Effects of lateral olfactory tract stimulation on Fos immunoreactivity in vasopressin neurons of the rat piriform cortex

Citation for published version:

Digital Object Identifier (DOI):
10.1111/jne.12531

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Journal of Neuroendocrinology
Effects of lateral olfactory tract stimulation on Fos immunoreactivity in vasopressin neurons of the rat piriform cortex

*Chiharu Tsuji, *Takahiro Tsuji, Andrew Allchorne, Gareth Leng and Mike Ludwig

Centre for Integrative Physiology, University of Edinburgh, Hugh Robson Building, George Square, Edinburgh EH8 9XD, UK

*These authors contributed equally to this work

Correspondence should be addressed to: Mike Ludwig
Centre for Integrative Physiology, University of Edinburgh, Hugh Robson Bldg, George Square, Edinburgh EH8 9XD, UK
Tel: +44 (0) 131 650 3275; email: mike.ludwig@ed.ac.uk

Abstract

In the main olfactory system, odours are registered at the main olfactory epithelium, then processed at the main olfactory bulb (MOB) and subsequently by the anterior olfactory nucleus (AON), the piriform cortex (PC) and the cortical amygdala. Previously, we reported populations of vasopressin neurons in different areas of the rat olfactory system, including the MOB, accessory olfactory bulb (AOB) and the AON and showed that these are involved in the coding of social odour information. Utilizing immunohistochemistry and a transgenic rat in which an enhanced green fluorescent protein reporter gene is
expressed in vasopressin neurons (eGFP-vasopressin), we show here a population of vasopressin neurons in the PC. The vasopressin neurons are predominantly located in the layer II of the PC and the majority co-express the excitatory transmitter glutamate. Furthermore, there is no sex difference in the number of neurons expressing vasopressin. Electrical stimulation of the lateral olfactory tract (LOT) leads to a significant increase in the number of Fos-positive nuclei in the PC, MOB, AOB, dorsal AON, and supraoptic nucleus (SON). However, there was only a significant increase in Fos expression in vasopressin cells of the PC and SON. Thus functionally distinct populations of vasopressin cells are implicated in olfactory processing at multiple stages of the olfactory pathway.

Abbreviations: AOB, accessory olfactory bulb; AON, anterior olfactory nucleus; BNST, bed nucleus of the stria terminalis; MOB, main olfactory bulb; LOT, lateral olfactory tract; PC, piriform cortex; SON, supraoptic nucleus

Keywords: anterior olfactory nucleus, main olfactory bulb, accessory olfactory bulb, supraoptic nucleus

Running title: Vasopressin and the piriform cortex

Competing Interests Statement: The authors declare that there are no conflicts of interest.
Funding information: Supported by grants from the Biotechnology and Biological Research Council (BB/J004723/1) and Medical Research Council (MR/M022838/1) (ML), and fellowships from the Japanese Society for the Promotion of Science (TT, CT).

Author contributions: C.T., T.T, G.L. and M.L. designed the research; C.T., T.T. and AA performed the research and analysed the data; and M.L. and G.L wrote the paper.

Acknowledgements: We thank R. Smith for his help with the cell counting and A. Kubasik-Thayil (IMPACT Imaging facility, Edinburgh) for technical assistance with confocal microscopy.

INTRODUCTION

Olfactory signals, including those of social odour cues, have powerful behavioural effects in many species, including man. The processing of olfactory cues in mammals is handled by two anatomically distinct pathways: the main, and the accessory olfactory systems (1-3). In the accessory olfactory system, pheromones are received at the vomeronasal organ, then processed at the accessory olfactory bulb (AOB) and then higher brain regions, most importantly the medial amygdala (4). In the main olfactory system, odours are registered at the main olfactory epithelium, then processed at the main olfactory bulb (MOB) and subsequently by the anterior olfactory nucleus (AON), the piriform cortex (PC) and the cortical amygdala (5, 6). The PC is more than a primary olfactory relay and plays an active role from sensory to more cognitive aspects of odour perception.
The neuropeptide vasopressin, produced in the hypothalamus and secreted from the pituitary, has a key role in electrolyte and fluid homeostasis, but recent interest in vasopressin has been dominated by its functions within the brain and, especially on its involvement in social recognition. Vasopressin is involved in the modulation of social recognition at the level of the olfactory bulbs (7, 8) and brain regions such as the lateral septum (9, 10). The neuropeptide also regulates social behaviours such as aggression (11, 12), pair-bonding (13, 14), and parental behaviour (15, 16) and has also been linked to human social behaviours in health (17-19) and during neurological disorders such as autism (20, 21).

