TITLE

Parenthood and gene expression of oxytocin receptors and vasopressin receptors in sensory cortices of the male California mouse (*Peromyscus californicus*)

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ABSTRACT

The onset of parental care is associated with shifts in parents' perception of sensory stimuli from infants, mediated by neural plasticity in sensory systems. In new mothers, changes in auditory and olfactory processing have been linked to plasticity at several points along both sensory pathways, including cortical changes that are modulated, at least in part, by oxytocin. In males of biparental species, vasopressin, in addition to oxytocin, is important for modulating parental behavior; however, little is known about sensory plasticity in new fathers. We examined variation in the mRNA expression of oxytocin and vasopressin receptors (*Oxtr* and *Avpr1a)* in sensory cortices of virgin males, paired nonbreeding males, and new fathers in the biparental California mouse (*Peromyscus californicus*), and variation among cortices using the visual cortex for comparison. Reproductive status did not affect gene expression for either receptor, but compared to the visual cortex, expression of both receptors was higher in the left auditory cortex and lower in the anterior olfactory nucleus. Additionally, expression for both receptors was higher in the left auditory cortex compared to the right auditory cortex. While oxytocin and vasopressin receptor expression may remain stable across reproductive stages in male California mice, our findings provide support for auditory cortex lateralization, with the left auditory cortex possibly displaying higher sensitivity to both oxytocin and vasopressin compared to the right.

KEY WORDS

Oxytocin, vasopressin, parenthood, olfactory plasticity, auditory plasticity, cortex, California mouse

INTRODUCTION

Mammals that exhibit parental care experience dramatic shifts in their detection, perception, and responses to infant-related stimuli during the transition to parenthood (Horrell et al. 2019; Numan 2020; Wilson et al. 2023). The valence of infant stimuli, such as odors and vocalizations, changes from being aversive to attractive around the time of parturition (Fleming et al. 1993; Fleming et al. 2002; González-Mariscal and Poindron 2002; Lévy et al. 2004). For example, CBA/CaJ and NMRI house mouse (*Mus musculus*) mothers are more sensitive to and better able to discriminate pup vocalizations than virgin females (Galindo-Leon et al. 2009; Liu et al. 2006; Rothschild et al. 2013; Shepard et al. 2013), and NMRI males with paternal experience prefer tones that are a similar frequency to pup calls, compared to lower-frequency tones, while males without paternal experience show no preference (Ehret 2005; Ehret and Koch 1989). Similarly, in both Sprague-Dawley rats (*Rattus norvegicus*) and house mice, new mothers are more attracted to pup-related odors than are virgin females (Kinsley and Bridges 1990; Lévy et al. 2004; Lévy and Keller 2009), and regardless of mating status, male prairie voles (*Microtus ochrogaster)* that exhibit paternal behavior prefer pup odors to control odors (Yamoah et al. 2008). Some of this sensory plasticity is associated with changes in neuroendocrine signaling in the brain (Fleming et al. 1989; Ziegler and Sosa 2016), specifically, along sensory pathways (Miranda and Liu 2009; Wilson et al. 2023).

The neuropeptides oxytocin (OXT) and arginine vasopressin (AVP) facilitate the onset of parental behavior, largely through actions in integrative forebrain regions (Bales and Saltzman 2016; Horrell et al. 2019; Numan 2020; Saltzman and Ziegler 2014). For example, soon after the birth of their first litter, female rats have higher OXT receptor (*Oxtr*) mRNA expression in integrative regions important for parental care (medial preoptic area [MPOA] and bed nucleus of

the stria terminalis [BNST]) compared to virgin females (Meddle et al. 2007), and injections of either an AVP or OXT antagonist into the MPOA of female rats soon after parturition reduce parental care (Pedersen et al. 1994). Similar findings have been reported for males in species in which new fathers spontaneously care for offspring. In mandarin voles (*Microtus mandarinus*), injecting an OXT antagonist into the MPOA reduces paternal behavior in new fathers (Yuan et al. 2019). Additionally, in biparental California mice (*Peromyscus californicus*), fathers have lower mRNA expression for *Oxtr* and AVP 1a receptor (*Avpr1a*) in the BNST compared to virgin males (Perea-Rodriguez et al. 2015), and fathers display increased responsiveness to newborns following intranasal administration of OXT (Guoynes and Marler 2022). Similarly, in the facultatively biparental meadow *(Microtus pennsylvanicus)*, AVP injection to the lateral ventricles increases parenting behavior in virgin males (Parker and Lee 2001).

