close proximity (< 0.3 µm). Analysis was performed in 3D in image stacks, the figure is represented in 2D for easier visualization. Scale bar: 5 µm. **m**, The percent of spines located within 0.3 µm to microglial processes was significantly reduced in $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$ mice ($cWT_{TXFbirth}$ mice, *n* = 9 mice, mixed males and females; $cKO^{Htr2b\text{-}\mu glia}_{TXFbirth}$ mice, *n* = 8 mice, mixed males and females; Mann-Whitney test, P = 0.0111). All graphs show mean±s.e.m. and points in (**c**, **f-g**, **i-j**, **m**) represent individual animals. *p< 0.05, ***p < 0.005.

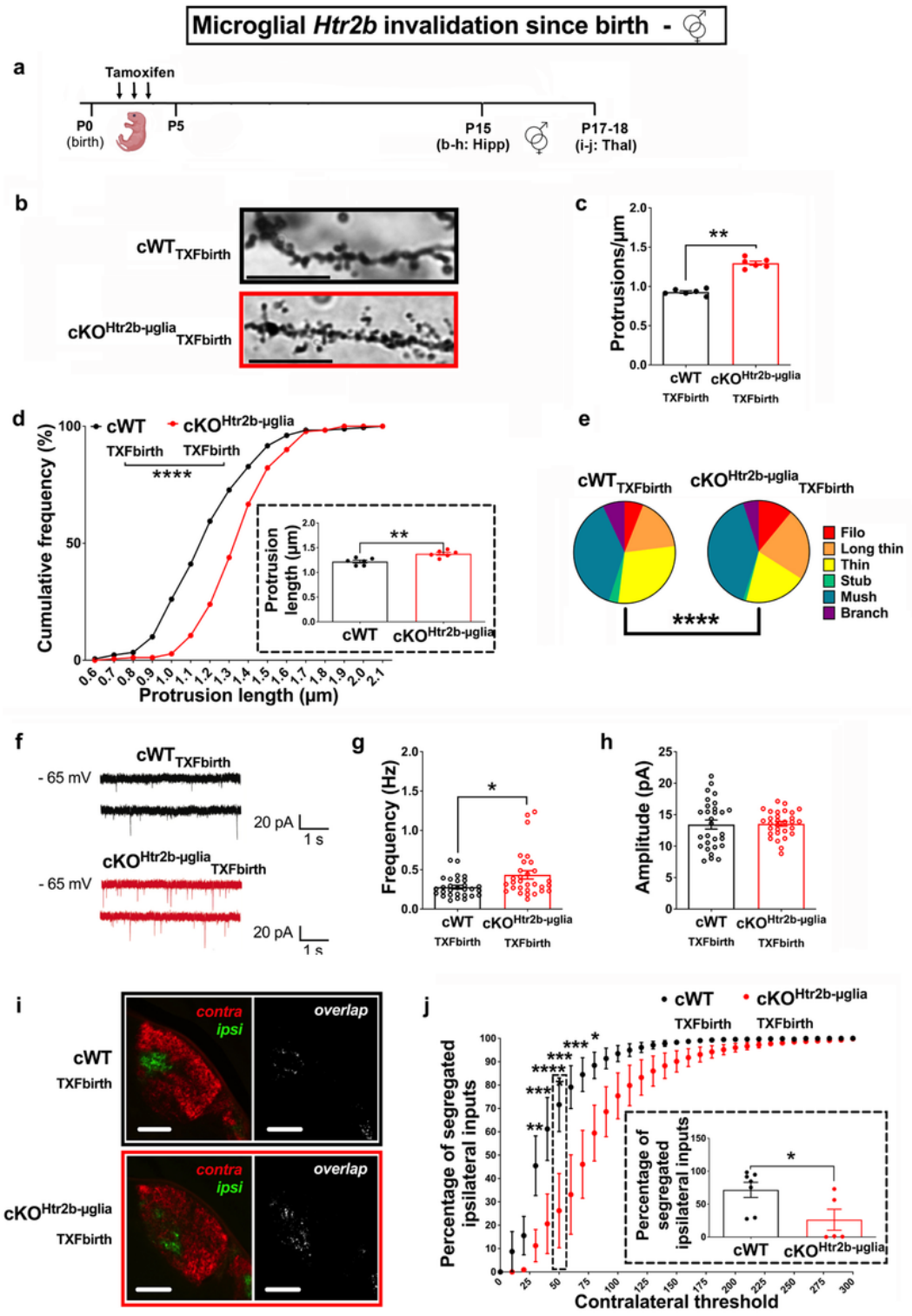

Figure 2

Absence of 5-HT$_{2B}$ receptors in microglia since birth impairs neuronal circuits refinement in the developing hippocampus and thalamus. a, Timeline of tamoxifen treatment for early *Htr2b* invalidation in microglia, and analyses of hippocampal synapses at P15 or of dLGN axonal segregation at P17-18. Data on males and females are pooled. **(b-e)** Analysis of dendritic protrusions on CA1 pyramidal neurons in cWT$_{TXFbirth}$ and cKO$^{Htr2b\text{-}µglia}_{TXFbirth}$ mice at P15 (*n* = 6 mice/genotype, 30 dendrites per mouse). **b**,

Representative images of secondary apical dendrites in hippocampal pyramidal neurons of $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ P15 mice labeled with Golgi staining, scale bar: 10 µm. **c**, Protrusions density on secondary apical dendrites; note the significant increase in $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice (Mann-Whitney test, p = 0.0022). **d**, Cumulative distribution plot for the average length of protrusions on secondary apical dendrites; note the significant rightward shift in $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice (*n* = 180 dendrites from 6 mice/genotype, Kolmogorov-Smirnov test, p < 0.0001). In the inset, quantification of protrusion length obtained averaging 30 dendrites/mouse, that confirms a significant increase in $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice (Mann-Whitney test, p = 0.0087). **e**, Pie charts showing the altered distribution of protrusion types in $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice (*n* = 180 dendrites from 6 mice/genotype, Chi-square test, p < 0.0001). Abbreviations: Filo: filopodia; Stub: stubby; Mush: mushroom. **(f-h)** Analysis of mEPSCs in CA1 in $cWT_{TXFbirth}$ (*n* = 29 cells from 5 mice) or $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice (*n* = 30 cells from 5 mice) at P15. **f**, Representative traces of mEPSC recordings in CA1 hippocampal acute slices from $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice. **g**, Increased mESPC frequency in $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice (Mann-Whitney test, p = 0.0120). **h**, Similar mESPC amplitude in $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice. **(i-j)** Analysis of dye-labeled retinogeniculate projections in dLGN of $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice (*n* = 7 and 5 mice, respectively) at P17-P18, 48h after intravitreal injection of AlexaFluor 488 or 555 in either eye. **i**, Representative images of axonal segregation in $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice. Left panels: projections from retinal ganglion cells from the ipsilateral retina are in green and those from the contralateral retina are in red; right panels: overlap between ipsi- and contralateral projections. Scale bars 100 µm. **j**, Percentage of pixels containing only ipsilateral signal (no contralateral signal) as a function of contralateral threshold (ipsilateral threshold is fixed); note the significant rightward shift in $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice, that demonstrate that ipsilateral fibers are less segregated from contralateral fibers (thus more overlapped) than in $cWT_{TXFbirth}$ mice (two-way RM-ANOVA: significant main effects of interaction P < 0.0001, $F_{30,300}$ = 4.118, contralateral threshold P = 0.0288, $F_{30,300}$ = 76.03 and genotype P = 0.0295, $F_{1,10}$ = 6.507; Sidak multiple comparisons: 30, p = 0.0027; 40, p = 0.0001; 50, p < 0.0001; 60, p < 0.0001; 70, p = 0.0003; 80, p = 0.0256. The inset shows a columnar representation of the values for the contralateral threshold set at 50 (Mann-Whitney test, p = 0.0303). All graphs (except cumulative curve in **d** and pie chart in **e**) show mean±s.e.m. and points in (**c**, inset of **d**, inset of **j**) represent individual animals. *p < 0.05, **p < 0.01, ***p < 0.005, ****p < 0.0001.