Previously, we reported that the rat olfactory system contains several population of interneurons which express vasopressin. They are localized in the MOB, AOB and anterior AON (7, 22). Vasopressin V1a receptors are expressed in the MOB and AON (7, 22-26) and V1b receptors in the AON, olfactory tubercle and PC (22, 27) which suggests that these cells might be sensitive to their own signal. Blocking the actions of vasopressin in the MOB impairs the social recognition abilities of rats and vasopressin agonists and antagonists can modulate the processing of information by olfactory bulb neurons (7, 8). Furthermore, exposure of adult rats to a conspecific juvenile, but not to a heterospecific predator odour, increases early growth response protein 1 (Egr-1) expression in vasopressin neurons of the AON (22). These data suggest that vasopressin neurons in the olfactory system are involved in the coding of social odour information (28, 29).

Here we describe a population of vasopressin neurons distributed across the length of the PC. As previously, by utilizing a transgenic rat line in which an enhanced green fluorescent protein reporter gene is expressed specifically in vasopressin cells (eGFP-vasopressin) (30) we characterised these neurons based on a number of other
chemical markers and determined whether there are sex differences in the number of vasopressin-expressing cells in the PC. Finally, to understand how the inputs to the olfactory system (OS) influence vasopressin neurons in the different parts of the olfactory system and the hypothalamus, we electrically stimulated the lateral olfactory tract (LOT) and measured the expression of the immediate early gene c-fos by immunocytochemical detection of Fos, the protein product of c-fos, in wild type and transgenic rats.

**MATERIALS AND METHODS**

*Ethical Approval*

Procedures conducted in the UK were approved by the local Ethics Committee and the UK Home Office under the Animals Scientific Procedures Act 1986. Experiments were performed on adult male and female wild-type Sprague-Dawley and transgenic rats (250-450 g), housed under controlled conditions (12 h light: 12 h dark, 21°C) with free access to food and water. Most of the immunohistochemistry was carried out on a homozygous line of transgenic rats expressing a vasopressin-eGFP (enhanced green fluorescent protein) fusion gene (30).

*LOT stimulation*

Rats were anaesthetised with an i.p. injection of sodium pentobarbital (60 mg/kg) and the level of anaesthesia was monitored throughout the surgical procedure. Supplementary doses were administered as necessary.

The rats were prepared for dorsal surgery, and holes were drilled over both the left and right LOT. A concentric stainless steel electrode (100 µm tip diameter, SNEX-100, Clark Electromedical Instrument, Kent, UK) was lowered into the LOT (below the
piriform cortex, 1.4 mm posterior to bregma and 3.2 mm lateral to midline, 9.5 mm deep) of the right hemisphere to deliver a biphasic pulse (1 mA peak-to-peak with a width of 1 ms) at 50 Hz for 10 min generated by a GRASS S88 stimulator with stimulus isolation and constant current units (Grass Products, Warwick, USA). This stimulus intensity was used to overwrite the spontaneous output of the MOB neurons; mitral cells show a firing rate up to 30 spikes/s (7, 31). Furthermore, recordings of the spontaneous activity of mitral cells have shown that mitral cells fire in a phasic discharge pattern, with periods of activity lasting on average 2 min with similar periods of quiescence between these bursts (31). Taking this into account, a constant stimulation over a prolonged period of time was applied, to disrupt the spontaneous output pattern.

The electrode was then removed and placed in the LOT of the left hemisphere for 10 min without any electrical stimulation. For the control group, the electrode was placed to the both sides of the LOT for 10 min without stimulation. To mimic the activation throughout the olfactory system by the input, we applied 10 min of 50 Hz electrical stimulation to the LOT and analysed the expression of Fos. At 90 min after the end of electrical stimulation, rats were terminally anesthetized and transcardially perfused for tissue collection. The position of the stimulating electrodes in LOTs was verified histologically (Fig. 4F).

### Tissue preparation

Rats were terminally anesthetized (isoflurane inhalation then sodium pentobarbital, 200 mg/kg body weight, i.p.) and transcardially perfused with a heparinised (20 U/ml) 0.9% saline solution followed by paraformaldehyde (PFA) 4% in 0.1 m phosphate buffer (PB). The brains were removed and immersed overnight in a solution
of 2% paraformaldehyde and 15% sucrose in 0.1 M PB at 4°C. Then the brains were placed in a solution of 30% sucrose in 0.1M PB and left for at least 72 h before they were processed. The rat brains were cut using a freezing microtome and stored in a cryoprotectant solution (30% ethylene glycol + 20% glycerol in 0.05 M sodium phosphate buffer, pH 7.3) at 4°C until required.

