SYNAPSE 27:14–25 (1997)

Vasopressin and Oxytocin Immunoreactive Neurons and Fibers in the Forebrain of Male and Female Common Marmosets (*Callithrix jacchus*)

ZUOXIN WANG,[1] KATHLEEN MOODY,[2] JOHN D. NEWMAN,[2] AND THOMAS R. INSEL[1]*
[1]*Department of Psychiatry and Behavioral Sciences, Emory University School of Medicine, and Yerkes Regional Primate Research Center, Emory University, Atlanta, Georgia 30322*
[2]*Laboratory of Comparative Ethology, National Institute of Child Health and Development, NIH, Poolesville, Maryland 20837*

KEY WORDS hypothalamus; stria terminalis; amygdala; sexual dimorphism

ABSTRACT Vasopressin (AVP) and oxytocin (OT) immunoreactive (ir) neurons and fibers were examined in the forebrain of male and female common marmosets (*Callithrix jacchus*). As expected from previous studies of cell distribution in the rodent and primate brain, AVP-ir cells were most evident in the paraventricularis, supraopticus, and suprachiasmaticus of the hypothalamus. AVP-ir cells were also widely distributed in the lateral hypothalamus and the bed nucleus of the stria terminalis. A sexually dimorphic pattern of AVP-ir cells was found in the bed nucleus of the stria terminalis, in which males had more AVP-ir cells than females. OT-ir cells were found in the paraventricularis and supraopticus of the hypothalamus as well as in the bed nucleus of the stria terminalis and the medial amygdala. Male and female marmosets did not differ in the distribution of OT-ir cells. Fibers for both AVP and OT were evident outside of the hypothalamic-neurohypophyseal tract, but a plexus of AVP-ir fibers in the lateral septum or lateral habenular nucleus, as seen in the rat brain, could not be detected for either peptide. **Synapse 27:14–25, 1997.**

INTRODUCTION

Vasopressin (AVP) and oxytocin (OT) are neuropeptide hormones that are primarily synthesized in magnocellular hypothalamic neurons and released via the posterior pituitary into the bloodstream, where they influence the maintenance of fluid homeostasis and blood pressure (Cowley and Liard, 1987; Valtin, 1987) and, in the case of OT, regulate uterine contraction and milk ejection (Cunningham and Sawchenko, 1991; Fuchs, 1985). AVP and OT are also produced by parvocellular hypothalamic neurons as well as in extrahypothalamic areas, such as the bed nucleus of the stria terminalis (ST) and medial amygdala (MAm), with projections to targets within the central nervous system where AVP and OT appear to act as neurotransmitters (Buijs, 1983; Caffé et al., 1987; De Vries and Buijs, 1983).

The distribution and characteristics of central AVP and OT pathways have been extensively studied in rodents. For example, AVP-producing neurons in the ST and MAm, as well as their projections to the lateral septum and lateral habenular nucleus, are sexually dimorphic—male rats have more AVP immunoreactive (AVP-ir) or AVP mRNA-labeled cells and denser projections than female rats (De Vries et al., 1981; Miller et al., 1989b; van Leeuwen et al., 1985; Wang and De Vries, 1995). These sexual dimorphisms are dependent upon gonadal steroids. Castration reduces AVP-ir staining and AVP mRNA expression, whereas testosterone treatment reverses these changes (De Vries et al., 1984; Miller et al., 1989a; van Leeuwen et al., 1985; Wang and De Vries, 1995). Oxytocin immunoreactive (OT-ir) pathways in the brain do not appear to be sexually dimorphic or steroid-dependent (Buijs et al., 1978; De Vries et al., 1986; Sofroniew and Weindl, 1981).

Central AVP or OT pathways show dramatic differences among mammalian species. For example, the dense cluster of AVP-ir fibers in the lateral septum found in rats and other rodents is not found in rabbit (Buijs, unpublished observations), cat (Caffé and Hol-

Contract grant sponsor: NIMH; Contract grant numbers: 54368, 54554, P51-RR00165.

*Correspondence to: Thomas R. Insel, Department of Psychiatry and Behavioral Sciences, Emory University School of Medicine, Atlanta, GA 30322. Email: insel@rmy.emory.edu

Received 3 September 1996; Accepted 22 November 1996

stege, unpublished observations), monkey (Caffé et al., 1989), or human brain (Fliers et al., 1986). Previous studies in primates have examined AVP-ir or OT-ir pathways (or their mRNA expression) in the hypothalamus of cynomolgus, rhesus, and squirrel monkeys as well as in humans (Caffé et al., 1989; Fliers et al., 1986; Ichimiya et al., 1988; Kawata and Sano, 1982; Sofroniew and Weindl, 1980; Sukhov et al., 1993; Ueda et al., 1983). In the present study, we examined the distribution of AVP and OT immunoreactive neurons and fibers throughout the forebrain of male and female common marmosets (*Callithrix jacchus*). Marmosets are members of the *Callithricidae*, a New World primate family characterized by group care of infants, twin births, and varying degrees of monogamy (Stevenson and Rylands, 1988). The objectives of the present study were to define the distribution pattern of AVP and OT immunoreactivity and to determine if sexual dimorphisms could be detected in a monogamous primate.

MATERIALS AND METHODS

Subjects

Subjects in this study were laboratory-born male and female common marmosets (*Callithrix jacchus*) living in family groups. Animals were housed in wire mesh cages (61 × 61 × 152 cm) provided with branches, PVC sleeping enclosures, plastic ladders, and swings. The colony room was provided with full spectrum fluorescent lights on a 12:12 h light-dark photoperiod with lights on at 0700. The humidity was controlled at about 60%, and the temperature was about 25°C. Animals were fed Zupreem (Hills Bros., Topeka, KS) twice daily and a slurry consisting of water, monkey chow, apple sauce, bananas, Poly-Vi-Sol vitamins without iron, Purina New World monkey chow (Ralston Purina, St. Louis, MO) and Karo syrup once a day. Several times per week the diet was supplemented with fresh fruit, mealworms, and peanuts. Purina New World dry monkey chow and water were provided ad libitum.

Subjects were anesthetized with sodium pentobarbital (60 mg/kg body weight) and perfused through the ascending aorta with 0.9% saline, followed by 5% acrolein in 0.1 M phosphate buffer (PBS), pH 7.6. Brains were removed, stored in 30% sucrose for 72 h, and then cut into 50 µm transverse sections with a microtome. Floating sections were stored in 0.1 M PBS at 4°C until they were processed for immunocytochemistry. To reduce variability in the background, we processed all sections in the same immunocytochemical staining.

Vasopressin immunocytochemistry

Brain sections from three male and three female marmosets at 150 µm intervals were processed for vasopressin immunoreactivity (AVP-ir). Floating sections were rinsed 3 × 15 min in 0.05 M Tris-HCl containing 0.9% NaCl (Tris-NaCl, pH 7.6), treated with 0.1% sodium borohydride for 15 min, and then rinsed again 3 × 5 min in Tris-NaCl. Sections were incubated 10 min in Tris-NaCl with 0.5% Triton (Tris-Triton) and 20% goat serum and 90 min in rabbit-anti-AVP serum (ICN, Lisle, IL) 1:4,000 in Tris-Triton containing 2% goat serum (TTG) at 37°C. The sections were then rinsed 3 × 5 min in TTG, incubated 60 min in biotinilated goat-anti-rabbit 1:300 in TTG at room temperature, rinsed 2 × 5 min in TTG and 2 × 5 min in Tris-NaCl, incubated 60 min in ABC complex, and rinsed 3 × 5 min in Tris-NaCl. Floating sections were stained with 0.05% 3-3′-diamino-benzidine (DAB) in Tris-NaCl with 0.003% H_2O_2. After three rinses in Tris-NaCl, sections were mounted on slides, air-dried, and coverslipped. Specificity control of antiserum was tested by staining the alternative sections with anti-AVP serum that was pretreated with 50 µM AVP, which eliminated specific staining, or with anti-AVP serum that was pretreated with 50 µM OT, which did not reduce staining.

