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Genetic Isolation of Hypothalamic Neurons that Regulate Context-Specific Male Social Behavior

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Summary

Nearly all animals engage in a complex assortment of social behaviors that are essential for the survival of the species. In mammals these behaviors are regulated by sub-nuclei within the hypothalamus, but the specific cell types within these nuclei responsible for coordinating behavior in distinct contexts is only beginning to be resolved. Here we identify a population of neurons in the ventral premammillary nucleus of the hypothalamus (PM_V) that are strongly activated in male intruder mice in response to a larger resident male, but are not responsive to females. Using a combination of molecular and genetic approaches we demonstrate that these PM_V neurons regulate intruder-specific male social behavior and social novelty recognition in a manner dependent upon synaptic release of the excitatory neurotransmitter glutamate. These data provide direct evidence for a unique population of neurons that regulate social behaviors in specific contexts.

eTOC blurb

Soden et al. characterize a population of neurons in the ventral premammillary nucleus of the hypothalamus that are genetically defined as dopaminergic, but do not release detectable dopamine. These neurons are activated in specific social contexts and function via glutamate release to regulate male same-sex social interactions.

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Author Contributions
M.E.S. performed electrophysiology, behavior, and histology experiments. S.M.M. performed RiboTag experiments and assisted with behavior. L.M.B. and M.E.S. performed voltammetry experiments. P.E.M.P. and T.S.H. provided resources. M.E.S. and L.S.Z. designed the experiments and wrote the paper.

Introduction

In rodents, olfactory information is a major modality for social communication. Inputs from the main olfactory bulb and accessory olfactory bulb directly innervate sub-nuclei of the medial amygdala that transmit this information to the hypothalamus (Scalia and Winans, 1975, Kevetter and Winans, 1981, Choi et al., 2005, Sosulski et al., 2011). The hypothalamus also receives direct olfactory information relevant to social cues (Yoon et al., 2005). Hypothalamic sub-populations have been identified within the ventrolateral ventromedial hypothalamus (VMH_{VL}) that regulate key social behaviors including aggressive responses to conspecific threats and mating (Lin et al., 2011, Lee et al., 2014). Neurons within the medial pre-optic area (MPO) of the hypothalamus have also been isolated in mice and shown to regulate parental care or agression towards pups depending on the animals' sexual experience (Wu et al., 2014). Numerous other sub-nuclei within the hypothalamus are implicated in the regulation of social behaviors (Swanson, 2000), but virtually nothing is known about the cell types within these regions that contribute to these behaviors.

The PM_V is highly connected with the brain's social networks (Canteras et al., 1992, Swanson, 2000, Cavalcante et al., 2014), and mapping studies using the immediate early gene *Fos* demonstrated that PM_V neurons are activated in multiple social contexts (Cavalcante et al., 2006, Borelli et al., 2009, Motta et al., 2009, Donato et al., 2010, Donato et al., 2013). Early analysis of catecholamine-producing neurons of the brain identified a non-canonical dopamine neuron population within the PM_V (Hedreen, 1978, Meister and Elde, 1993, Zoli et al., 1993), but whether these neurons regulate social behavior and whether they use dopamine as a neurotransmitter is not known. Based on previous evidence that neurons in the PM_V express mRNA for the dopamine transporter (DAT; Meister and Elde, 1993), we used DAT as a genetic marker to isolate this population. We demonstrate that PM_V-DAT neurons are connected to brain regions implicated in conspecific social behavior and are principally glutamatergic, but do not release detectable dopamine. We find that PM_V-DAT neurons are most highly activated when male mice are intruders into the residence of a larger male. Chemogenetic inhibition of PM_V-DAT neurons reduces exploratory social behavior specifically in intruder males and impairs social novelty recognition. Activation of PM_V-DAT neurons increases exploratory social investigation of familiar mice in a manner dependent upon synaptic glutamate release. Our genetic isolation and characterization of this unique neuronal population provides direct evidence for a hypothalamic cell type that regulates male intruder behavior and social novelty in specific contexts.

Results

Genetic isolation of PM_V-DAT neurons

Given the previous identification of neurons in the PM_V that express DAT (Hedreen, 1978, Meister and Elde, 1993), we sought to determine the function of these neurons within social contexts. To confirm the presence of these neurons we performed a differential search of the Allen Institute for Brain Science Mouse Brain Atlas *in situ* hybridization data (Lein et al., 2007). Three of the top thirty genes enriched in the PM_V were canonical markers for synthesis and release of the neurotransmitter dopamine: dopamine transporter (DAT; *Slc6a3*), dopa-decarboxylase (DDC; *Ddc*), and the vesicular monoamine transporter (VMAT; *Slc18a2*). Of these markers, DAT appeared to be the most selective for the PM_V within the hypothalamus. Based on this observation, along with previous data demonstrating DAT mRNA in the PM_V (Meister and Elde, 1993) and observations that mice expressing Cre recombinase from the DAT locus are the most reliable for isolating dopamine-producing neurons (Lammel et al., 2015), we genetically isolated PM_V-DAT neurons utilizing the DAT-Cre mouse line ($Slc6a3^{Cre/+}$, Zhuang et al., 2005). To validate the expression data from the Mouse Brain Atlas, we performed immuno-isolation of actively translating mRNA using RiboTag mice (Sanz et al., 2009), which allow for Cre-dependent expression of an affinity tagged ribosomal protein, Rpl22-HA, and subsequent immunoprecipitation (IP) of polyribosomes. $Slc6a3^{Cre/+};Rpl22^{HA/+}$ mice were used to isolate mRNA from DAT neurons in the PM_V following microdissection (Figure 1A–C). We observed a significant enrichment of *Slc6a3*, *Ddc, Slc18a2*, and tyrosine hydroxylase (*Th*) mRNA in the IP relative to the input, which contains mRNA from all cell types in the region (Figure 1D). Similar enrichment of these markers was observed when mRNA was isolated from canonical dopamine neurons in the ventral tegmental area (VTA) of $Slc6a3^{Cre/+};Rpl22^{HA/+}$ mice (Figure S1A–B).