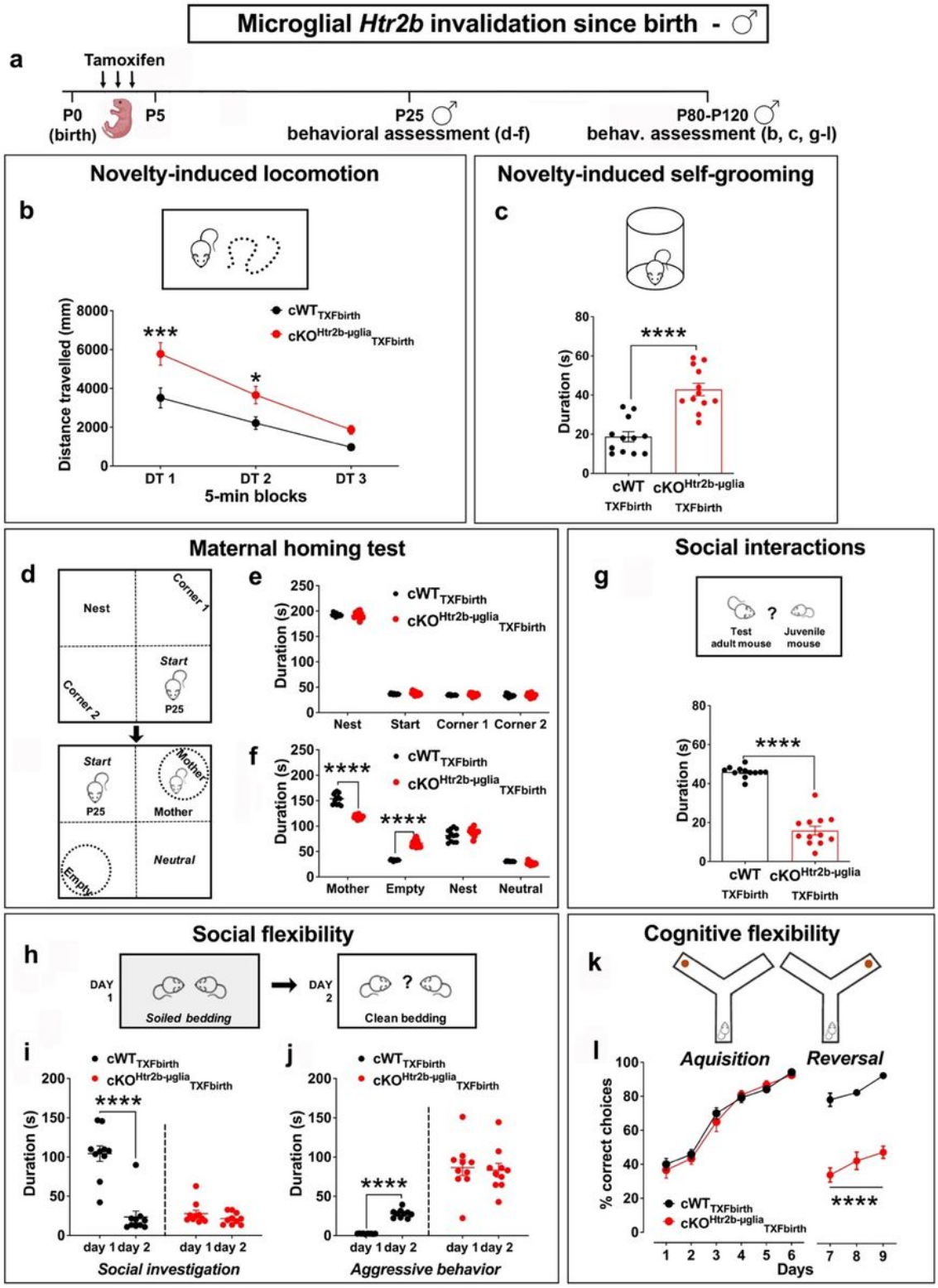

Figure 3

Absence of 5-HT$_{2B}$ receptors in microglia since birth impacts activity in a novel environment, sociability and flexibility in male mice. a, Timeline of tamoxifen treatment for early microglial *Htr2b* invalidation, and the behavioral tests performed in juvenile (maternal homing test) or adult male mice. **b**, Distance travelled (DT) by male mice placed in a novel environment in 5-min blocks (DT1, 2, 3) (*n* = 12 male mice/genotype, two-way RM-ANOVA: significant main effect of DT P < 0.0001, F2,44 = 69.85 and genotype P = 0.0040,