Immunocytochemistry

Immunocytochemistry on free-floating sections was performed for both wild type and transgenic rats. For wild-type rats, coronal sections were cut at 40 μm and washed in PB + 0.2% Triton X-100 for 3 times to remove excess fixative/cryoprotectant. Sections were then given a 5-min wash in PB before blocking endogenous peroxidase using the methanol solution (PB + 20% v/v methanol + 0.3% w/v hydrogen peroxide). Again, the sections were washed with PB+ 0.2% Triton X-100 three times for 5 min. To block non-specific staining, sections were incubated for 30 min in a PB blocking buffer consisting of 1% normal sheep serum + 0.3% Triton X-100. The sections were incubated in the c-Fos antibody (Ab-2, Oncogene Sciences, Cambridge Bioscience, UK) at 1:1000 dilution in PB blocking buffer for an optimum of 36 h at 4°C. After sections were washed in PB + 0.2% Triton X-100 for three times, they were incubated for 60 min with Biotinylated-anti-rabbit IgG (1:100, Vector Laboratories, Inc., Peterborough, UK) in PB+ 3% normal goat serum+0.2% Triton X-100 at room temperature. Sections were next incubated for 60 min in ABC complex diluted as detailed by the manufacturer (Vectorstain elite ABC kit, Vector Laboratories, Inc., Peterborough, UK). The sections were rinsed twice in PB + 0.2% Triton X-100, followed by 0.2M acetate buffer (pH 6.0) and visualized by incubating the sections in the glucose oxidase-Ni DAB (3, 3’-diaminobenzidine) solution
(0.025% DAB + 2.5% Nickel II sulphate + 0.08% ammonium chloride + 0.4% β-D-Glucose + 0.003% Glucose oxidase + 0.2M acetate buffer).

Brain tissues from transgenic rats were cut as 40-μm sagittal sections and double immunochemistry was performed for Fos and eGFP as previously described (7, 32). Briefly, after washing in 0.1M PB to remove all cryoprotectant, sections were incubated for 20 min in 0.3% H$_2$O$_2$ in 0.1M PB to quench endogenous peroxidase activity. Sections were washed at least four times with 0.1 M PB + 0.3% Triton X-100 between each of the following steps unless otherwise specified. To block non-specific interaction of secondary antibodies with the tissue, sections were then incubated for 60 min in a blocking buffer consisting of 3% normal goat serum + 0.3% Triton X-100 in 0.1M PB. Then sections were incubated for 48 h at 4 °C in c-Fos polyclonal antibody raised in rabbit diluted in the blocking buffer (1:30,000, Synaptic systems, Goettingen, Germany). After extensive washing in 0.1M PB, the sections were incubated for 60 min with biotinylated-anti-rabbit IgG (1:100, Vector Laboratories, Inc., Peterborough, UK). Sections were next incubated for 60 min in ABC complex diluted as detailed by the manufacturer (Vectorstain elite ABC kit, Vector Laboratories, Inc., Peterborough, UK) Fos immunoreactivity was visualized using a solution of 0.025% DAB + 2.5% Nickel II sulphate + 0.08% ammonium chloride + 0.015% H$_2$O$_2$ in 0.1 M Tris. For eGFP immunostaining, sections were incubated in chicken anti-GFP polyclonal antibody (Abcam, Cambridge, UK) diluted 1:5000 for 48 h at 4 °C. The sections were then incubated for 1 h in Biotinylated-anti-chicken IgG (1:100, Vector Laboratories, Inc., Peterborough, UK). To visualise the eGFP immunoreaction, a solution containing 0.025% DAB and 0.015% H$_2$O$_2$ in 0.1 M Tris was used. All the sections from wild-type and transgenic rats were mounted on the gelatinised slides and air dried. After dehydration in
191 ascending concentrations of ethanol (70% and 90% for 5 min each then 95% and 2 x
192 100% for 10 min each and then Xylene 2 x 10 min), slides were cover slipped using DPX
193 mountant.
194
195 For immunohistochemistry involving exposure to a biotinylated secondary and
196 fluorescently tagged streptavidin, sections were blocked for endogenous biotin by
197 incubating them first in 0.01% avidin in 0.1 M PB for 30 min, washing and then
198 incubating in 0.001% biotin in 0.1 M PB for 30 min. After washing, sections were
199 incubated for 60 min in a blocking buffer consisting of 3–5% normal serum (matched to
200 the host of secondary animal) + 0.1% Triton X-100 diluted in 0.1 M PB. The sections
201 were incubated with primary antibodies (Table 1) diluted in the blocking buffer. The
202 primary antibodies were applied for 1–5 days at room temperature for the first day and
203 thereafter at 4°C. After washing in 0.1 M PB, sections were incubated for 60 min with the
204 appropriate secondary antibody (Table 2) and then washed in 0.1 M PB. Sections exposed
205 to biotinylated secondary antibodies were then incubated for 60 min with fluorescently
206 labelled streptavidin conjugate (1:500). Both secondary antibodies and fluorescently
207 labelled streptavidin were diluted in 0.1 M PB + 0.03% Tween20. After further washing,
208 sections were incubated in 4,6-diamidino-2-phenylindole (DAPI, 1:33 000, Life
209 Technologies Ltd, UK) for 5 min at room temperature, washed and coverslipped using
210 Permafluor Aqueous Mounting Medium (Thermofisher scientific, Waltham, MA, USA).
211 No fluorescent labelling was detected when primary antibodies were omitted or when the
212 primary antibodies (Table 2) were incubated with a fivefold (w/v) control immunogen
213 before being exposed to the tissue sections (the latter control was conducted whenever a
214 control peptide was available from the supplier of that primary antibody).
Microscopy