Oxytocin can also modulate sensory plasticity during the transition to motherhood (Bester-Meredith et al. 2015; Numan 2020; Valtcheva and Froemke 2019; Wilson et al. 2023). Oxytocin receptors have been identified in the auditory (AC), piriform (Pir), visual (VC) and somatosensory cortices as well as in the anterior olfactory nucleus (AON) of mouse mothers, virgin females and virgin males (Mitre et al. 2016) and in sensory association areas of virgin male and female prairie voles (Duchemin et al. 2017). Primiparous female rats have higher *Oxtr* mRNA expression in the olfactory bulbs compared to virgin females (Meddle et al. 2007), and elevated OXT enhances maternal behavior in response to pup calls in mice (Banerjee and Lui 2013; Marlin et al. 2015; Yoshihara et al. 2018). Interestingly, Marlin et al. (2015) found that OXT infusion into the left auditory cortex (L-AC), but not the right (R-AC), reduced latency to retrieve pups in primiparous mouse mothers. AVP may also modulate sensory plasticity, since AVP 1a receptors have been identified in cortical regions of rats of both sexes including the

AON and Pir (Wacker and Ludwig 2019). However, it remains unclear whether expression of *Oxtr* and *Avpr1a* in sensory cortical regions changes during the transition to parenthood.

The distribution of *Oxtr* and *Avpr1a* in the sensory cortices of fathers relative to reproductively inexperienced males is, to our knowledge, unknown. However, evidence suggests that OXT and AVP can act in sensory pathways of males. Male C57BL/6 house mice have receptors for OXT and AVP in their vomeronasal organs (VNOs), and i.p. injection of OXT reduces VNO activity and pup-directed aggression (Nakahara et al. 2020). Additionally, i.p. injection of AVP raises auditory brainstem response thresholds in virgin male Wistar rats, indicating reduced ability to detect auditory stimuli (Naganuma et al. 2014).

In the present study, we examined the effects of fatherhood on *Oxtr* and *Avpr1a* mRNA expression in the auditory and olfactory cortices of male California mice, a monogamous, biparental rodent in which fathers provide extensive care for their offspring (Gubernick and Alberts 1987). The onset of parenthood in this species alters males' behavioral and neural (as measured by expression of Fos, the product of the immediate early gene *c-fos*) responses to pups as well as to isolated pup odors and vocalizations (Arquilla et al. 2023; de Jong et al. 2009; Wilson et al. 2022). Preliminary findings indicate that electrophysiological responses of the auditory cortex to pup vocalizations differ between fathers and virgin males (Deane, K.E., Saltzman, W., Razak, K.A., unpub). In addition, preliminary data suggest that treatment with an OXTR antagonist mildly inhibits parental care in California mouse fathers (Hussein, M., Unal, A., Saltzman, W., unpub. data), and fathers have lower levels of both *Oxtr* and *Avpr1a* in the BNST than virgin males (Perea-Rodriguez et al. 2015). However, effects of fatherhood on *Oxtr* and *Avpr1a* in brain regions associated with sensory processing have not been evaluated. Therefore, we quantified mRNA expression for both *Oxtr* and *Avpr1a* in four cortical regions

involved in acoustic (L-AC, R-AC) or olfactory (Pir and AON) processing, and as a control, in the visual cortex (VC). The VC was used as a control because rodents rely more heavily on olfactory and acoustic pathways for processing social cues, compared to visual pathways (Chen and Hong 2018), and previous work by Mitre et al. (2016) showed that the percent of VC cells containing *Oxtr* does not differ between mothers and virgins in C57BL/6 house mice. Because AVP and OXT impact the saliency of a range of social cues (Rigney et al 2022), two control groups (males paired with another male and males paired with a tubally ligated female) were employed in order to address potential effects not only of fatherhood but also of cohabitation with a female.