F1,22 = 10.36); note that the increased locomotion is significant only in the first 10 min of test (Sidak multiple comparisons: $cWT_{TXFbirth}$ vs. $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$, DT1, p = 0.0006; DT2, p = 0.0416). **c**, The time spent self-grooming when male mice are placed in an unknown cylindrical arena is strongly enhanced in $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ compared to $cWT_{TXFbirth}$ adult male mice (*n* = 12 male mice/genotype, unpaired *t*-test, p < 0.0001). **(d-f)** Maternal homing test at P25, *n* = 12 male mice/genotype**. d**, Scheme of maternal homing test: habituation (upper panel) and test (lower panel). **e,** Similar behavior of $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice during the habituation period. **f**, Time spent in each corner during the homing test (two-way RM-ANOVA: significant main effects of interaction $P < 0.0001$, $F_{3,66} = 77.11$, zone $P < 0.0001$, $F_{3,66} = 847.0$ and genotype $P = 0.0004$, $F_{1,22} = 17.74$); note that with $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ mice, the time spent in the mother corner is strongly reduced (Sidak multiple comparisons: mother corner, $cWT_{TXFbirth}$ vs. $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$, p < 0.0001), at the benefit of the empty corner (Sidak multiple comparisons: empty corner, $cWT_{TXFbirth}$ vs. $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$, p < 0.0001). **g**, The time spent interacting with an unfamiliar juvenile in a neutral territory is strongly reduced in $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ adult male mice compared to $cWT_{TXFbirth}$ (*n* = 12 male mice/genotype, unpaired *t*-test, p < 0.0001). (**h-j)**, Assessment of social flexibility, *n* = 10 male mice/genotype**. h**, Scheme of the approach used to assess spontaneous social behavior in the home cage and social flexibility of males, using the change of litter bedding on day 2 as an environmental challenge. **i**, Duration of social investigation, before (day 1) and after (day 2) litter bedding change; note that only $cWT_{TXFbirth}$ mice modified their behavior in agreement to the change in social hierarchy induced by environmental challenge, showing less social investigation on day 2 (two-way RM-ANOVA: significant main effects of interaction $P < 0.0001$, $F_{1,18} = 64.13$; day $P < 0.0001$, $F_{1,18} = 87.52$ and genotype $P = 0.0098$, $F_{1,18} = 22.76$; Sidak multiple comparisons: $cWT_{TXFbirth}$, day 1 vs. day 2, p < 0.0001). **j**, Duration of aggressive behavior before (day 1) and after (day 2) litter bedding change; note that on day 2, only $cWT_{TXFbirth}$ mice showed an increased aggressive behavior compared to day 1 (two-way RM-ANOVA: significant main effects of interaction $P < 0.0001$, $F_{1,18} = 68.52$; day $P < 0.0001$, $F_{1,18} = 40.81$ and genotype $P < 0.0001$, $F_{1,18} = 55.91$; Sidak multiple comparisons: $cWT_{TXFbirth}$, day 1 vs. day 2, p < 0.0001). (**k-l)**, Assessment of cognitive flexibility, *n* = 12 male mice/genotype. **k**, Scheme of the Y-maze reversal learning task. In the acquisition phase, male mice were trained to find the food reward in one arm of the Y-maze. In the reversal procedure, the reward location was switched to the other arm. **l**, During the acquisition phase, all mice reached the criterion to choose the correct arm of the Y-maze; however, $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ male mice failed to perform the reversal phase of the test (two-way RM-ANOVA: significant main effects of phase $P = 0.0001$, $F_{2,44} = 11.28$ and genotype $P < 0.0001$, $F_{1,22} = 138.0$); Sidak multiple comparisons: $cWT_{TXFbirth}$ vs. $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$, day 7, p < 0.0001; day 8, p < 0.0001; day 9, p < 0.0001. All graphs show mean±s.e.m. and points in (**c, e-g, i-j**) represent individual animals. *p < 0.05, ***p < 0.005, ****p < 0.0001.