Oxytocin immunocytochemistry

Another set of brain sections from three male and three female common marmosets at 150 µm intervals was processed for oxytocin immunoreactivity (OT-ir). Similar to AVP-ir staining, brain sections were treated with 0.1% sodium borohydride, rinsed with Tris-NaCl, and incubated in Tris-Triton with 20% goat serum. Sections were then incubated in rabbit-anti-OT serum (gift from Dr. Mariana Morris, Bowman Gray School of Medicine), 1:20,000, 72 h at 4°C, biotinilated goat-anti-rabbit, 1:300, 60 min at room temperature, and ABC complex, 60 min at room temperature. Sections were stained by DAB with H_2O_2 in Tris-NaCl. Control sections were incubated with rabbit-anti-OT serum that was pretreated with 50 µM OT, which eliminated specific staining. Conversely, pretreatment of rabbit-anti-OT serum with 50 µM AVP did not reduce staining.

Data quantification and analysis

Slides were coded so that the experimenter was not aware of the identity of the subjects. Diagrammatic representative brain sections from Stephan et al. (1980) were used for defining anatomic regions in the marmoset brain. All brain sections were initially examined with the ×4 objective under a microscope. For each brain area, three to five sections that spanned the area with the highest number of AVP-ir or OT-ir cells were chosen for further examination under the ×20 objective. The number of AVP-ir cells in the stria terminalis (ST), area of praeoptica periventricularis (APP), suprachiasmaticus hypothalami (ScH), and area of lateralis hypothalami (ALH) and of OT-ir cells in the APP, ST, and ALH was counted bilaterally in the sections for each brain area. For data analysis, sections that con-

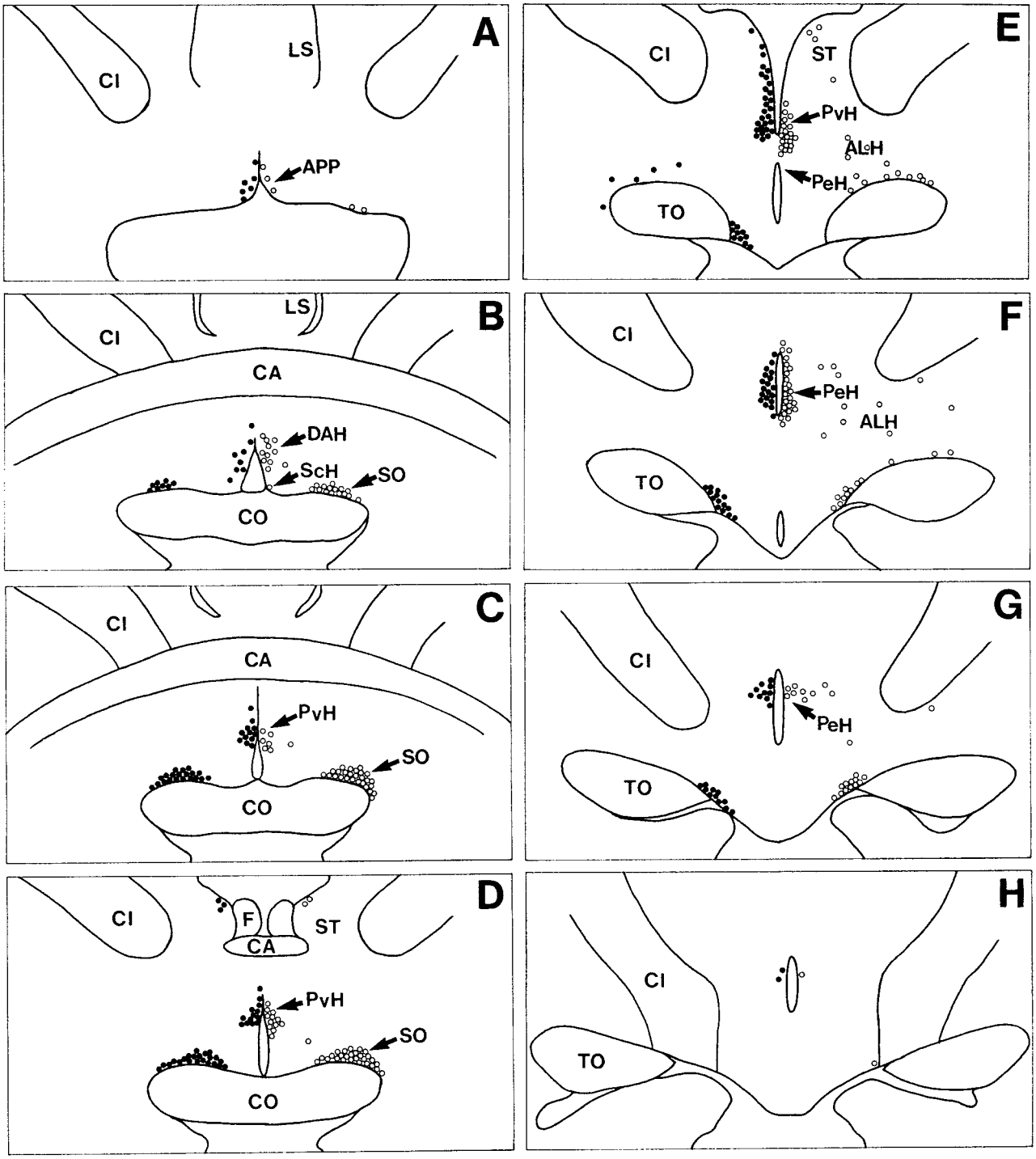

Fig. 1. Camera lucida drawing of series of paired sections stained for AVP (right, open circles) and OT (left, solid dots) immunoreactive cells in a common marmoset. Coronal sections spaced at 600 µm intervals are shown with A, most rostral and H, most caudal. Each dot represents three to four cells. ALH, area of lateralis hypothalami; APP, area of praeoptica periventricularis; CA, commissurae anterioris; CI, capsula interna; CO, chiasma opticum; DAH, dorsalis anterior hypothalami; F, fornix; LS, lateralis septi; PeH, periventricularis hypothalami; PvH, paraventricularis hypothalami; ScH, suprachismaticus hypothalami; SO, supraopticus hypothalami; ST, stria terminalis; TO, tractus opticus.

tained the highest number of AVP-ir or OT-ir cells on each side of the brain area were chosen, and the average from both sides of each area was used to represent each subject. The number of AVP-ir or OT-ir cells in each brain area between males and females was analyzed by a Student's *t*-test.