Quantification of PM_V-DAT neurons revealed that these cells make up 25% of neurons in this region (952 YFP+ cells/3767 NeuN+ cells, alternate sections counted from 3 mice; Figure S1C). Connectivity mapping of PM_V-DAT neurons through conditional expression of an EGFP-tagged synaptic marker protein, synaptophysin-EGFP (AAV1-FLEX-synapto-EGFP) revealed axonal projections to numerous downstream targets previously implicated in the regulation of social behavior (Canteras et al., 1992). These included the VMH_{VL}, the MPO, the medial postero-ventral subdivision of the medial amygdala (MeA_{PV}), the amygdalo-hippocampal region of the medial amygdala (MeA_{AHi}), the postero-dorsal and ventral subdivisions of bed nucleus of the stria-terminalis ($BNST_{PD}$ and $BNST_{PV}$), the anterior hypothalamic nucleus (AHN), and the periaqueductal gray (PAG; Figure 1E–J). Analysis of PM_V-DAT projections obtained from the Allen Brain Institute Mouse Connectivity Atlas (Oh et al., 2014) revealed similar results. To establish the density of PM_V-DAT projections to various targets, we generated an analysis program to quantify fluorescent pixels in target areas using data from the Connectivity Atlas. While the BNST received the most total input, the densest innervation was seen in the VMH_{VL} (Figure S1D).

PM_V-DAT neurons release glutamate, but not detectable dopamine

Although previous studies have demonstrated the presence of 6-OH-DA-sensitive neurons in the PM_V (Hedreen, 1978) these neurons were not immunoreactive for dopamine (Zoli et al., 1993). To test whether PM_V-DAT neurons release detectable dopamine, we expressed ChR2 in PM_V-DAT neurons and assayed for light-evoked dopamine release using fast-scan cyclic voltammetry (FSCV) in acute slices from multiple target regions (VMH_{VL}, MeA_{MPV}, and BNST). We did not detect any dopamine transients following optical stimulation of PM_V-DAT fibers using multiple stimulus parameters (5, 10, 20, and 30 Hz; Figure 2A–B). In contrast, expression of ChR2-mCherry in VTA dopamine neurons and optical stimulation of terminals in the nucleus accumbens resulted in robust dopamine release (Figure 2A–B). Pretreating mice with L-DOPA, the dopamine precursor shown to be transported by PM_V neurons (Zoli et al., 1993), did not enhance detection of dopamine release (Figure 2A–B). These data do not rule out that dopamine may be released below the level of detection of FSCV. However, consistent with our FSCV results, we did not detect any protein for TH or DAT in the cell bodies or terminal fields of DAT-PM_V neurons using immunohistochemistry (Figure S2A–B).

Because we detected mRNA, but no protein, for dopamine markers in PM_V-DAT neurons, we compared the relative amounts of mRNA for these markers in PM_V-DAT neurons versus VTA-DAT neurons using the IP fractions from our RiboTag analysis. Although mRNA for dopaminergic markers is highly enriched in PM_V-DAT neurons relative to other neurons within the region, these cells contained only 5–10% the amount of dopaminergic mRNAs compared to VTA-DAT neurons (Figure S2C). In contrast, PM_V-DAT neurons contained three times as much mRNA encoding the vesicular glutamate transporter vGluT2 (*Slc17a6*) as did VTA-DAT neurons. Additional electrophysiological analysis of PM_V-DAT neurons revealed that these neurons do not share common electrophysiological properties with VTA dopaminergic neurons (Figure 2C–G and Figure S2D–G), indicating that these neurons are unique population.

Consistent with the detection of mRNA encoding vGluT2, analysis of synaptic connectivity in the VMH_{VL} (Figure 2H) revealed the majority of light-evoked responses from ChR2-expressing terminals of PM_V-DAT neurons are monosynaptic excitatory currents that are blocked by the glutamatergic antagonist CNQX (Figure 2I). Delayed and unsynchronized inhibitory and excitatory currents were also seen in a small number of cells (5 inhibitory, 7 excitatory; Figure 2J–K). A smaller sample of recordings from the BNST (n=6/15 cells connected) and MPN (n=9/14 cells connected) found similar results.