Fluorescence signals were acquired either using a Nikon AIR confocal or a Zeiss LSM510 Axiovert confocal laser scanning microscope. In either case, the images were acquired at 1024x1024 pixels, using a Nikon Plan Apochromat 1.4 NA x 60 oil immersion objective or a Zeiss Plan NeoFLUAR 1.4 NA x 63 oil-immersion objective respectively. In all cases, emissions for each fluorophore were obtained consecutively to avoid channel cross-talk. Those images taken throughout each cell at Nyquist sampling rates were deconvolved using Huygens software (Scientific Volume Imaging, Hilversum, Netherlands) and all images were analysed using NIH ImageJ software (v1.48) and figures constructed using Microsoft PowerPoint.

Cell count

Immunohistochemically stained sections were imaged (Leica DFC490, 20x objective) for subsequent cell counting. Images were taken consecutively across the length of the PC. Seven sagittal sections from each of 12 brains (n=6/group) of eGFP-AVP transgenic rats, immunostained for GFP, were used to determine whether there are sex differences in the number of vasopressin expressing cells in the PC. We also analysed sections of the bed nucleus of the stria terminalis (BNST; three sections from each rat), since it has previously been shown that there is a sexual dimorphism in the number of vasopressin expressing cells in this area (33, 34).

Quantification of Fos positive cells

The number of Fos positive cells was quantified in a number of brain regions, including the PC, MOB, AOB, AON and SON. The investigators were blinded to the
treatments at the time of counting. The images were acquired using a Leica upright microscope, ×10 objective and digital camera and the Leica system acquisition software (Leica Microsystems, Wetzlar, Germany). For counting Fos and GFP positive nuclei, we carried out the counting directly under the microscope using × 20 magnification to avoid miscounting areas in which neurons are densely packed. For each brain region, counts were made on at least 3 sections for each animal and the mean values (± SEM) were calculated. For counting Fos positive nuclei in the mitral cell layer in wild-type rats, coronal sections are used (6.7 mm anterior to bregma). For counting Fos expression in vasopressin cells we used vasopressin-eGFP transgenic rats. Counting was conducted in sagittal sections (1.4-1.9 mm lateral to the midline) including the MOB, AOB, AON, SON. For counting in the piriform cortex, sagittal sections 3.4 - 3.9 mm lateral to the midline were used (35).

Using ImageJ (NIH, Bethesda, MD, USA), acquired images were converted to 8-bit, thresholded using the same parameters, and Fos-positive nuclei were counted manually using the Cell Counter tool. The number of Fos-positive nuclei within each region of interest (ROI) was normalised to the area of that ROI to allow comparison (mean ± SEM/10^4 μm^2), except for the PC. The total number of Fos-positive nuclei was counted and is expressed as mean ± SEM per section. Vasopressin neurons are densely packed in some regions and cell structures in the sections overlap, sometimes making it hard to distinguish between single neurons, which might affect counting Fos-positive nuclei in vasopressin stained neurons. Therefore, we also counted a proportion of clearly distinguishable vasopressin neurons and vasopressin neurons expressing Fos protein directly under the microscope (x 20 magnification in at least six regions in every rat, and the values are expressed as percentages).
Statistics

Statistical analysis was performed using the Prism software. To compare data between two independent groups the Mann-Whitney Rank Sum Test was used. All data are shown as mean ± SEM.