METHODS

Animal housing and care

California mice were bred at the University of California, Riverside (UCR) and were descendants of mice purchased from the Peromyscus Genetic Stock Center (University of South Carolina, Columbia, USA). All animals were housed in 44 × 24 × 20 cm polycarbonate cages with aspen shavings for bedding, cotton for nesting material, and ad libitum access to food (Purina 5001 Rodent Chow) and water. The lights were on a 14:10 h cycle with lights on at 2300 h. Ambient temperature was maintained at approximately 23° C, and humidity was around 65%. All procedures were approved by UCR's Institutional Animal Care and Use Committee and were conducted in accordance with the recommendations of the *Guide for the Care and Use of Laboratory Animals*. UCR is accredited by the Association for Assessment and Accreditation of Laboratory Animal Care.

115 Mice were housed with both parents until weaned at 27-31 days of age. They were then
116 housed in single-sex groups with 1-3 other age-matched mice until they were used for this study.
117 Male mice were assigned to three groups, each with 8 males: fathers, paired nonbreeders, and
118 virgins. Fathers and paired nonbreeders were housed with an unrelated (less closely related than
119 first cousins), age-matched female, and virgins were housed with a male from their original
120 group of juveniles to reduce the potential of aggressive interactions between cage mates (Trainor
121 and Marler 2001).
122 Prior to pair formation, females to be paired with fathers underwent sham tubal ligation
123 (see below), and females to be paired with nonbreeding males underwent tubal ligation (see
124 below). No surgeries were performed on males. In total, male subjects were from 16 different
125 families, with no more than 3 males used from the same family. When siblings were used, they
126 were assigned to different groups.
127
128 **Surgeries and Pairing**
129 Before being paired with a male, females were housed in same-sex groups of 2-4 mice until 75 -
130 91 days of age ($X \pm SD = 82.5 + 6.0$), at which time they underwent tubal ligation or sham tubal
131 ligation following previously established protocols (Zhao et al. 2018). Briefly, females were
132 anesthetized with 2.5% isoflurane vapor, a midline incision (approximately 1 cm) was made
133 across the lower abdomen, and the fallopian tubes were located. For tubal ligation surgeries, each
134 fallopian tube was tied in two places using absorbable sutures and cut between the ties. For sham
135 tubal ligations, the fallopian tubes were left intact. The abdominal muscle layer was closed using
136 absorbable sutures, and the skin was sealed using tissue glue. Lidocaine was applied topically at
137 the site of the incision, and females were given s.c. buprenorphine (Hospira Inc., Lake Forest, IL,

USA) every 7-10 hours for 48 hours and Carprofen (Carprieve [Norbrook Laboratories; Overland Park, KS, USA]) every 24 hours for 48 hours, with the first dose of both given immediately before surgery.

Following surgery, females were allowed to recover in isolation for 7 days, reunited with their original female cage mates for an additional 7 days, and then paired with a male mate. At the time of pairing, males were between 88 and 138 days old and age did not differ between groups (t-test $P > 0.35$; X ± SD: fathers = 106 $\pm$ 6.4; nonbreeding = 114.4 $\pm$ 5.8).

Brain collection

Brains were collected from breeding males 2-3 days after the birth of their first litter and from nonbreeders and virgins on the same day in an age-matched manner. The length of time mice were paired prior to brain collection did not differ between breeding and nonbreeding pairs (t-test $P < 0.67$, X and SD: breeding = 51.4 $\pm$ 7.2; nonbreeding = 55 $\pm$ 4.4). Brain collection from virgin males occurred at a younger age than males paired with a female (ANOVA, model $P = 0.007$, $F = 6.5$, post-hoc P's < 0.04. X and SD: virgin = 135.75 $\pm$ 6.7; fathers = 157.4 $\pm$ 7.1; nonbreeding = 169.4 $\pm$ 6.7).