PM_V-DAT neurons regulate context-specific social behavior

To confirm previous observations of *Fos* induction in the PM_V following exposure of animals to opposite- and same-sex odorants (Cavalcante et al., 2006, Leshan et al., 2009, Donato et al., 2010), we exposed male and female mice to clean bedding (control) or bedding soiled by a same-sex or opposite-sex mouse, followed by immunohistochemistry for

Fos. We observed a modest increase in Fos protein in response to opposite-sex odorants in male and female mice. However, male mice, but not female mice, showed increased Fos in response to same-sex odorants that was significantly higher than Fos observed in response to opposite-sex odorants (Figure S3A–C).

To establish whether PM_V-DAT neurons are activated in male mice in a context-dependent manner, we quantified Fos expression in virally labeled cells. Mice were exposed to one of five social encounter conditions: no encounter (control), intruder into the cage of a male resident, intruder into the cage of a female resident, resident exposed to a male intruder, and resident exposed to a female intruder. Fos levels in PM_V-DAT neurons were significantly higher in male same-sex intruders relative to all other contexts (Figure 3A–B). PM_V-DAT neurons were a subset of the total Fos+ PM_V neurons, but comprised a significantly larger subset in the same-sex intruder context compared to other contexts (Figure S3D). To test whether Fos activation in male intruder mice was primarily driven by the odorant context of the resident cage or by the resident mouse itself, we measured Fos in an “intruder” male following an encounter with a “resident-like” male (i.e. larger, singly housed, sexually experienced) in a neutral environment (clean cage). Fos in PM_V-DAT neurons was only modestly activated in this context (Figure 3A–B), indicating that contextual odorants play a large role in driving PM_V-DAT activation in intruder mice.

Our observation that PM_V-DAT neurons are most strongly activated in male mice when these animals are intruders is consistent with previous reports (Borelli et al., 2009, Motta et al., 2009) and suggests that these neurons may function preferentially within this context. To test this hypothesis, we selectively attenuated the activity of PM_V-DAT neurons through conditional expression of the inhibitory DREADD receptor hM4Di (AAV1-FLEX-hM4Di-YFP). Consistent with previous reports (Armbruster et al., 2007), activation of hM4Di by the selective agonist clozapine-N-oxide (CNO) reduced the excitability of PM_V-DAT neurons (Figure S3E–H). Behavioral analysis of hM4Di and control mice (AAV1-FLEX-mCherry) revealed that reduced excitability of PM_V-DAT neurons was associated with a significant reduction in social investigation (anogenital sniffing, oral-facial sniffing, and grooming) by male intruder mice, but had no effect on resident male behavior or on male response to females, nor did it affect an encounter with a “resident-like” male in a neutral cage (Figure 3C–E and Figure S3I).

A reduction in social exploratory behavior by intruder mice may represent a deficit in social recognition within this context. To test this hypothesis we analyzed behavior in a three-chamber social preference and social recognition assay. Reduced excitability of PM_V-DAT neurons through hM4Di activation did not alter behavioral preference for a novel mouse versus a novel object, but did reduce social recognition of a novel versus familiar mouse (Figure 3F–G and Figure S3J–K).

PM_V-DAT neurons regulate social behavior through glutamate release

To further investigate the extent to which activation of PM_V-DAT neurons influences social recognition and social investigation, we developed a co-habitation assay to monitor social investigation of a familiar cage-mate while PM_V-DAT neurons are selectively activated using the light-activated ion channel ChR2. Because PM_V-DAT neurons should be minimally activated in this context, this assay allows us to establish the sufficiency of activation of PM_V-DAT neurons for social investigation behaviors.

To determine the optimal stimulation parameters for this assay, we analyzed the synaptic fidelity of light-evoked action potentials in postsynaptic VMH_{VL} neurons using a common stimulation paradigm (5 ms light stimuli at 20 Hz). Fidelity diminished with repetitive stimulation at this frequency (Figure S4A). This decrease was not observed when action potential firing was recorded in PM_V-DAT neuron cell bodies (Figure S4B). Quantitative analysis of light-evoked postsynaptic currents confirmed a significant synaptic rundown at frequencies of 5 Hz and above (Figure S4C–D), suggesting that low frequency stimulation in these neurons is optimal for maintaining synaptic connectivity.

To monitor exploratory social behavior between familiar mice we tested conspecific males that were co-housed from birth. One mouse was surgically injected with either AAV1-FLEX-ChR2-mCherry or AAV1-FLEX-mCherry and a fiber-optic was implanted above the PM_V (Figure 4A). Mice were assayed for investigatory behavior of their cage-mate with or without optical stimulation (Figure 4B). While 3-Hz light stimulation had no effect on social interaction in control mice, mice expressing ChR2 significantly increased social investigation (anogenital sniffing, oral-facial sniffing, and grooming) of their cage-mate during light stimulation (Figures 4C and S4E). Light stimulation had no effect on exploration of a familiar object in the home cage (Figure 4D) and did not affect distance traveled in the cage (Figure S4F). Light stimulation also had no effect in a real-time place preference (RTPP) assay, suggesting that activation of the PM_V is neither rewarding nor aversive (Figure 4E). Finally, light stimulation did not affect behavior in an open field assay (Figure S4G–H), indicating no overt role for PM_V-DAT neurons in regulating anxiety.