RESULTS

Characterization of eGFP-vasopressin neurons in the PC

We first discovered these cells in our transgenic rat strain in which eGFP is expressed under the control of the vasopressin promoter (Fig. 1A,B). In these transgenic rats, eGFP expressing cells were distributed widely throughout the whole PC. Using double immunocytochemistry, we established that every cell immunoreactive for eGFP was also immunoreactive for vasopressin (Fig. 1B). We confirmed the expression of vasopressin in PC cells in wild-type rats using antibodies against vasopressin-neurophysin (Fig. 1C). Whereas vasopressin cells were seen across the whole PC, the signal was less intense and the number of vasopressin immuno-reactive cells in wild-type rats was lower than seen in eGFP-vasopressin transgenics.

Most of the vasopressin-immunoreactive cells were localised in layer II of the PC, however a few were also seen in layer Ib and layer III (Fig. 1B); 63% of these cells co-expressed glutamate (140 of 221 examined eGFP cells, Fig. 1D) and 20% co-expressed GABA (56 of 257, Fig. 2). In very few cells, eGFP was co-localised with calbindin (10.5%, 21 of 200) and calretinin (0.7%, 2 of 287), but not parvalbumin (0 of 323, Fig. 2), which label known subpopulations of PC neurons (36-38). There was no co-
localisation with cholecystokinin (CCK, 0 of 423) or vasoactive intestinal polypeptide (VIP, 0 of 323) which have been described in neurons of the PC (Fig. 2) (36, 39).

Vasopressin receptor staining was abundant in the PC, but very few eGFP-vasopressin cells were immunoreactive for V1a (6%, 22 of 365) and V1b receptors (1.8%, 3 of 163, Fig. 2).

Sex differences

To determine whether there are sex differences in the number of vasopressin expressing cells in the PC as described for other areas harbouring vasopressin cells (33, 40), sagittal sections from eGFP-AVP transgenic rats were immunostained for GFP. There was no significant difference between male and female rats in the number of immunoreactive vasopressin cells in the PC (males 533 ± 71, females 589 ± 127; P=0.71, Students t-test, n =6/group, Fig. 3B,C). By contrast, as expected, in the BNST there were fewer immunoreactive vasopressin cells in female rats than in male rats (females 105 ± 15, males 204 ± 31, n = 4/group, P = 0.04; Fig. 3D).

Fos induction after LOT stimulation

Initially we studied the effects of electrical stimulation of the LOT on Fos induction in the MOB mitral cell layer in coronal sections from wild-type SD rats. The number of Fos-positive neurons was higher in the mitral cell layer ipsilateral to LOT stimulation compared to the controls (61.6 ± 13.1 vs 20.7 ± 3.7 nuclei/section, p=0.02). There was no significant difference in Fos expression in the mitral cell layer on the contralateral side (contralateral stimulated, 11.0 ± 5.8 cells/section vs control, 17.2 ± 2.5 cells/section). To determine the effects of LOT stimulation on Fos expression specifically
in vasopressin neurons, subsequent studies were performed in vasopressin-eGFP transgenic rats.

Main and accessory olfactory bulb

We repeated this experiment and analysed sagittal sections of the MOB, AOB, AON and PC. LOT stimulation again increased Fos expression in the ipsi-, but not contralateral side in the mitral cell layer of the MOB (ipsilateral, 12.9 ± 2.2, vs 2.4 ± 0.8 cells/10⁴ μm², p = 0.001; contralateral, 2.8 ± 1.3 cells/10⁴ μm² vs 2.0 ± 0.2 cells/10⁴ μm², Fig. 4A). In the AOB, the number of Fos-positive nuclei in the mitral cell layer following LOT stimulation was also significantly higher in the ipsilateral side than on the ipsilateral side of the control rats (6.7 ± 0.8 vs 3.7 ± 1.0 cells/10⁴ μm², p = 0.041, Fig. 4B). An equivalent amount of Fos was induced in the contralateral mitral cell layer in response to LOT stimulation, however this failed to reach statistical significance compared to the control group (stimulated contralateral 6.8 ± 0.9 cells/ 10⁴ μm² vs control contralateral, 4.1 ± 0.9 cells/ 10⁴ μm², p = 0.1091, Fig. 4B).

There are no vasopressin expressing cells in the mitral cell layer of the MOB and very few in the AOB. The proportion of vasopressin neurons expressing Fos protein in the mitral cell layer of the ipsilateral AOB in response to LOT stimulation was 2.5 ± 0.5% (no Fos protein expression was observed in the contralateral side and in the control unstimulated animals).