Each mouse was removed from its home cage between 0900 and 1000 h, placed into a DecapiCone (Braintree Scientific; Braintree, MA, USA), and immediately decapitated using a guillotine. The brain was then rapidly dissected from the skull. Following a previously described protocol (Duchemin et al. 2017), the two cortical hemispheres were separated, flattened and placed on dry ice. Cortical punches (1 mm diameter) were collected and pooled from the left and right VC, Pir and AON. Punches were also collected from the right and left ACs but were kept

160 separate based on the possibility of lateralization (Marlin et al. 2015). All samples were stored at
161 -80˚ C.
162
163 **qPCR**
164 Quantitative PCR was performed following previously established procedures (Laredo et al.
165 2014). In brief, we extracted RNA from each punch sample using Trizol (Fisher Scientific) and
166 assessed RNA quality using spectrographic analyses on a Nanodrop. For each sample, 1 μg of
167 RNA was used for reverse transcription using iScript (BioRad). We performed duplicate real-
168 time PCR reactions for *Oxtr* (Genbank accession: MN265350.1, FisherSci Catalog number 43-
169 320-78) and *Avpr1a* (Genbank accession: XM_052753487.1, FisherSci Catalog number 43-320-
170 78), and 18s ribosomal RNA (FisherSci Catalog number: 43-108-93E) was used for a reference
171 transcript. All samples were run using Taqman chemistry (FisherSci catalog number: 44-49-63)
172 on an Applied Biosystems 7500 detection system (Applied Biosystems). For each plate, relative
173 expression levels were calculated for each sample using the ΔΔCT method. To compare samples
174 across plates, we made a pool of cDNA from each brain region. Samples of this pool was run for
175 each transcript on every plate. For each sample, the expression value for each transcript was
176 divided by the expression value from the pool.
177
178 **Statistical Analyses**
179 Linear mixed-effect models were used to determine whether receptor mRNA expression varied
180 with male reproductive status (virgin, nonbreeding and father). All models included reproductive
181 status as the main effect and male age as a covariate. Age was removed from models when it did
182 not predict mRNA expression ($\alpha \leq 0.05$). Since not all variables could be transformed effectively

using the same method of transformation (see below), non-parametric Kruskal-Wallis tests were used to evaluate whether mRNA expression differed among cortices. . Significant results were further evaluated using Dunn's tests.

STATA 17 (StataCorp LP, College Station, TX, USA) was used for all analyses. Assumptions of normality were assessed using Shapiro-Wilk analyses and quantile-quantile plots. Data were either log-transformed (VC, Pir, L-AC and R-AC) or inverse square-root-transformed (AON) to meet assumptions of normality for LMMs. Within each receptor type for each brain region, transformed mRNA expression data were analyzed for outliers, which were considered to be values that were ≥ 1.5 interquartile ranges above or below the 75^{th} and 25^{th} quartiles, respectively. Across all data, 12 outlier values were identified and removed prior to analyses (VC *Oxtr*: n = 3; VC *Avpr1a*: n = 1; AON *Oxtr*: n = 5; AON *Avpr1a*: n = 3). For all tests, the critical P-value was set at 0.05 (two-tailed).

RESULTS

Expression of *Oxtr* and *Avpr1a* mRNA varied widely among individual mice within each cortical region, but this variation was not explained by male reproductive status. We found no differences in mRNA expression of *Oxtr* or *Avpr1a* among male California mice housed with a male (virgins), a tubally ligated female (nonbreeding males), or a sham-tubally ligated female and their first little of pups (fathers) in any of the cortical regions examined (LMM, model *P*'s > 0.18; Table 1). The covariate of male age was non-significant and, thus, was removed from all models except for *Oxtr* expression in the AON (LMM, model $P = 0.17$, male reproductive status $P = 0.18$, male age $P = 0.03$; Table 1).

Expression of both *Oxtr* and *Avpr1a* mRNA differed significantly among cortical regions. Specifically, *Oxtr* mRNA expression was significantly lower in the AON compared to the Pir, VC and L-AC, and significantly higher in the L-AC compared to all other regions (Kruskal-Wallis test and Dunn's post-hoc test, Table 2, Fig. 1A). Similarly, expression of *Avpr1a* mRNA was significantly lower in the AON compared to all other regions, and significantly higher in the L-AC compared to all other regions (Kruskal-Wallis test and Dunn's post-hoc test, Table 2, Fig. 1B). Notably, both *Oxtr* and *Avpr1a* mRNA levels were significantly higher in the L-AC compared to the R-AC (paired t-tests, *Oxtr*: $P = 0.004$, *Avpr1a*: $P = 0.0007$, Fig. 1).