To further establish the extent to which activation of PM_V-DAT neurons can enhance social investigation we stimulated PM_V-DAT neurons in resident animals, a context in which PM_V-DAT neurons are not robustly activated but in which animals are already actively engaged in social investigation. We observed an increase in investigation time in ChR2-expressing animals, indicating that artificially activating PM_V-DAT neurons can drive increased social behavior even when animals are already socially engaged (Figure S4I). In contrast, stimulation of PM_V-DAT neurons in intruder mice did not enhance social investigation (Figure S4J), indicating that these neurons are already optimally functioning in this context.

To confirm that glutamate is the critical neurotransmitter responsible for the effect of PM_V-DAT neurons on social behavior we repeated our co-habitation experiments by expressing ChR2 in DAT-PM_V neurons in mice in which the gene encoding vGluT2, *Slc17a6,* is inactivated in dopamine neurons (*Slc6a3*$^{iCre/+}$; *Slc17a6*$^{lox/lox}$, or DAT-vGlut2 KO; (Hnasko et al., 2010)). Consistent with PM_V-DAT neurons being glutamatergic, light-induced EPSCs were observed in control mice (*Slc6a3*$^{Cre/+}$; *Slc17a6*$^{lox/+}$), but not DAT-vGlut2 KO mice (Figure 4F, inset). Optical stimulation of PM_V-DAT neurons significantly enhanced social investigation in control mice, but not in DAT-vGlut2 KO mice (Figure 4F). Stimulation of PM_V-DAT neurons in DAT-vGlut2 KO and control mice was not associated with increased investigation of a familiar object (Figure 4G), or with RTPP (Figure 4H).

Because DAT-vGlut2 KO mice are a loss of function, we next asked whether these mice have altered baseline social behavior in the resident-intruder assay in the absence of light stimulation. Consistent with hM4Di-mediated inhibition of PM_V-DAT neurons, DAT-vGlut2 KO mice displayed significantly reduced social exploratory behavior when they were intruders in the cage of a resident male (Figure 4I). This effect was not observed when the mice were residents in response to a male or female intruder (Figure 4J–K). A caveat to this approach is that genetic inactivation of vGlut2 in DAT-expressing neurons removes this protein from all such neurons, including those in the VTA. It has been demonstrated that inactivation of DAT-expressing neurons in the VTA disrupts social behavior (Gunaydin et al., 2014, Yu et al., 2014). Therefore, we inactivated DAT neurons in the VTA by expressing hM4Di in these cells (Figure S4K). Inhibition of DAT neurons in the VTA did not affect investigatory behavior in intruder mice, but did reduce this behavior in resident males towards male intruders (Figure S4L–N).

Discussion

Our data identify a unique population of neurons in the mouse hypothalamus that regulate intruder-specific male behavior. Numerous studies have identified the hypothalamus as a key regulator of socially motivated behavior (Swanson, 2000), but to date a defined group of neurons specifically tuned to influence conspecific behavior exclusively in intruder males had not been demonstrated. Our observations are supported by previous findings of increased Fos in the PM_V of male intruder rats (Borelli et al., 2009, Motta et al., 2009). Motta and colleagues also observed increased Fos protein in the dorsal premammillary nucleus (PM_D) and found that lesioning the PM_D reduced exploratory social behavior and defensive behavior by much smaller subordinate intruder rats (Motta et al., 2009). These data collectively point to specific populations within the PM_V and PM_D that regulate intruder-specific behavior.

It has been reported that lesions of the PM_V increase aggressive behavior in male rats (Vandenberg et al., 1983). Since PM_V-DAT neurons only constitute approximately 25% of the total neurons of the PM_V, and there are numerous Fos-positive PM_V neurons in the resident-intruder assays that are not DAT-positive, it is likely that PM_V-DAT neurons are not the only population involved in context-specific social behavior. Thus, lesioning of the entire PM_V may disrupt multiple cell types that when collectively destroyed lead to different behavioral outcomes.

We also found that optogenetic stimulation of PM_V-DAT neurons engages social exploration of a familiar mouse. These findings, together with our observations that social recognition is impaired when PM_V-DAT neurons are inhibited, suggest that these neurons influence exploration and novelty detection that is specific for socially relevant stimuli. Similarly, it has also been demonstrated that dopamine neurons of the VTA selectively influence social exploration but not novelty exploration (Gunaydin et al., 2014). Interestingly, we find that inhibition of VTA-DAT neurons reduces social behavior by resident males, but not intruder males, and this behavior is not sensitive to inactivation of vGlut2, further supporting the notion that VTA-DAT neurons and PM_V-DAT neurons operate through distinct neurotransmitter systems in different behavioral contexts.