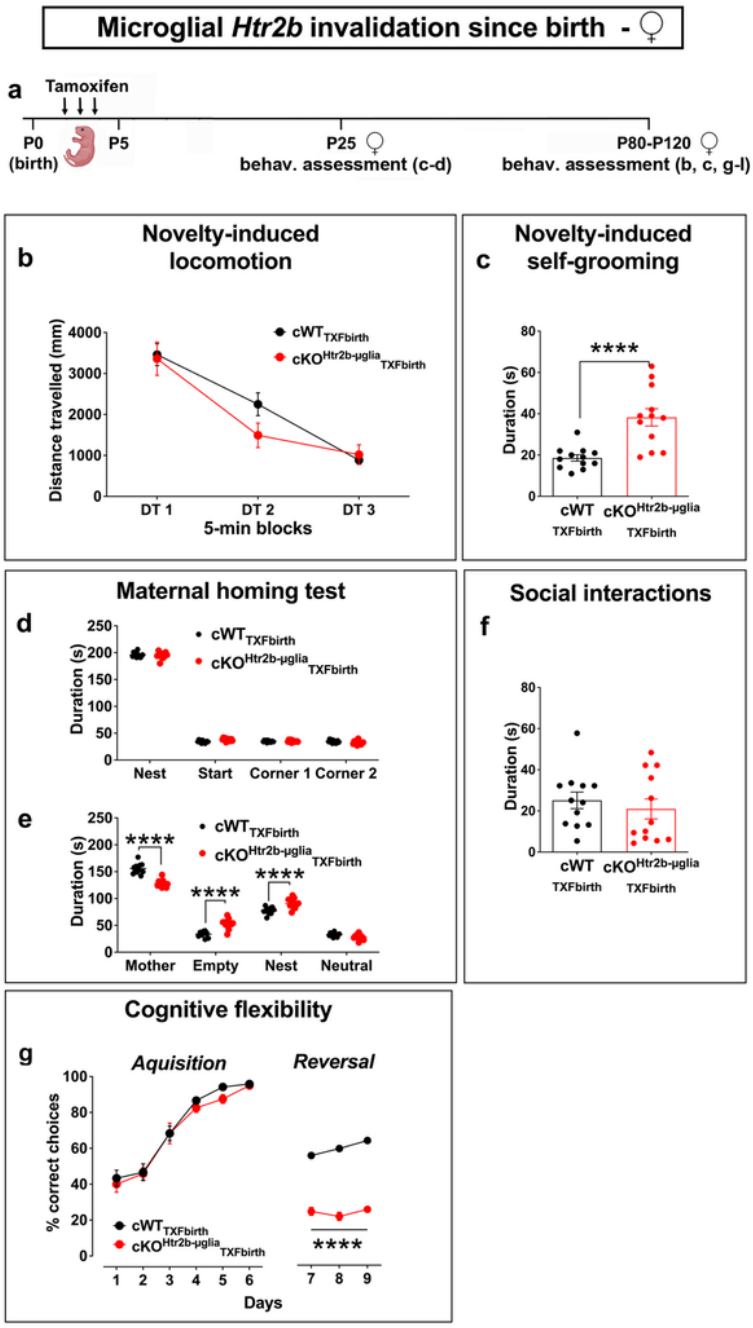

Figure 4

Absence of 5-HT$_{2B}$ receptors in microglia since birth impacts activity in a novel environment, sociability and flexibility in female mice. a, Timeline of tamoxifen treatment for early microglial *Htr2b* invalidation, and the behavioral tests performed in juvenile (maternal homing test) or adult female mice. (**b-g**), Behavioral assessment in cWT$_{TXFbirth}$ and cKO$^{Htr2b\text{-}µglia}_{TXFbirth}$ female mice, *n* = 12 female mice/genotype. **b**, Distance travelled by female mice placed in a novel environment in 5-min blocks (DT1,