TABLES

Table 1. Expression of oxytocin (*Oxtr*) and vasopressin (*Avpr1a*) receptor mRNA in cortical brain regions of fathers, virgin males and nonbreeding males. Parental status did not impact mRNA expression in any region, and family identity did not contribute significantly to any model. Reported means and confidence intervals are for transformed data. LMMs, log-transformed: visual cortex [VC], piriform cortex Pir], left auditory cortex [L-AC] and right auditory cortex [R-AC]; inverse square root-transformed: anterior olfactory nucleus [AON].

Brain region	*Oxtr*					*Avpr1a*				
	Mean	95% CI	N	χ^2	*P*	Mean	95% CI	N	χ^2	*P*
VC			19	0.49	0.783			21	2.98	0.225
Virgin	1.83	1.10 to 2.57	6			3.62	2.31 to 4.93	7		
Nonbreeding	1.50	0.86 to 2.13	8			2.33	1.10 to 3.55	8		
Father	1.73	0.92 to 2.53	5			3.78	2.36 to 5.20	6		
Pir			23	0.76	0.684			23	1.42	0.491
Virgin	2.20	1.01 to 3.38	7			2.98	1.63 to 4.32	7		
Nonbreeding	2.48	1.37 to 3.59	8			3.33	2.07 to 4.59	8		
Father	1.78	0.67 to 2.89	8			2.26	1.01 to 3.52	8		
AON[a]			16	5.11	0.164			18	0.80	0.671
Virgin	0.84	0.70 to 0.99	6			0.54	0.44 to 0.65	7		
Nonbreeding	0.63	0.49 to 0.77	6			0.47	0.36 to 0.59	6		
Father	0.71	0.56 to 0.85	4			0.53	0.40 to 0.66	5		
L-AC			19	0.65	0.724			19	0.97	0.614
Virgin	3.45	2.02 to 4.87	7			5.81	4.27 to 7.34	7		
Nonbreeding	4.31	2.77 to 5.85	6			6.92	5.26 to 8.58	6		
Father	3.79	2.26 to 5.33	6			6.11	4.45 to 7.77	6		
R-AC			18	3.09	0.214			18	2.37	0.306
Virgin	0.72	-0.08 to 1.52	7			1.98	0.91 to 3.06	7		
Nonbreeding	1.52	0.72 to 2.32	7			2.90	1.83 to 3.98	7		
Father	1.78	0.72 to 2.84	4			3.25	1.83 to 4.67	4		

[a] Male age varied positively with *Oxtr* receptor mRNA ($z = 2.20$; $P = 0.028$).

Table 2. Comparison of expression of oxytocin (*Oxtr*) and vasopressin (*Avpr1a*) receptor mRNA among sensory cortical regions of male California mice from all three reproductive groups combined. Kruskal-Wallis tests (top row of results) followed by post-hoc Dunn's tests. Pir – piriform cortex, VC – visual cortex, AON – anterior olfactory nucleus, L-AC– left auditory cortex, R-AC – right auditory cortex. P-values <0.05 are in bold.

Brain region	*Oxtr*			*Avpr1a*		
	N	χ^2	*P*	N	χ^2	*P*
		30.26	**0.0001**		38.35	**0.0001**
Pir versus:	23			23		
VC	19		0.252	21		0.295
AON	16		**0.001**	18		0.008
L-AC	19		**0.007**	19		**< 0.0001**
R-AC	18		0.056	18		0.414
VC versus:						
AON			**0.009**			**0.002**
L-AC			**0.002**			**0.0004**
R-AC			0.186			0.236
AON versus:						
L-AC			**< 0.0001**			**< 0.0001**
R-AC			0.0692			**0.019**
L-AC versus:						
R-AC			**0.0001**			**< 0.0001**