Direct optogenetic stimulation of all neurons or a specific subpopulation of neurons within the VMH_{VL} results in robust aggressive posturing in resident male mice towards intruders (Lin et al., 2011, Lee et al., 2014) and towards inanimate objects (Lin et al., 2011). Optogenetic stimulation of excitatory neurons of the MeA, many of which project to the VMH_{VL}, also increases male aggressive behavior (Hong et al., 2014), and similar results have been reported for stimulation of a subpopulation of aromatase neurons in the MeA (Unger et al., 2015). We find that PM_V-DAT inputs to target structures, including the VMH_{VL}, are principally excitatory and are most effective at high-fidelity synaptic transmission at low frequencies. Stimulation of PM_V-DAT neurons promotes social exploration, but not aggression, and does not evoke aggression towards inanimate objects. Thus, we propose that social behavior engaged by PM_V-DAT neurons is tightly controlled to promote social exploration without escalating to aggression.

Isolation of mRNA associated with polyribosomes from DAT-expressing neurons of the PM_V reveals that these cells are highly enriched for dopaminergic markers compared to cells in the surrounding tissue, making them the only known population to contain mRNA for all dopaminergic markers but not to release detectable dopamine. A likely explanation for our inability to detect dopamine release from these neurons is that while these neurons do contain mRNA for the molecular machinery to synthesize and release this neurotransmitter, their mRNA levels are an order of magnitude less than those in conventional VTA-DAT neurons. The reason for neurons in the PM_V to contain any mRNA at all for dopaminergic enzymes is not clear. One possibility is that these neurons are derived from a common lineage of other dopamine neurons in the hypothalamus and midbrain that express these markers, but the mRNA in PM_V-DAT neurons is not translated into protein or these proteins are rapidly degraded and thus are in quantities below the level of detection. A second possibility is that these neurons utilize dopamine as a neurotransmitter early during development, then switch to becoming glutamatergic once circuit connectivity is established, maintaining residual dopaminergic mRNA expression following this switch. Evidence for developmental neurotransmitter switching has been widely reported (Spitzer, 2015). A third possibility is that these neurons have the capacity to enhance dopamine production and release under specific environmental demands. Neurotransmitter switching has been previously reported in the adult hypothalamus (Dulcis et al., 2013). Future experiments designed to determine the relevance of dopamine marker mRNA expression in PM_V-DAT neurons will further inform the identity and function of the unique neuronal population.

Experimental Procedures

See supplemental information for additional experimental procedures.

Mice

All procedures were approved and conducted in accordance to the guidelines of the Institutional Animal Care and Use Committee of the University of Washington. Mice 8 weeks or older were used for all experiments except slice electrophysiology, where 5- to 8-week-old mice were used.

RiboTag

Immunoprecipitation was performed as described previously (Sanz et al., 2009). Briefly, 1 mm × 1 mm punches of PM_V and VTA were removed, homogenized, and incubated with anti-HA antibody (Covance) coupled to magnetic beads (Pierce) overnight at 4°C. Following elution from magnetic beads, RNA from both IP and input samples was obtained using the RNeasy micro kit (Qiagen). cDNA was generated using oligo dT primers (Invitrogen). TaqMan (Applied Biosystems) primers were used for qRT-PCR analysis.

Electrophysiology and Voltammetry

Whole-cell recordings were made using an Axopatch 700B amplifier (Molecular Devices). Light-evoked synaptic transmission was induced with 5-ms light pulses delivered from an optic fiber placed directly in the bath. I_h currents were induced by 2-s hyperpolarizing voltage steps from −70 mV to −120 mV. SK currents were induced by depolarizing voltage steps from −70 to 0 mV. Capacitance measurements were calculated by Clampex software using 5 mV hyperpolarizing steps. Fast-scan cyclic voltammetry was performed using carbon-fiber microelectrodes as described (Clark et al., 2010). 5-ms light stimuli were delivered as described for electrophysiology.

Fos Induction

For social encounter mice were assigned to the resident, intruder, or control condition. Resident animals were singly housed for at least two weeks, while intruder and control mice were group housed. Animals experienced a 20-min social encounter with an appropriately matched resident or intruder animal, and were euthanized and perfused 90 min following the start of the encounter. Control animals remained in their home cage. Fos-positive neurons were identified and counted automatically using ImageJ software. Virally transduced DAT neurons and Fos-positive DAT neurons were counted by hand by an experienced investigator blind to condition.

Behavior

For resident/intruder encounters, resident mice were singly housed for at least two weeks, were sexually experienced, and were 3–4 weeks older than intruder animals, which were group housed. Saline or CNO (1 mg/kg) was administered intraperitoneally 40 min prior to the start of the encounter. Each mouse received saline and CNO on subsequent days (order of administration was counterbalanced across groups) and encountered a different resident or intruder mouse on each day. Social behaviors scored included anogenital sniffing, oronasal sniffing, following, and grooming. For the 3-chamber assay mice were given 10 min to explore the empty arena, then were briefly returned to their home cage while the novel object (empty wire pencil cup) was introduced to one chamber and first mouse (contained in a wire pencil cup) was introduced to the opposite chamber. The experimental animal was returned to the arena for a 10-min exploration and then briefly removed again while the novel mouse was added, before a final 10-min exploration. The first 5 min of each exploration period was scored for the time spent in each chamber. For home cage social encounters mice implanted with fiber optics were housed with a single littermate. After the implanted mouse was connected to the fiber optic cable they were allowed a 10 minute habituation period, which was not scored, followed by a 5-min baseline period and 5 min of light stimulation (3 Hz, 5 ms, 3 s on, 3 s off).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Highlights

- A group of neurons in the ventral premammillary nucleus express dopamine markers.
- These neurons are activated in male intruder, but not resident, mice.
- These neurons regulate same-sex social behavior in specific contexts.
- They function via the release of glutamate, and do not release detectable dopamine.