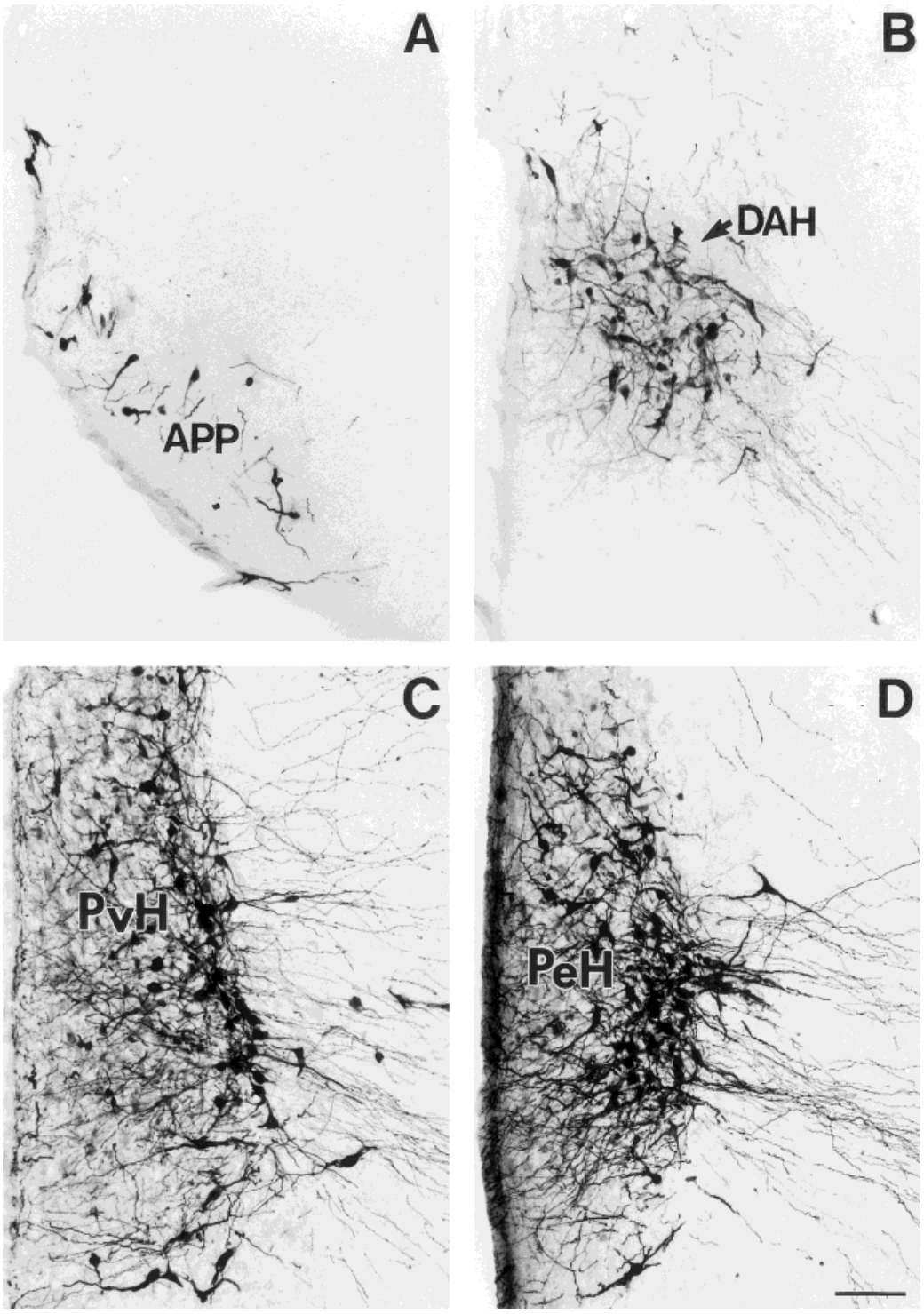

Fig. 2. Photomicrographs displaying AVP-ir cells in the praeoptica periventricularis (APP) (**A**), dosalis anterior hypothalami (DAH) (**B**), paraventricularis hypothalami (PvH) (**C**), and periventricularis hypothalami (PeH) (**D**) of a common marmoset. Scale bar = 100 µm.

RESULTS

AVP immunoreactivity

The distribution of AVP-ir cells in the hypothalamus of common marmosets is illustrated in Figure 1. A small number of AVP-ir cells that were either bipolar or multipolar were found in the area of praeoptica periventricularis (APP) (Fig. 2A) and dorsalis anterior hypothalami (DAH) (Fig. 2B), but in general there was no

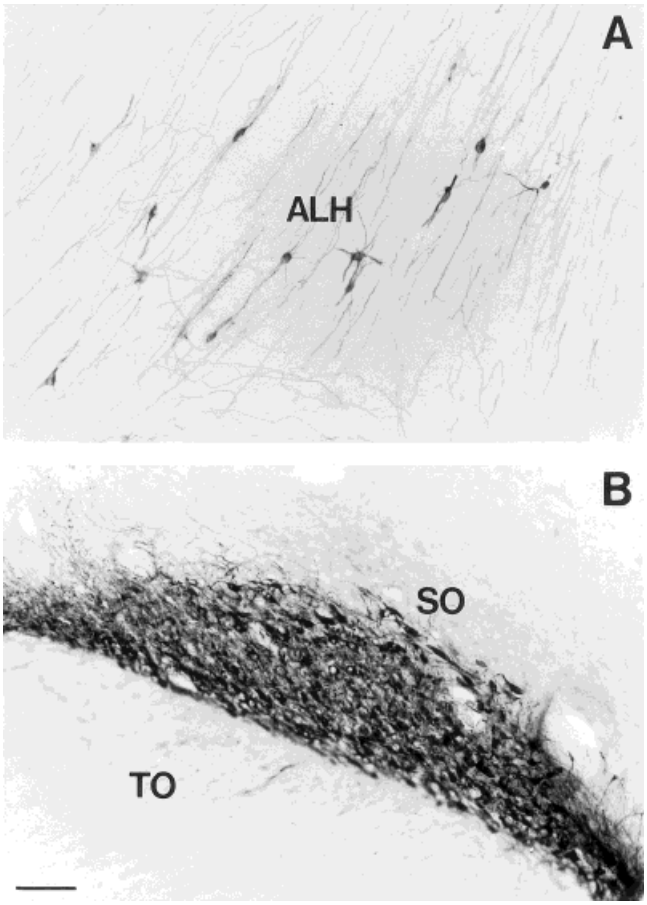

Fig. 3. Photomicrographs displaying AVP-ir cells in the area of lateralis hypothalami (ALH) (**A**) and supraopticus hypothalami (SO) (**B**) of a common marmoset. TO, tractus opticus. Scale bar = 100 μm.

clear demarcation between magnocellular and parvocellular immunopositive neurons anywhere in the hypothalamus. A dense cluster of AVP-ir cells was found in the paraventricularis hypothalami (PvH) (Fig. 2C) and caudally in the periventricularis hypothalami (PeH) (Fig. 2D). In addition, clustered AVP-ir cells were also found in the supraopticus (SO) (Fig. 3B). The number of these cells increased caudally and then expanded in a trapezoid appearance, followed by division into dorsolateral and dorsomedial parts. Scattered multipolar AVP-ir cells were found in the area of lateralis hypothalami (ALH) (Fig. 3A) and stria terminalis (ST) (Fig. 4). Finally, a few AVP-ir cells were found in the suprachiasmaticus hypothalami (ScH). The number of AVP-ir cells were counted bilaterally in the ST, APP, ScH, and ALH. The only area that showed a sexually dimorphic pattern of AVP-ir was the ST, in which males had more AVP-ir cells than females ($t = 5.00$, $n = 4$, $P < 0.01$) (Figs. 4, 5). Due to the overlap of stained cells in the SO, PvH, and PeH, the number of AVP-ir cells in these areas could not be counted reliably. However, male and female common marmosets did not show evident differences in the number of AVP-ir cells in these areas.