Anterior olfactory nucleus

In the AON, we separately analysed the dorsal and lateral parts of the AON (22). The number of Fos-positive nuclei differed between the ventral and dorsal part of the
AON, but this did not reach statistical significance (control-ipsilateral of ventral vs dorsal, 11.8 ± 4.7 cells/10^4 μm^2 vs 11.8 ± 4.7 cells/10^4 μm^2, p = 0.051, 4.7-5.2 mm anterior to bregma).

In the dorsal AON, LOT stimulation induced a significant increase in the number of Fos-positive nuclei in the ipsilateral side compared to the control group (5.7 ± 1.4 cells/10^4 μm^2 vs control 1.1 ± 0.4 cells/10^4 μm^2, p = 0.019, Fig. 4C). In the ventral AON, there was no significant difference in the levels of Fos expression between the control and LOT stimulated group on either side (stimulated ipsilateral, 8.4 ± 3.6 cells/10^4 μm^2 vs control ipsilateral, 11.8 ± 4.7 cells/10^4 μm^2, p = 0.53).

There is a large number of vasopressin-expressing cells in the AON, but there was no significant change in the proportion of vasopressin cells expressing Fos in response to LOT stimulation in both groups ipsi- and contralateral (dorsal, control vs stimulated, 3.8 ± 1.9 vs 5.1 ± 1.9 %, p=0.90 , ventral, 14.5 ± 3.9 vs 7.0 ± 2.4 %, p=0.44) and contralateral (dorsal, control vs stimulated, 2.0 ± 1.4 vs 1.2 ± 0.4 %, p=0.90 , ventral, 10.0 ± 1.8 vs 9.8 ± 1.7 %, p=0.72, Fig.4G).

Piriform cortex

The PC runs in a band from the rhinal fissure to the ventral surface of the brain following the curvature of the lateral wall. LOT stimulation induced a striking increase in Fos expression in the PC (Fig. 4D). Following LOT stimulation 253 ± 61 cells/section expressed Fos in the ipsilateral side, compared to 59 ± 12 cells/section in control rats (p = 0.042). LOT stimulation also significantly increased the number of Fos-positive nuclei in the contralateral side indicating a bilateral connection between the two hemispheres of
the olfactory system (stimulated contralateral, $252.2 \pm 80.9$ cells/section vs control ipsilateral $58.8 \pm 12.3$ cells/section, $p = 0.029$, Fig. 4D).

There was also a significant increase in the proportion of Fos-positive eGFP cells in the PC in the electrically stimulated ipsilateral side compare to control (stimulated ipsilateral $37 \pm 7\%$, vs control ipsilateral $6.0 \pm 0.8\%$, $p = 0.02$, Fig. 4H).

Supraoptic Nucleus

Connectivity between the SON and the olfactory system has been described previously (41-44). Therefore, we also analysed Fos induction after electrical stimulation of the LOT in the SON (Fig. 5A). There was a significant difference between the control and the electrically stimulated group in both hemispheres (stimulated ipsilateral $10.0 \pm 1.3/10^4 \mu m^2$ vs control ipsilateral, $2.3 \pm 0.7/10^4 \mu m^2$, $p = 0.02$, stimulated contralateral, $6.9 \pm 0.8/10^4 \mu m^2$ vs control ipsilateral, $2.3 \pm 0.7/10^4 \mu m^2$, $p = 0.03$, Fig. 5B).

There was a significant increase in the proportion of Fos-positive eGFP cells in the LOT stimulated ipsilateral and contralateral side compare to control (stimulated ipsilateral $63.7 \pm 5.8\%$, stimulated contralateral $54.5 \pm 4.8\%$ vs control ipsilateral $18.7 \pm 6.7\%$, $p = 0.02$, 0.03, Fig. 5C).

DISCUSSION

Here we show a large number of cells expressing vasopressin in the PC. The PC has been characterised both electrophysiologically and immunocytochemically (45-47) and comprises a sparsely populated superficial layer I, a main input layer II containing the densely-packed somata of glutamatergic principal neurons, and a deep layer III containing principal neurons at lower density (48). Most of the vasopressin cells in the
PC are located in layer II and also co-express glutamate. Scattered more uniformly across all layers are GABA-releasing interneurons that provide feedforward or feedback synaptic inhibition to principal cells and some of these also contain vasopressin. Of the vasopressin cells in the PC, 30% showed an increase in Fos expression after LOT stimulation. These cells are likely to be glutamatergic pyramidal neurons since most cells which receive direct bulbar inputs in layer II are pyramidal neurons (48).