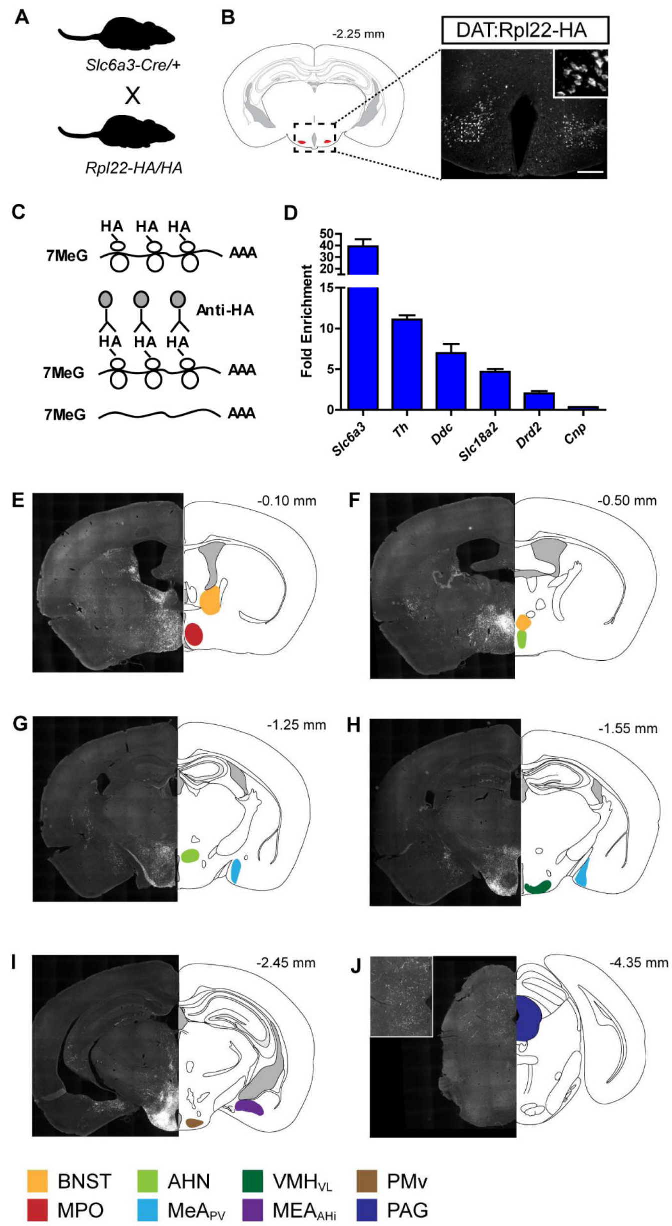

Figure 1. Molecular profile and connectivity of PM_V-DAT neurons

(A) Schematic generation of DAT-Cre-RiboTag mice. (B) Atlas image depicting the PM_V; boxed region is depicted in immunohistochemistry image of Rpl22-HA (right) and inset. Scale bar: 250 μm. (C) Cartoon depicting RiboTag technique: in Cre-positive cells the ribosomal protein Rpl22 is labeled with an HA tag; immunoprecipitation of HA isolates ribosome-associated mRNAs. (D) Fold enrichment (IP compared to input) of specific mRNAs isolated from PM_V-DAT neurons (n=3 pooled samples, each from 2–3 mice). (E–F) Projections of PM_V-DAT neurons are revealed by expression of synapto-EGFP in axon terminals. Atlas images show approximate distance from bregma; indicated brain regions are color-coded.

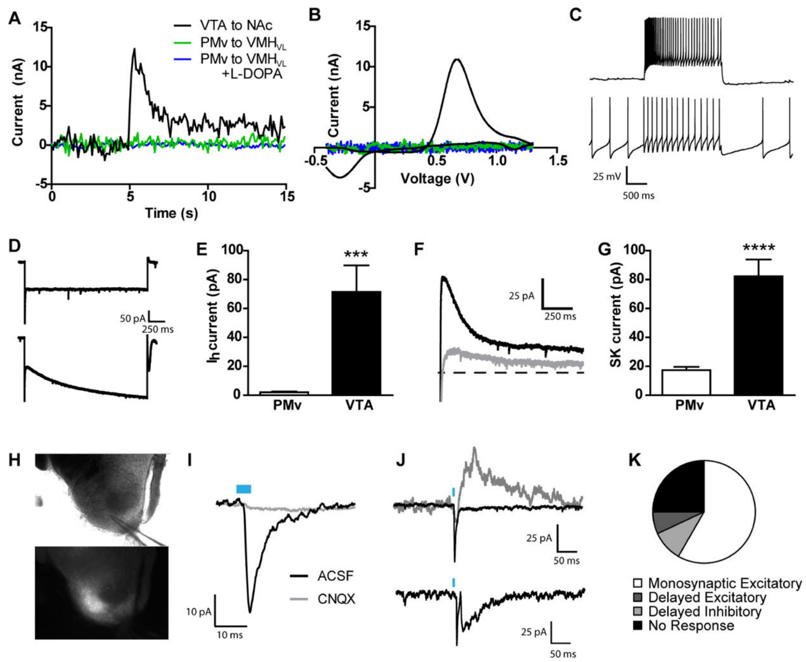

Figure 2. PM_V-DAT neurons are principally glutamatergic and do not release dopamine