Dense AVP-ir fibers from the SO projected towards the infundibulum forming neurohypophyseal tract, while some other fibers projected dorsally to the lateralis hypothalami. Dense AVP-ir cells in the PvH appeared throughout the rostrocaudal extent and also in the PeH regions. Fibers from these AVP-ir cells projected ventrolateral to the SO and dorsal to the ST. Some fibers also projected towards the third ventricle, where they ended at the subependymal layers.

In addition to the heavy staining of AVP-ir fibers that formed the paraventriculo-supraoptico-neurohypophyseal tract, scattered AVP-ir fibers were found in the nucleus accumbens (AC) (Fig. 6B), septi, fasciculi diagonalis brocae (DB), praeoptica lateralis (APL) (Fig. 6D) and the ST (Fig. 6C). A few AVP-ir fibers were found in the lateralis septi (LS) (Fig. 6A), but these fibers did not form a plexus as found in rodents. In the medialis posterior septi, scattered AVP-ir fibers extended ventral to the fasciculi diagonalis brocae (DB). The stria terminalis, particularly the pars interna, also contained AVP-ir fibers. In the rostral part, AVP-ir fibers were found in the pars interna adjacent to the lateral ventricle and extended from superior to the inferior of the commissurae anterioris (CA). In the caudal part, AVP-ir fibers from the pars interna extended to the PvH and SO, respectively. AVP-ir fibers were not detected in any aspect of the amygdalae (Am).

OT immunoreactivity

The distribution of OT-ir cells in the brain of common marmosets is also illustrated in Figure 1. A small number of OT-ir cells were found in the APP and DAH (Fig. 7A,B), whereas clustered OT-ir cells were found in the PvH, PeH (Fig. 7C,D), and SO (Fig. 8B). Scattered OT-ir neurons were found in the ST, especially in the area of pars interna that ventrally borders the ventricular wall (Fig. 8A). A few OT-ir cells were found in the dorsal aspects of the medialis amygdalae (MAm) and in the ALH. No OT-ir cells were found in the ScH. The number of OT-ir cells in the APP, ST, and ALH were counted bilaterally, and male and female common marmosets did not differ in the number of OT-ir cells in any of these areas (Fig. 9). OT-ir cells were overlapped in the SO, PvH, and PeH and thus could not be counted reliably. However, there did not appear to be noticeable differences between males and females.

OT-ir fibers also formed a clear paraventriculo-supraoptico-neurohypophyseal tract. In addition, OT-ir fibers were found in the APP, ST (Fig. 10A), PeH, and the MAm (Fig. 10C), where OT-ir cells were present. OT-ir fibers were also found in the ventromedialis hypothalami (Vm) (Fig. 10B) and corticalis amygdalae (CAm) (Fig. 10D) in which no OT-ir cells were detected.

DISCUSSION

In the present study, we used immunocytochemistry to map the distribution of AVP and OT immunoreactiv-

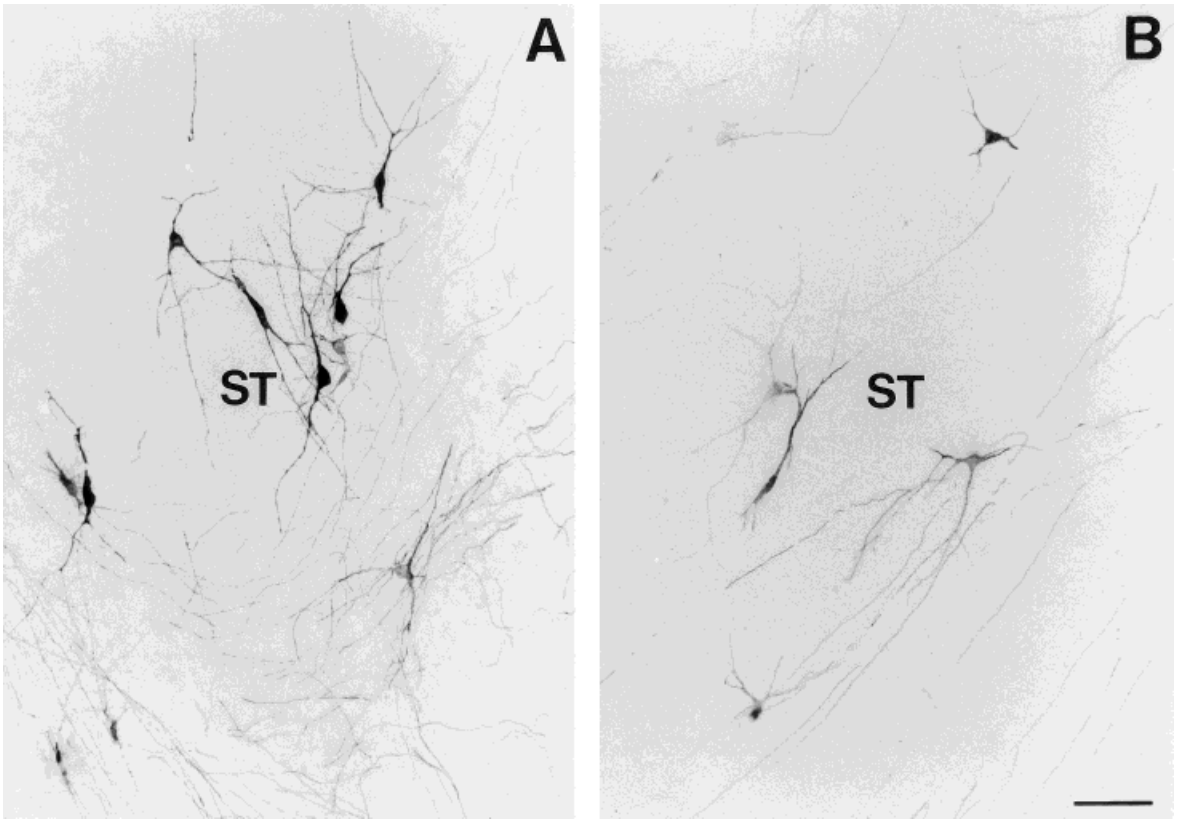

Fig. 4. Photomicrographs displaying AVP-ir cells in the stria terminalis (ST) of a male (**A**) and a female (**B**) common marmoset. Scale bar = 100 μm.

ity in the forebrain of male and female common marmosets. Previous studies have demonstrated a conserved pattern of immunostaining across mammals, with AVP cells present in the PvH, SO, and ScH and OT cells in the PvH and SO. The current study extended this map to a New World primate and found some variations from previous reports in other mammalian species.