FIGURES

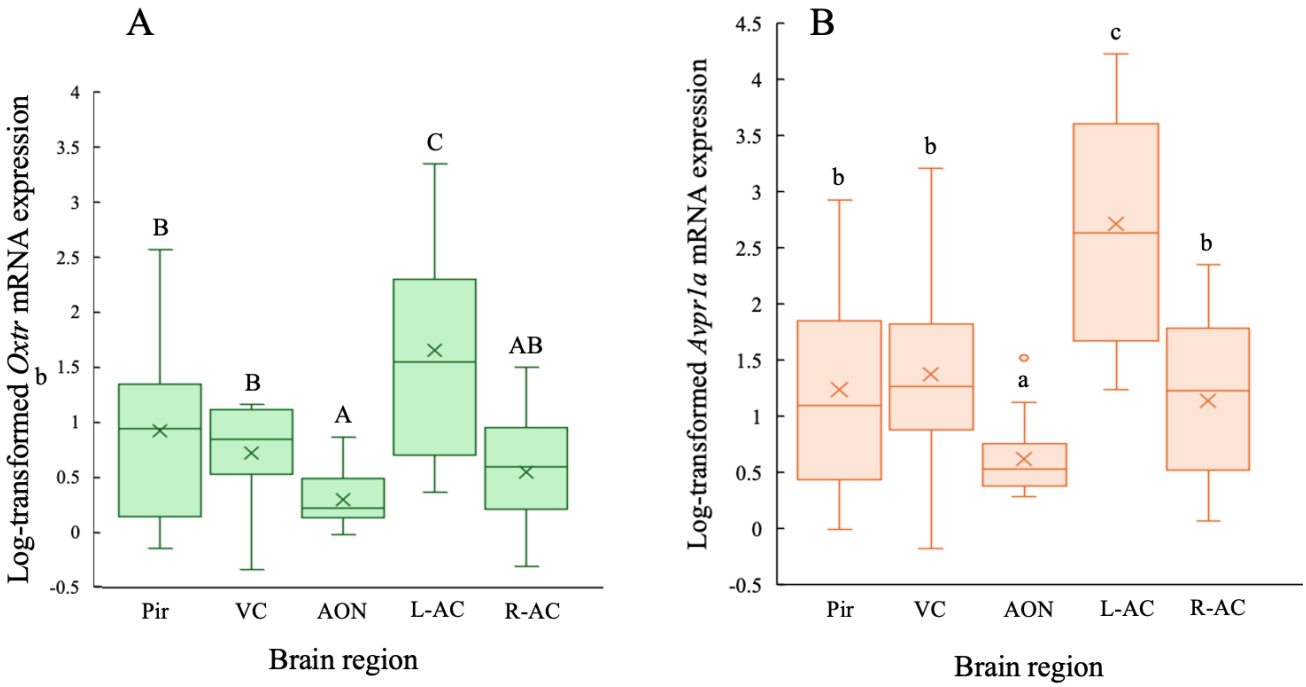

Fig. 1: Expression of (A) oxytocin (*Oxtr*) and (B) vasopressin (*Avpr1a*) receptor mRNA in sensory cortical brain regions of male California mice from all three reproductive groups compared to the visual cortex. Box plots show median, 1st and 3rd quartiles. Error bars show minimum and maximum values. Letters denote significant ($P < 0.05$) differences from post-hoc Dunn's test following Kruskal-Wallis tests. Pir – piriform cortex, VC – visual cortex, Aon – anterior olfactory nucleus, L-AC – left auditory cortex, R-AC – right auditory cortex.

DISCUSSION

The transition to parenthood can induce plasticity in sensory cortical regions in new mothers, which facilitates the expression of maternal care (Valtcheva and Froemke 2019). However, cortical plasticity in new fathers is poorly studied and, for both sexes, it is unclear whether plasticity involves changes in neuropeptide signaling in sensory brain regions. We found that neither *Oxtr* nor *Avpr1a* mRNA expression in the sensory cortices differed between males housed with another male and males housed with a nonbreeding female, or between either of these controls and fathers. Across reproductive groups, however, levels of both *Oxtr* and *Avpr1a* mRNA differed significantly across brain regions, with expression highest in the L-AC and lowest in the AON. These differences across regions may provide further insight into the role of different sensory cortices in modulating behavioral changes observed in new parents.

Previous studies have identified receptors for OXT and AVP in sensory cortices and sensory association areas of adult rodents (Duchemin et al. 2017; Mitre et al. 2016; Vaccari et al. 1998; Wacker and Ludwig 2019), and expression of OXTR and Avpr1a along sensory pathways can be modulated by early-life experience (Bester-Meredith and Marler 2001; Zeng et al. 2014). Our findings suggest that, unlike early-life events, the transition to parenthood in males does not induce plasticity in sensory cortices through variation in *Oxtr* or *Avpr1a* expression, which aligns with previous findings that OXTR labeling in sensory cortices did not differ between house mouse mothers and virgin females (Mitre et al. 2016).