We first discovered these cells in our transgenic rat strain in which eGFP is expressed under the control of the vasopressin promoter. These rats have been extensively used by us and others to study vasopressin-expressing neurons in distinct brain regions (7, 22, 32, 49, 50). The vasopressin-eGFP transgene encodes a modified vasopressin precursor with eGFP fused in-frame at the C terminus ((30) and D. Murphy, personal communication). The signal peptide, vasopressin and neurophysin portions of the precursor are intact, and may be expressed from the transgene, thus the vasopressin-associated neurophysin in eGFP rats may reflect either endogenous expression or transgene-driven expression. We therefore confirmed the expression of vasopressin in PC cells in wild-type rats using antibodies against vasopressin-neurophysin.

Here we confirmed the presence of vasopressin receptor expression in the PC (22, 27), however the receptors are not on the vasopressin cells themselves, indicating that the neuropeptide is not involved in autoregulation as it is in the hypothalamus (51, 52). The PC is part of a network involved in the processing of olfactory cues used for social communication (53-55) integrating odour features into odour objects (56). We and others have previously shown that vasopressin is involved in the modulation of social recognition at the level of the OB (7, 8) and the AON (22), suggesting that vasopressin neurons in the olfactory system are involved in the coding of social odour information.
It is believed that vasopressin and the closely related neuropeptide oxytocin modify the state of early olfactory presentation to enhance salience of concurrently-presented odours and to help detect relevant information of conspecifics during social encounters. This is supported by experiments showing longer conspecific exploration times in rodents where the oxytocin receptor was deleted in the AON, or vasopressin receptor blocked or downregulated in the MOB (7, 57). These animals may have shown less efficient information extraction due to peptide effects on the gain of odour representations. Through cortical top-down projections into the olfactory system, the peptides may modify the global gain control of olfactory coding before MOB outputs spreads into divergent higher-order pathways including the PC, the ventral striatum (olfactory tubercle), the amygdala, and the entorhinal cortices (58, 59). Many of these higher-order brain regions are activated during social interactions and also express oxytocin and vasopressin receptors, allowing for further modifications of information through these peptides during particular types of social behaviour. It is also likely that storage of recognition memory involves brain regions like the PC. Oxytocin for example promotes formation of association learning of an initially neutral odour with a potential mating partner (60). Activation of the PC was found to be crucial for the consolidation and for the recall of long-term social memory (61). However, the exact role of vasopressin in these processes has still to be determined in more detail.

Lack of sex differences

Here we show that there was no sex difference in the number of vasopressin expressing cells in the PC, but that there was in the BNST. A lack of sexual dimorphism has also been shown in other vasopressin cell populations of the olfactory system,
including the MOB, AOB or the AON (7, 22). By contrast, immunoreactive vasopressin projections in the lateral septum and the lateral habenular nucleus are much denser in male than in female rats (40) and a similar imbalance in peptide expression was identified in the BNST (33, 62). The role of vasopressin in modulating social behaviours is different in male and female rodents. Vasopressin V1a receptor knock-out female mice display significantly less anxiety-related behaviour than male equivalents (9) and variations in maternal care is influenced by the expression of oxytocin and vasopressin receptors in the lateral septum and amygdala in a gender-specific manner (63); both areas show sex dimorphic vasopressin expression (40).

**Fos expression in response to LOT stimulation**

LOT stimulation increased Fos expression in the ipsilateral, but not in the contralateral side, of the mitral cell layer of the MOB and the AON. There are no direct inter-bulbar connections, and no direct connections to the contralateral cortex regions from mitral/tufted cells of the MOB (64). However, the increase in Fos expression in the AOB cannot be explained by the direct activation through LOT stimulation. The vomeronasal system has separate circuitries and the mitral/tufted cells of the AOB project through the accessory lateral olfactory tract to the bed nucleus of stria terminalis (BNST), nucleus of accessory olfactory tract, and the medial portion of the amygdala (vomeronasal amygdala) from which tertiary projections target certain regions of the hypothalamus (65, 66). Whether the increase in Fos expression in the AOB in response to LOT stimulation reflects activation of feed forward connections to the AOB needs to be determined in more detail.
We observed a significant increase in Fos expression in the contralateral side of the PC following stimulation. The cortical feedback projection from PC to olfactory bulb is complex and direct bilateral connections between PC have not yet been shown. However, an ipsilateral projection from the anterior PC to the pars lateralis of AON has been demonstrated (67) and thus the information transfer may occur to the contralateral PC through the AON (68).