The distribution of AVP-ir cells and fibers in the SO, PvH, and ScH and of OT-ir cells and fibers in the SO and PvH in the common marmosets was in agreement with previous reports in other species of primates (Caffé et al., 1989; Fliers et al., 1986; Ginsberg et al., 1994; Kawata and Sano, 1982). However, the distribution pattern of AVP-ir cells in the ST was unexpected. AVP-ir cells in the ST were found in the area adjacent to the lateral ventricle as well as in the ventromedial part of the ST in the common marmosets. In the macaque monkey (Caffé et al., 1989; Ginsberg et al., 1994) and the human (Fliers et al., 1986), most of the AVP cells in the ST were found in the area adjacent to the lateral ventricle (few cells were found in the ventromedial part of the ST in the macaque monkey [cf. Caffé et al., 1989]), whereas in rats these cells were found mostly in the ventromedial part of the ST (De Vries et al., 1994; Miller et al., 1989b; van Leeuwen and Caffé, 1983). The pattern of AVP cell distribution in the ST in marmosets

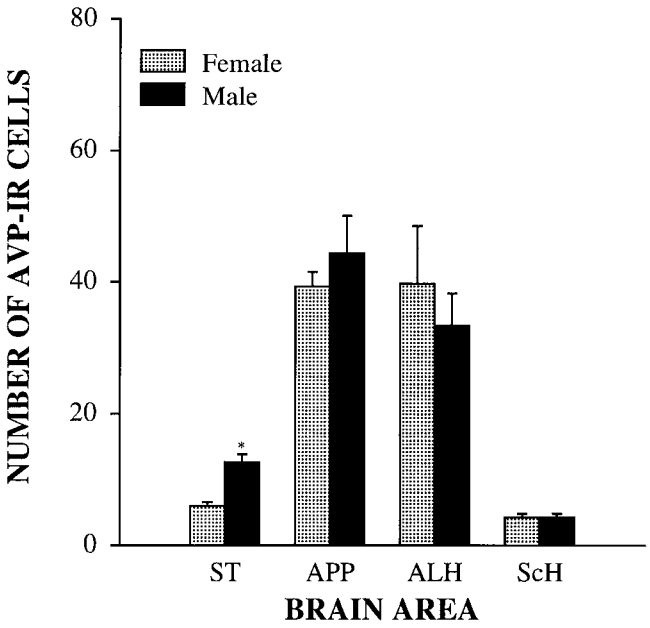

Fig. 5. Mean number of AVP-ir cells per section in the stria terminalis (ST), praeoptica periventricularis (APP), lateralis hypothalami (ALH), and suprachiasmaticus hypothalami (ScH) in female and male common marmosets. Females had fewer AVP-ir cells in the ST than males (*$P < 0.05$). Error bars indicate standard errors of the means.

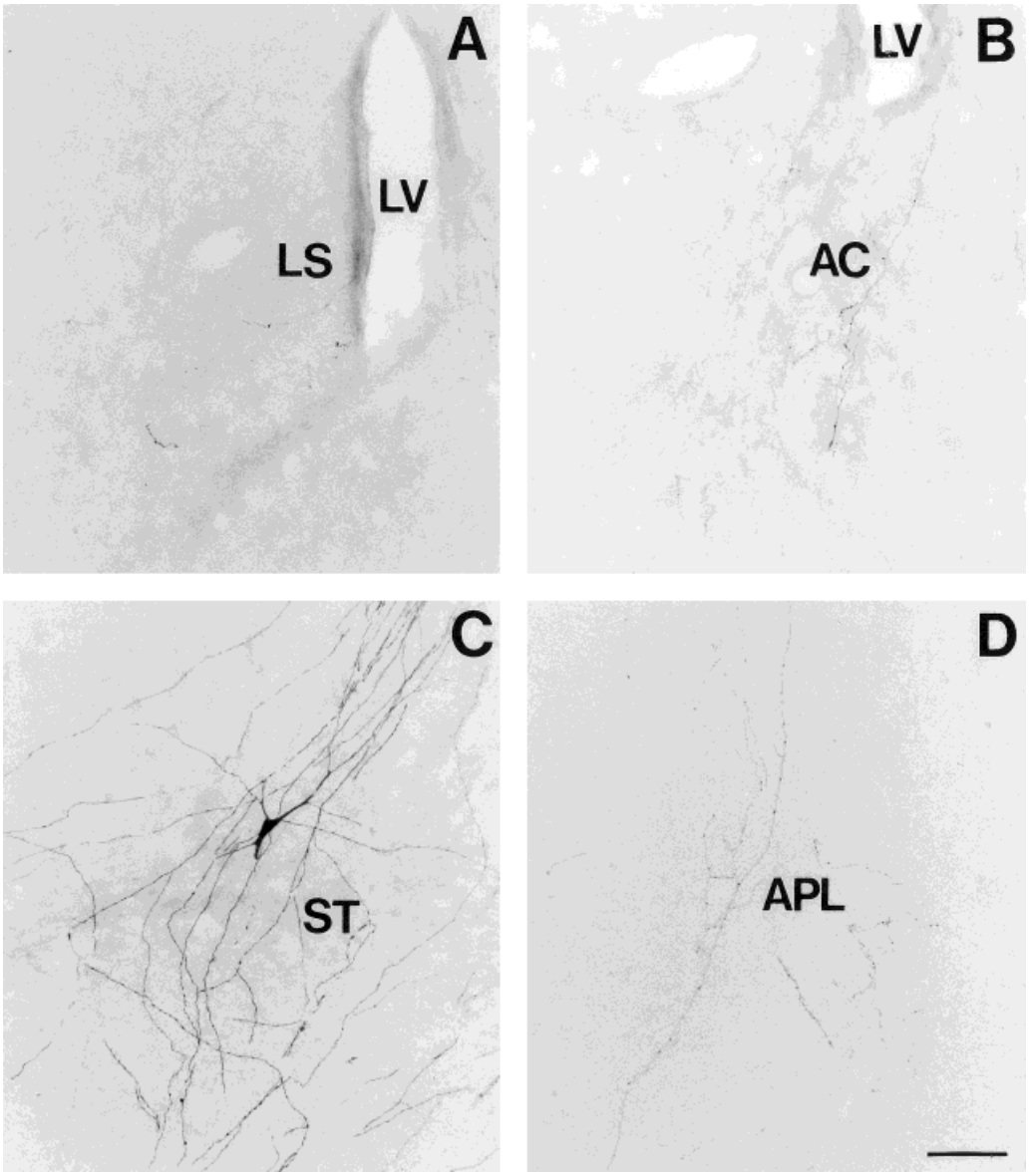

Fig. 6. Photomicrographs displaying AVP-ir fibers in the lateralis septi (LS) (**A**), nucleus accumbens (AC) (**B**), stria terminalis (ST) (**C**), and praeoptica lateralis (APL) (**D**) of a common marmoset. LV, lateral ventricle. Scale bar = 100 μm.

may represent a transitional expression of the AVP cell distribution between rodents and Old World primates.

In previous studies in primates, although the number of AVP-ir cells in the ST was not counted, there was no indication of a sexual dimorphism (Caffé et al., 1989; Fliers et al., 1986; Ginsberg et al., 1994). In the current study, male marmosets had more AVP-ir cells in the ST than females, suggesting a sexually dimorphic AVP pathway in the ST. Such a sexually dimorphic AVP pathway has been found in a variety of rodent species such as rats, mice, gerbils, and voles (Crenshaw et al., 1992; Hermes et al., 1990; van Leeuwen et al., 1985; Wang et al., 1996b). In rodents, steroid hormones regulate this sexually dimorphic AVP pathway through an androgen- or estrogen-mediated mechanism (Axelson and van Leeuwen, 1990; De Vries et al., 1994; Zhou et al., 1994). The mechanism in the marmoset is still unknown. Although male marmosets had more androgen immunoreactive neurons in the ST than females, no colocalization between androgen and AVP immunoreactivity was detected (Wang et al., 1996a).