2, 3) (two-way RM-ANOVA: significant main effect of DT $P < 0.0001$, $F_{2,44}) = 84.07$). **c**, The time spent grooming in response to a novel environment is strongly enhanced in $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ adult female mice compared to $cWT_{TXFbirth}$ (unpaired *t*-test, $p < 0.0001$). **d**, In the habituation phase of the maternal homing test, $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ P25 female mice displayed similar behavior, with a strong preference for the nest corner. **e**, In the test phase however, the time spent in each corner differed between $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ P25 female mice (two-way RM-ANOVA: significant main effects of interaction $P < 0.0001$, $F_{3,66} = 41.29$ and zone $P < 0.0001$, $F_{3,66} = 933.1$); note that the preference for the mother corner was strongly reduced in $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ compared to $cWT_{TXFbirth}$ mice (Sidak multiple comparisons: mother corner, $cWT_{TXFbirth}$ vs. $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$, $p < 0.0001$), at the benefit of the time spent in the empty and nest corners (Sidak multiple comparisons: empty corner, $cWT_{TXFbirth}$ vs. $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$, $p < 0.0001$; nest corner, $cWT_{TXFbirth}$ vs. $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$, $p < 0.0001$). **f**, Duration of interaction with a juvenile conspecific in a neutral territory is similar in $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ adult female mice. **g**, In the reversal learning test to assess cognitive flexibility, $cWT_{TXFbirth}$ and $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ female mice similarly reached the acquisition criterion; however, $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$ female mice failed to perform the reversal phase of the test (two-way RM-ANOVA: significant main effects of interaction $P = 0.0068$, $F_{2,44} = 5.607$; phase $P = 0.0004$, $F_{2,44} = 9.250$ and genotype $P < 0.0001$, $F_{1,22} = 427.3$; Sidak multiple comparisons: $cWT_{TXFbirth}$ vs. $cKO^{Htr2b\text{-}\mu glia}{}_{TXFbirth}$, day 7, $p < 0.0001$; day 8, $p < 0.0001$; day 9, $p < 0.0001$). All graphs show mean±s.e.m. and points in (**c-f**) represent individual animals. ****$p < 0.0001$.