On the other hand, changes in central concentrations of OXT and AVP might provide a mechanism through which sensory processing in the cortex is altered in parents. In some rodents, including the biparental prairie vole and Mandarin vole, the transition to fatherhood can result in increased synthesis of OXT and AVP in the paraventricular nucleus (PVN) and supraoptic

nucleus (SON) of the hypothalamus and of AVP in the bed nucleus of the stria terminalis and medial amygdala (Bales and Saltzman 2016; Song et al. 2010; Wang et al. 2000; Zimmermann-Peruzatto et al. 2015), which facilitates increased central release of OXT and AVP. Although *Avp* mRNA expression in the PVN and number of OXT- and AVP-stained neurons in the PVN and bed nucleus of the stria terminalis do not differ based on reproductive state in male California mice (De Jong et al. 2009, 2013), other potential sources of AVP (such as the SON) have not, to our knowledge, been explored. Thus, even though receptor expression may not change, the effects of OXT and AVP on synaptic activity in sensory cortices might be altered in fathers compared to virgin males.

This suggestion is consistent with the role of OXT in maternal cortical plasticity proposed by Valtcheva and Froemke (2019), whereby sensory inputs stimulate synthesis of OXT in, for example, oxytocin neurons in the PVN, which then modulates changes in sensory cortices that alter saliency of sensory stimuli from pups. Studies that demonstrate a connection between elevated levels of OXT and changes in cortical activity in females support the suggestion that cortical plasticity is driven by increased nonapeptide binding, and that the L-AC is specifically important for processing pup acoustic stimuli. Synaptic inhibition in the L-AC and Pir, as measured by whole-cell recordings from brain slices, was reduced for virgin female house mice in the presence of OXT compared to baseline inhibitory post-synaptic potentials (Mitre et al. 2016). Additionally, infusion of an OXT antagonist into the L-AC, but not the R-AC, of maternally experienced mice resulted in faster pup retrieval, and topical administration of OXT to virgin female mice resulted in neuronal responses to pup calls that were comparable to new mothers (Marlin et al. 2015). Interestingly, lateralization of *Oxtr* in the AC was observed in female mice, regardless of maternal status, but not males (Mitre et al. 2016). In our study,

biparental male California mice, regardless of paternal status, displayed the same lateralization of *Oxtr* and *Avpr1a* in their auditory cortices: males had higher expression of mRNA for both receptors in the L-AC compared to the R-AC. Thus, it is possible that the nonapeptides play a similar role in modulating responses to pup vocalizations for males of a biparental species and females of a uniparental species. Lateralization of *Oxtr* (and *Avpr1a)* in the auditory cortex could reflect increased receptor expression in L-AC within cell types that also express the receptors in R-AC. Alternatively or additionally, it is possible that some cell types express *Oxtr* (or *Avpr1a*) in L-AC but not in R-AC. These possibilities could be evaluated by using single-nucleus RNA sequencing.

We found that expression of both *Oxtr* and *Avpr1a* mRNA differed across sensory cortices in male California mice. The highest levels of receptor mRNA were found in the L-AC, while the lowest were found in the AON, which is important for olfactory memory and social behavior (Johnson and Young 2017; Oettl and Kelsch 2018). These findings suggest that the olfactory, auditory, and visual cortices may differ in the extent to which they are modulated by OXT and AVP. However, the functional significance of these differences remains to be determined. To our knowledge, the relative expression of OXT and AVP receptors, or the extent of cortical modulation by OXT and AVP, has not been compared systematically across sensory cortices in other species (but see Duchemin et al. 2017).

In conclusion, we found no evidence that either paternal status or cohabitation with a female influences expression of *Oxtr* and *Avpr1a* in sensory cortices of male California mice. It is possible, however, that fatherhood and/or cohabitation with a female alters receptor expression in subcortical regions of sensory pathways, or that *Oxtr* and/or *Avpr1a* expression undergoes transient changes during the onset of fatherhood or pair-bonding that were

not apparent at the time points used in our study. Further research into potential changes in OXT and AVP signaling within sensory systems will provide better context for the results reported here and may expand our understanding of the mechanisms by which these neuropeptides influence the onset of paternal care.

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