The sexually dimorphic structures are usually found to generate sex differences in behavior and function. For example, sexually dimorphic AVP-ir pathways in the LS play an important role in social recognition in male but not female rats (Bluthe and Dantzer, 1990; Bluthe et al., 1990; Dantzer et al., 1988). Why do the marmosets, with few gender differences in anatomy

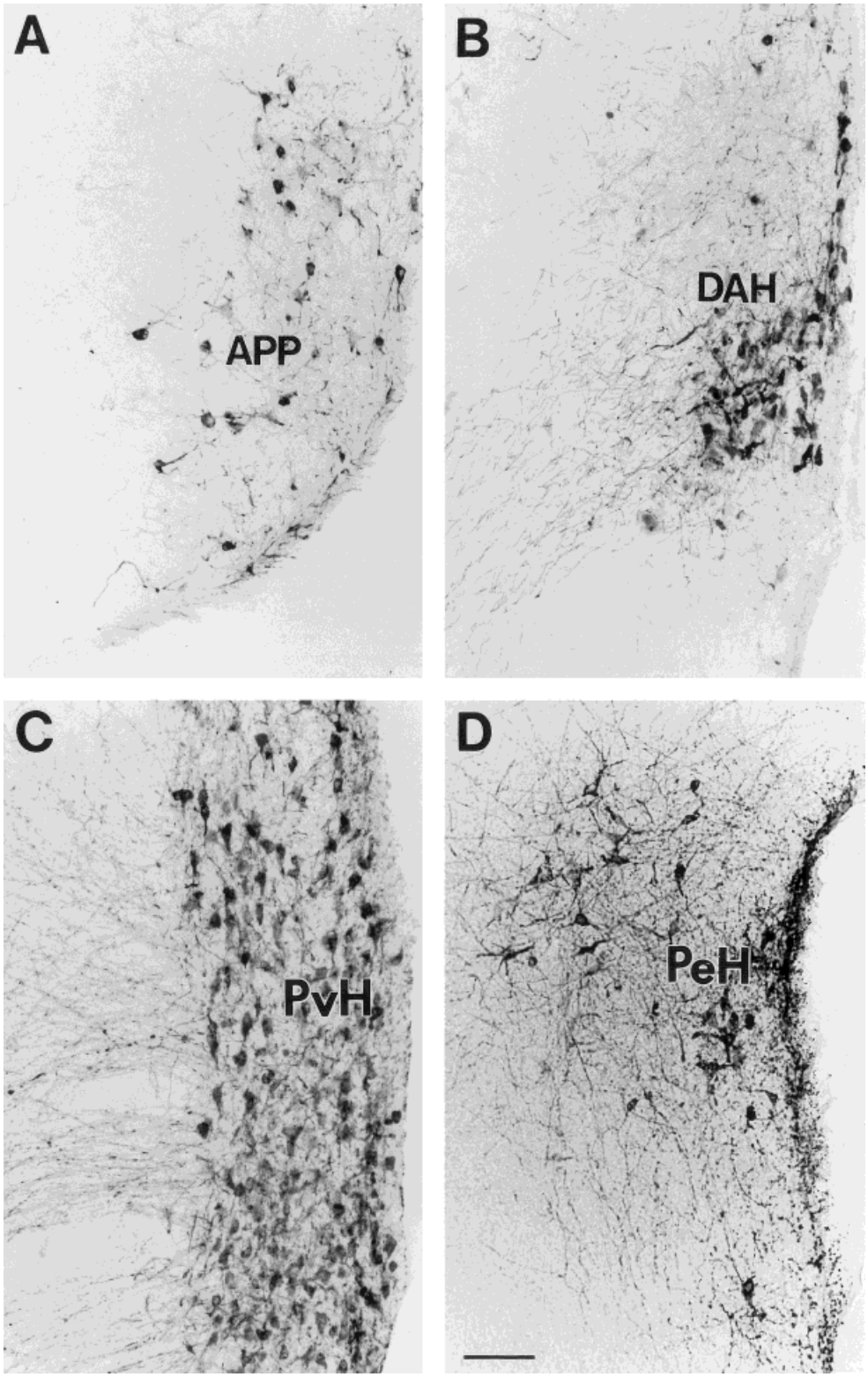

Fig. 7. Photomicrographs displaying OT-ir cells in the praeoptica periventricularis (APP) (**A**), dosalis anterior hypothalami (DAH) (**B**), paraventricularis hypothalami (PvH) (**C**), and periventricularis hypothalami (PeH) (**D**) of a common marmoset. Scale bar = 100 µm.

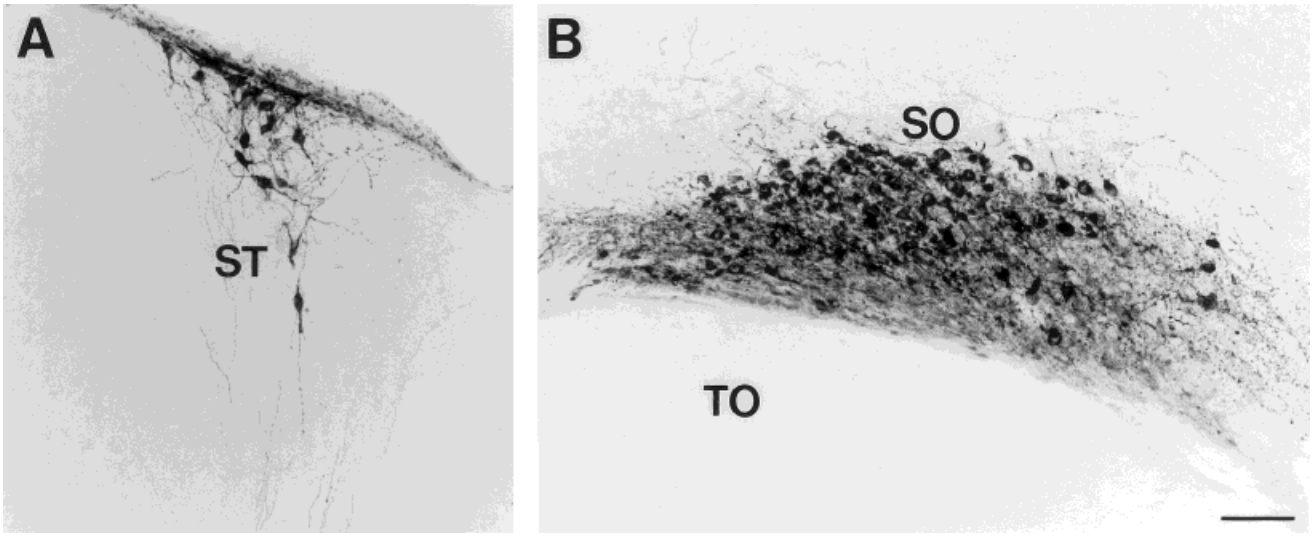

Fig. 8. Photomicrographs displaying OT-ir cells in the stria terminalis (ST) (**A**) and supraopticus hypothalami (SO) (**B**) of a common marmoset. TO, tractus opticus. Scale bar = 100 µm.