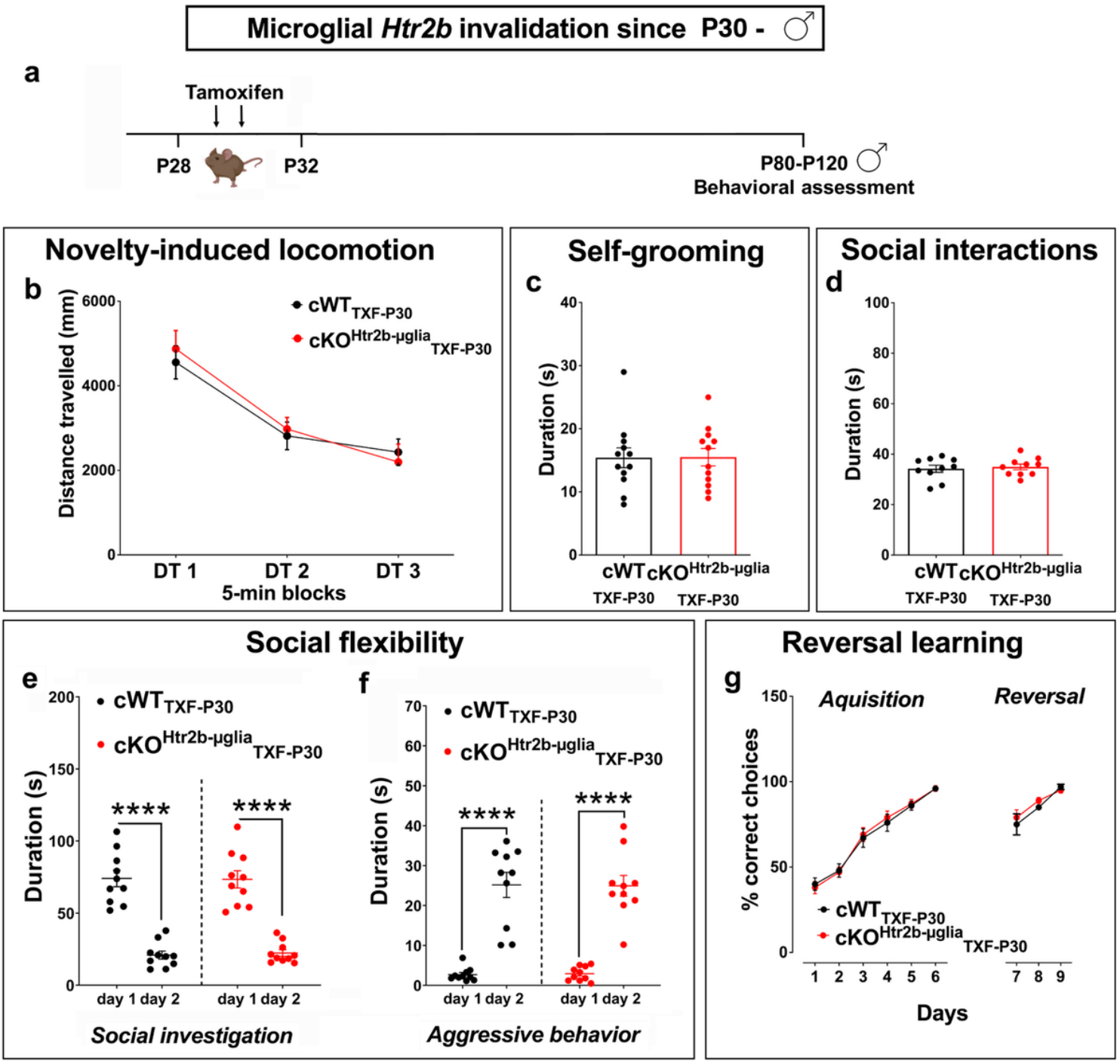

Figure 5

Ablation of 5-HT$_{2B}$ receptors in microglia at P30 does not alter spontaneous behaviors in adult male mice. a, Timeline of tamoxifen treatment for late microglial *Htr2b* invalidation (P28-32), and the behavioral tests performed in adult male mice. **b**, Similar distance travelled in response to a novel environment in 5-min blocks (DT) (n = 10 male mice/genotype, two-way RM-ANOVA: significant main effect of DT $P < 0.0001$, $F_{2,36} = 70.78$). **c**, Similar time spent self-grooming in response to a novel environment in cWT$_{TXF-P30}$ and cKO$^{Htr2b-µglia}_{TXF-P30}$ adult male mice (n = 12 male mice/genotype). **d**, Similar time spent interacting with a juvenile conspecific in a neutral territory in cWT$_{TXF-P30}$ and cKO^{Htr2b-}

$^{\mu glia}_{TXF\text{-}P30}$ adult male mice (*n* = 10 male mice/genotype). (**e-f)**, Similar social flexibility of $cWT_{TXF\text{-}P30}$ and $cKO^{Htr2b\text{-}\mu glia}_{TXF\text{-}P30}$ adult male mice, in response to a challenge of social hierarchy induced by the change of litter bedding on day 2 (*n* = 10 adult male mice/genotype). **e**, The change of litter bedding on day 2 induced a decrease in the time spent in social investigation in both genotypes (two-way RM-ANOVA: significant main effect of day $P < 0.0001$, $F_{1,18} = 203.7$; Sidak multiple comparisons: $cWT_{TXF\text{-}P30}$, day 1 vs. day 2, $p < 0.0001$; $cKO^{Htr2b\text{-}\mu glia}_{TXF\text{-}P30}$, day 1 vs. day 2, $p < 0.0001$). **f,** The change of litter bedding on day 2 induced an increase in the time spent in aggressive behavior in both genotypes (two-way RM-ANOVA: significant main effect of day $P < 0.0001$, $F_{1,18} = 145.8$; Sidak multiple comparisons: $cWT_{TXF\text{-}P30}$, day 1 vs. day 2, $p < 0.0001$; $cKO^{Htr2b\text{-}\mu glia}_{TXF\text{-}P30}$, day 1 vs. day 2, $p < 0.0001$). **g**, Y-maze reversal learning test shows no difference in cognitive flexibility task in $cWT_{TXF\text{-}P30}$ and $cKO^{Htr2b\text{-}\mu glia}_{TXF\text{-}P30}$ adult male mice **(***n* = 10 male mice/genotype). All graphs show mean±s.e.m. and points in (**c-f**) represent individual animals. ****p < 0.0001.

Supplementary Files

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- SupplementaryFigures.docx