(A) Example trace and (B) current/voltage plot showing light-evoked dopamine release detected using FSCV in control slices expressing ChR2 in VTA-DAT neurons, recording in the NAc. No signal was detected in the VMH_{VL} when ChR2 was expressed in PM_V-DAT neurons, even with pre-loading of L-DOPA. (C) Example traces showing that PM_V-DAT neurons did not fire spontaneously in slice but did fire accommodating action potentials with current injection (top trace), while VTA-DAT neurons did fire spontaneously (bottom trace). (D–E) Example traces and quantification of I_h current in PM_V-DAT neurons (top) and VTA-DAT neurons (bottom). (F–G) Example traces and quantification of SK currents in PM_V-DAT neurons (gray) and VTA-DAT neurons (black). (H) DIC (top) and fluorescent (bottom) images of an acute slice with fluorescent ChR2-mCherry fibers in the VMH_{VL} and patch electrode visible. Scale bar: 250 μm. (I) Example trace of EPSC in the VMH_{VL} evoked by 5 ms blue light stimulation; the EPSC could be blocked by bath application of CNQX (10 μM). (J) Top: Example recordings showing a light-evoked monosynaptic EPSC (black trace, holding at −60 mV) and a delayed, unsynchronized IPSC (gray trace, holding at 0 mV); Bottom: Example recording showing a light-evoked monosynaptic EPSC (initial fast depolarization) and a delayed, unsynchronized EPSC. All traces are averages of 15 sweeps. (K) Proportion of VMH_{VL} neurons recorded that received each type of synaptic input.