Fos labelling in the SON

In our experiments, LOT stimulation increased Fos expression in the SON. Connectivity between the SON and the olfactory system has been described previously (41-44, 69). Labelling studies have shown a monosynaptic pathway between the olfactory bulb and the SON (42, 43, 70) and connections between olfactory sensory neurons and the vasopressin neurons in the PVN and SON (44). In addition, Hatton and Yang performed electrophysiological recordings in vitro and upon electrical stimulation of the LOT they found that cells within the SON responded with short latency excitatory responses supportive of a direct pathway from the olfactory bulb to the SON (41). Recent studies indicate a role for oxytocin in the connections between the olfactory bulb and PVN in the context of social interaction (57, 60). However, besides studies showing anatomical connectivity between olfactory bulb and SON and PVN, the interplay between these connections and the role of vasopressin needs to be determined in more detail.

Taken together, populations of vasopressin neurons in different areas of the rat olfactory system, including the MOB, AOB and the AON have been shown to be involved in the coding of social odour information (7, 22). Here we describe an additional population of
vasopressin cells in the PC. Together these functionally distinct populations of
vasopressin cells in different parts of the olfactory system suggest that vasopressin
signalling is involved in information processing at multiple levels of the olfactory
pathway.

**FIGURE LEGENDS**

**Figure 1: Vasopressin neurons in the piriform cortex.**

A, Coronal section from rat atlas indicating area of piriform cortex (PC) where images in (Aii, Aiii) have been taken from, showing that eGFP-expressing cells are distributed widely throughout the PC. eGFP-cells express vasopressin-neurophysin (VP-NP); the images show (B) fluorescence for eGFP, (Bi) immunoreactive VP-NP, and (Bii) overlaid images. C, vasopressin labelling in the PC of a wild-type rat. Ci, higher magnification of a cell. eGFP-cells co-express the vesicle glutamate transporter vGLUT-2 (white arrows) indicating that they use glutamate as a neurotransmitter; the images show (D) fluorescence for eGFP, (Di) vGLUT-2, (Dii) nuclear marker DAPI and (Diii) overlaid images.

**Figure 2: Vasopressin neurons in the piriform cortex.**

Immunohistochemistry for PC cell types Fluorescence immunohistochemistry showing that some eGFP-expressing cells (green) do co-express GABA, calcium binding proteins such as calbindin and calretinin, but not parvalbumin. There is no co-localisation with cholecystokinin (CCK) or vasoactive intestinal polypeptide (VIP). Whereas vasopressin receptor staining was abundant in the PC, only a very few eGFP-vasopressin cells were immunoreactive for V1a or V1b receptors.
Figure 3: Sex differences in the number of vasopressin cells

A, Sagittal section from the rat atlas showing quadrants analysed to determine the number of eGFP-expressing cells. Quantification of the number of GFP-positive cells along the PC show no sex differences (B) along the quadrants and (C) in the total number. D, Analysis of the number of GFP-positive cells in the BNST show significant fewer GFP-positive cells in females.

Figure 4: Fos expression in the olfactory system after LOT stimulation

A-D, Quantification of Fos-positive cells and (Ai-Di) representative images with (Aii-Dii) enlargements from (A) mitral cell layer in the MOB, (B) mitral cell layer of the AOB, (C) dorsal area of the AON and (D) PC. E, Coronal section from brain atlas showing target for electrode placement and (F) photograph of brain section showing electrode tract in the LOT. Proportion of Fos-positive vasopressin cells in the (G) AON and (H) PC. Mean ± SEM, *P ≤ 0.05, **P ≤ 0.01.

Figure 5: Fos expression in the SON after LOT stimulation

A, representative image of a SON showing Fos expression in vasopressin co-labelled cells. Quantification of (B) Fos-positive cells per section of the SON and (C) proportion of Fos-positive vasopressin cells in response to LOT stimulation. Mean ± SEM, *P ≤ 0.05,


40. de Vries GJ, Buijs RM, Swaab DF. Ontogeny of the vasopressinergergic neurons of the suprachiasmatic nucleus and their extrahypothalamic projections in the rat brain---presence of a sex difference in the lateral septum. *Brain Res*. 1981; **218**: 67-78.


70. Meddle SL, Leng G, Selvarajah JR, Bicknell RJ, Russell JA. Direct pathways to the supraoptic nucleus from the brainstem and the main olfactory bulb are activated at parturition in the rat. *Neuroscience.* 2000; **101**: 1013-21.