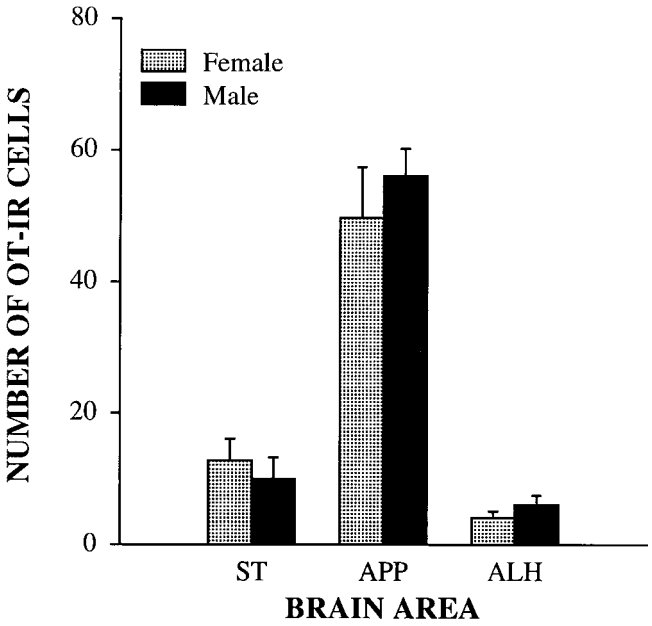

Fig. 9. Mean number of OT-ir cells per section in the stria terminalis (ST), praeoptica periventricularis (APP), and lateralis hypothalami (ALH) in female and male common marmosets. Error bars indicate standard errors of the means.

and behavior, show evidence of a gender difference in AVP-ir distribution? In rodents, monogamous prairie voles that exhibit mating-induced pair bonding and biparental care also have sexually dimorphic AVP-ir pathways in the ST and LS (Bamshad et al., 1993; Wang et al., 1996b). OT is found to facilitate female pair bonding, whereas AVP plays an important role in male pair bonding and parental care (Wang et al., 1994; Williams et al., 1994; Winslow et al., 1993). These data suggest that the sexually dimorphic structures also enable animals to display certain behavior and function in remarkably similar ways between males and females although their physiological conditions differ dramatically. Nevertheless, the functional significance of the gender dimorphic AVP pathways in the marmoset needs to be further studied.

AVP-ir or OT-ir fibers were found in various brain regions in the marmoset, and their distribution patterns are similar to the pattern found in other species of primates (Caffé et al., 1989; Fliers et al., 1986; Ginsberg et al., 1994). In the present study, we did not detect a plexus of AVP-ir fibers in either the lateral septum or the lateral habenular nucleus in common marmosets. In rodents, a plexus is evident in both of these regions (in males more than in females) due to a dense projection from the ST and MAm (Caffé et al., 1987; De Vries and Buijs, 1983; De Vries et al., 1985). These sexually dimorphic AVP projections play an important role in physiological and behavioral functions in rodents such as temperature regulation (Demotes-Mainard et al., 1986), aggression (Compaan et al., 1993; Koolhass et al., 1990), learning, and memory (Bluthe et al., 1990; Dantzer et al., 1988). Lack of AVP-ir fibers in the lateral septum and lateral habenular nucleus from the present study is consistent with a previous study in macaques, which also failed to detect a plexus of AVP-ir fibers in both areas (Caffé et al., 1989). Similarly, only a small number of AVP-ir fibers in the lateral septum was found in the human brain (Fliers et al., 1986). This discrepancy between primates and rats suggests that, in primates, AVP neurons in the ST may project to different target sites.

It should be noted that immunocytochemistry as performed in the current study may be underestimating the number of AVP- (and OT-) positive cells. In

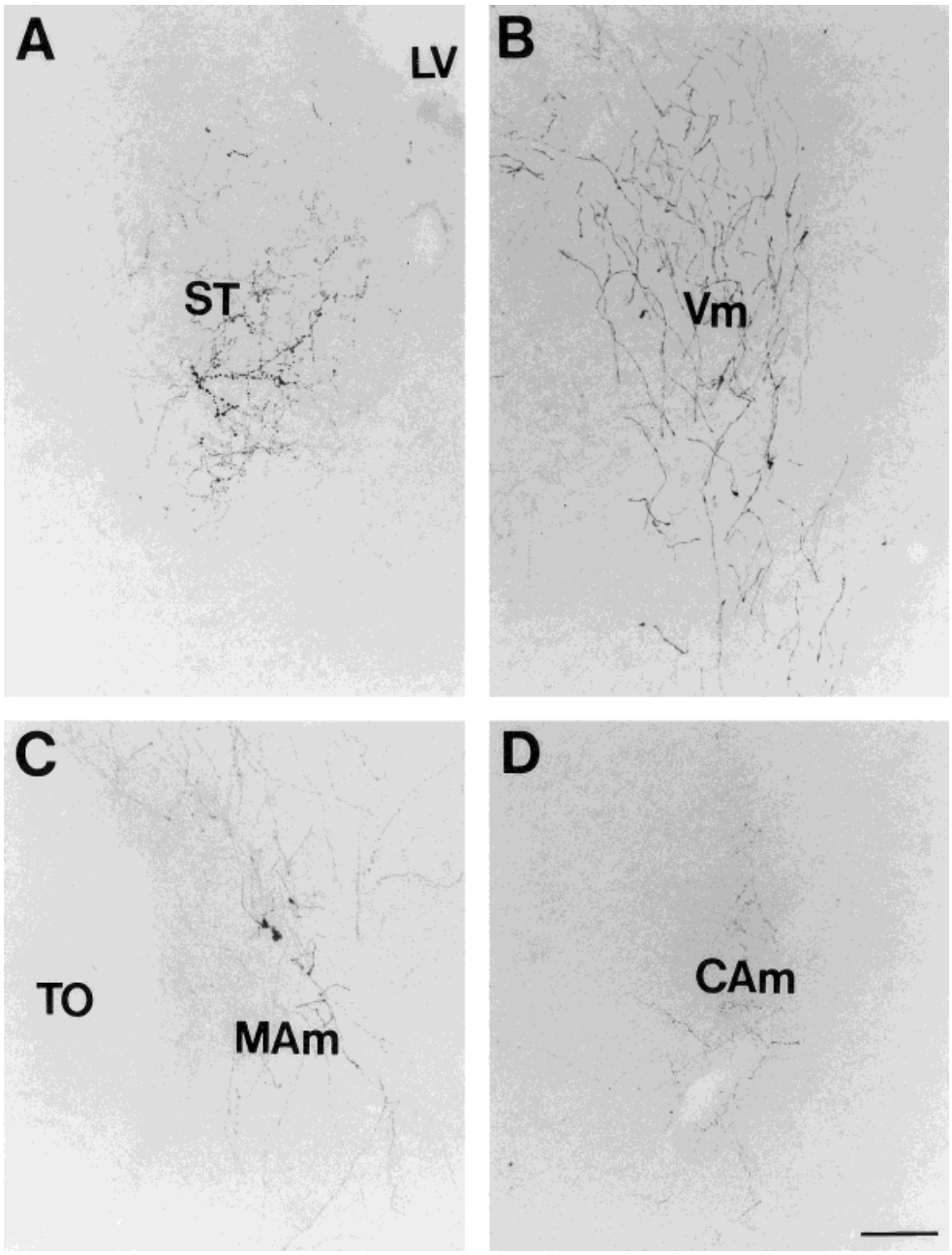

Fig. 10. Photomicrographs displaying OT-ir fibers in the stria terminalis (ST) (**A**), ventromedialis hypothalami (Vm) (**B**), medialis amygdalae (MAm) (**C**), and corticalis amygdalae (CAm) (**D**) of a common marmoset. LV, lateral ventricle; TO, tractus opticus. Scale bar = 100 µm.

rodents, AVP cells in the ST and MAm could be examined reliably only by using in situ hybridization to label AVP mRNA (Miller et al., 1989b; Wang and De Vries, 1995) or by using immunocytochemistry on animals that were treated with colchicine to visualize these cells (Miller et al., 1992; van Leeuwen and Caffé, 1983). In the monkey, AVP-ir cells in the extrahypothalamic areas could not be observed consistently in the animals that received no colchicine treatment (Caffé et al., 1989). Although this would not be expected to differentially affect males and females, it seems likely that the total number of AVP-producing cells in the ST is greater than detected in the present study. In addition, we noticed that the density and distribution of AVP-ir fibers in marmosets, especially in the extrahypothalamic areas in the present study, were less than that in colchicine-treated Macaca monkeys (Caffé et al., 1989). It is not clear whether the peptide concentration in these areas was below the detectable level by immunocytochemistry and whether colchicine treatment will

enhance fiber staining, although it did not have obvious effects on Macaca monkeys (Caffé et al., 1989) and rats (G.J. De Vries, personal communication).