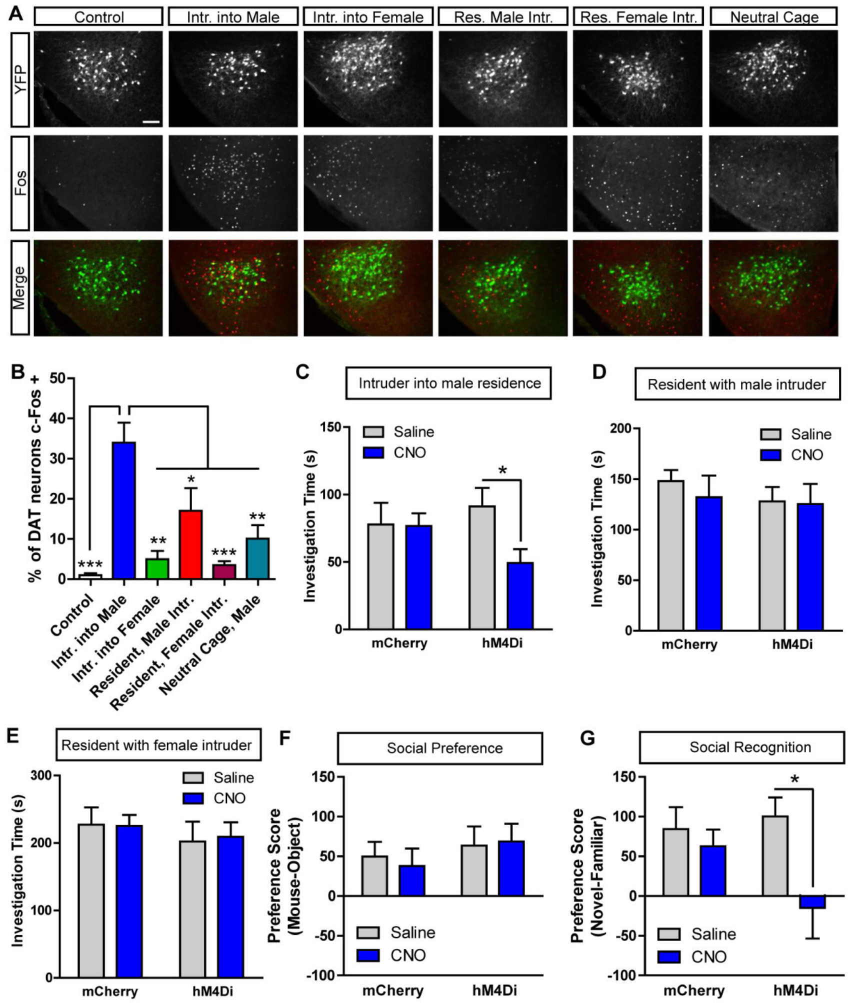

Figure 3. PM_V-DAT neurons regulate intruder-specific behavior

(A–B) Images and quantification of Fos levels in PM_V-DAT neurons during social encounters (n=3 mice/group; One-way ANOVA $F_{(5,12)}$=12.26, p<0.001; Tukey's Multiple Comparison *p<0.05, **p<0.01, ***p<0.001; Scale bar: 100 μm). (C) Social investigation of resident animal by intruder (experimental) was decreased following inhibition of PM_V-DAT neurons by CNO/hM4Di (n=10–11 mice/group; Two-way repeated measures ANOVA Virus x CNO $F_{(1,19)}$=4.43, p<0.05; Bonferroni multiple comparisons *p<0.05). Inhibition of PM_V-DAT neurons did not affect the investigation of a male (D) or female (E) intruder by a resident (experimental). (F) Inhibition of PM_V-DAT neurons by CNO/hM4Di did not affect preference for a mouse over an object. (G) Inhibition of PM_V-DAT neurons eliminated the preference for a novel mouse vs. a familiar mouse; n=10–11 mice/group; 2-way repeated measures ANOVA: $F_{(1,19)}$=7.38, p<0.05; Bonferroni multiple comparisons: *p<0.05). Data are represented as mean ± SEM.

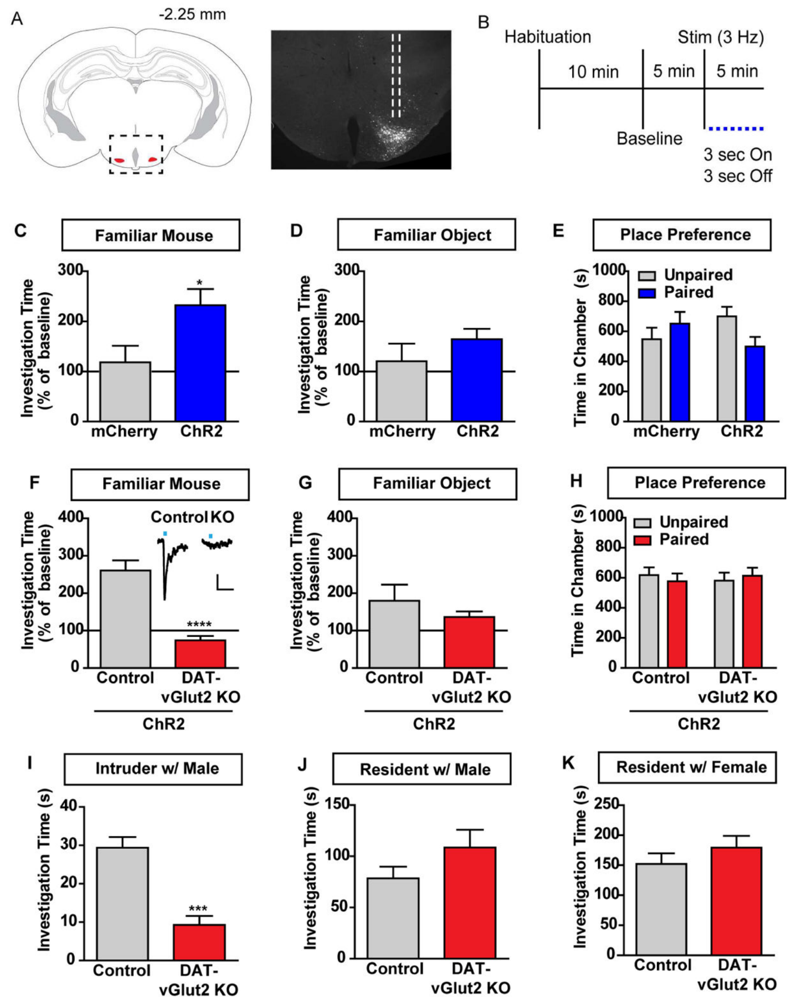

Figure 4. PM_V-DAT neurons regulate social behaviors through glutamate release

(A) Atlas and histology images showing ChR2-mCherry expression in the PM_V; dashed lines indicate track mark from fiber optic. (B) Schematic of cohabitation behavioral assay. (C) Activation of PM_V-DAT neurons increased social investigation of a familiar cage mate (n=6–8 animals/group; Student's *t* test *p<0.05). (D) Activation did not increase investigation of a familiar object. (E) Pairing one side of a 2-chambered box with light stimulation did not lead to a significant preference for either side. (F) Inactivation of vGlut2 in DAT-vGlut2 KO mice eliminates light-evoked excitatory currents driven by ChR2 expression in DAT-PM_V neurons and recorded in VMH_{VL} (inset). Light activation of PM_V-DAT neurons expressing ChR2 increased social investigation of a cage mate in DAT-vGlut2 heterozygous animals (control), but not in DAT-vGlut2 knockout animals (n=6 animals/group; Student's *t* test ****p<0.0001). (G) Activation did not increase investigation of a familiar object in either group. (H) Pairing one side of a 2-chambered box with light stimulation did not cause a significant preference in either group. (I) Social investigation of a resident male by an intruder male was reduced in DAT-vGlut2 knockout animals (n=6 animals/group; Student's *t* test ***$p<0.001$). Social investigation of a male (J) or female (K) intruder by a resident was unaffected. Data are represented as mean ± SEM.