In conclusion, AVP and OT immunoreactivities in the brain of the common marmoset, a New World primate, generally resembled previous reports in rodents and Old World primates. Male marmosets had more AVP-ir cells in the ST than females, indicating a sexual dimorphism found previously in rodents. In addition, no AVP-ir plexus was found in the lateral septum, suggesting that AVP cells in the ST in the marmoset may project into different brain areas. The mechanism for the sexually dimorphic AVP pathways in the ST and lack of AVP-ir fibers in the lateral septum in common marmosets need to be further studied.

ACKNOWLEDGMENTS

We thank Dr. Larry J. Young for critically reading the manuscript and Mr. Frank Kiernan for his professional assistance for photomicrographs. This research was partially supported by NIMH 54368 and 54554 to Z.X. Wang and P51-RR00165 to T.R. Insel.

REFERENCES

Axelson, J.F., and van Leeuwen, F.W. (1990) Differential localization of estrogen receptors in various vasopressin synthesizing nuclei of the rat brain. J. Neuroendocrinol., 2:209–216.

Bamshad, M., Novak, M.A., and De Vries, G.J. (1993) Sex and species differences in the vasopressin innervation of sexually naive and parental prairie voles, *Microtus ochrogaster*, and meadow voles, *Microtus pennsylvanicus*. J. Neuroendcrinol., 5:247–255.

Bluthe, R.M., and Dantzer, R. (1990) Social recognition does not involve vasopressinergic neurotransmission in female rats. Brain Res., 535:301–304.

Bluthe, R.M., Schoenen, J., and Dantzer, R. (1990) Androgen-dependent vasopressinergic neurons are involved in social recognition in rats. Brain Res., 519:150–157.

Buijs, R.M. (1983) Vasopressin and oxytocin—their role in neurotransmission. Pharmacol. Ther., 22:127–141.

Buijs, R.M., Swaab, D.F., Dogterom, F.W., and van Leeuwen, F.W. (1978) Intra- and extrahypothalamic vasoprressin and oxytocin pathways in the rat: Pathways to the limbic system, medulla oblongata and spinal cord. Cell Tissue Res., 186:423–435.

Caffé, A.R., van Leeuwen, F.W., and Luiten, P.G.M. (1987) Vasopressin cells in the medial amygdala of the rat project to the lateral septum and ventral hippocampus. J. Comp. Neurol., 261:237–252.

Caffé, A.R., van Ryen, P.C., vand der Voude, T.P., and van Leeuwen, F.W. (1989) Vasopressin and oxytocin systems in the brain and upper spinal cord of *Macaca fascicularis*. J. Comp. Neurol., 287:302–325.

Compaan, J.C., Buijs, R.M., Pool, C.W., de Ruiter, A.J.H., and Koolhaas, J.M. (1993) Differential lateral septal vasopressin in aggressive and non aggressive mice. Brain Res. Bull., 30:1–6.

Cowley, A.S., and Liard, J.F. (1987) Cardiovascular actions of vasopressin. In: Vasopressin, Principles and Properties. D.M. Gash and G.J. Boer, eds. Plenum, New York, pp. 389–433.

Crenshaw, B.J., De Vries, G.J., and Yahr, P. (1992) Vasopressin innervation of sexually dimorphic structures of the gerbil fore brain under various hormonal conditions. J. Comp. Neurol., 322:1–10.

Cunningham, E.T., and Sawchenko, P.E. (1991) Reflex control of magnocellular vasopressin and oxytocin secretion. Trends Neurosci., 14:406–411.

Dantzer, R., Koob, G.F., Bluthe, R.M., and Le Moal, M. (1988) Septal vasopressin modulates social memory in male rats. Brain Res., 457:143–147.

Demotes-Mainard, J., Chauveau, J., Rodrigues, F., Vincent, J.D., and Poulain, D.A. (1986) Septal release of vasopressin in response to osmotic, hypovolemic and electrical stimulation in rats. Brain Res., 381:314–321.

De Vries, G.J., and Buijs, R.M. (1983) The origin of vasopressinergic and oxytocinergic innervation of the rat brain with special reference to the lateral septum. Brain Res., 273:307–317.

De Vries, G.J., Buijs, R.M., and Swaab, D.F. (1981) Ontogeny of the vasopressinergic neurons of the suprachiasmatic nucleus and their extrahypothalamic projections in the rat brain–presence of a sex difference in the lateral septum. Brain Res., 218:67–78.

De Vries, G.J., Buijs, R.M., and Sluiter, A.A. (1984) Gonadal hormone actions on the morphology of the vasopressinergic innervation of the adult rat brain. Brain Res., 298:141–145.

De Vries, G.J., Buijs, R.M., van Leeuwen, F.W., Caffé, A.R., and Swaab, D.F. (1985) The vasopressinergic innervation of the brain in normal and castrated rats. J. Comp. Neurol., 233:236–254.

De Vries, G.J., Duetz, W., Buijs, R.M., Heerikhuize, J.V., and Vreeburg, J.R.M. (1986) Effects of androgen and estrogen on the vasopressin and oxytocin innervation of the adult rat brain. Brain Res., 399:296–302.

De Vries, G.J., Wang, Z.X., Bullock, N.A., and Numan, S. (1994) Sex differences in the effects of testosterone and its metabolites on vasopressin messenger RNA levels in the bed nucleus of the stria terminalis. J. Neurosci., 14:1789–1794.

Fliers, E., Guldenaar, S.E.F., van der Wal, N., and Swaab, D.F. (1986) Extrahypothalamic vasopressin and oxytocin in the human brain: Presence of vasopressin cells in the bed nucleus of the stria terminalis. Brain Res., 375:363–367.

Fuchs, A.R. (1985) Oxytocin in animal parturition. In: Oxytocin, Clinical and Laboratory Studies. J.A. Amico and A.G. Robinson, eds. Elsevier Science, Amsterdam, pp. 207–235.

Ginsberg, S.D., Hof, P.R., Young, W.G., and Morrison, J.H. (1994) Noradrenergic innervation of vasopressin- and oxytocin-containing neurons in the hypothalamic paraventricular nucleus of the macaque monkey: Quantitative analysis using double-label immunohistochemistry and confocal laser microscopy. J. Comp. Neurol., 341: 476–491.

Hermes, M.L., Buijs, R.M., Masson-Pevet, M., and Pevet, P. (1990) Seasonal changes in vasopressin in the brain of the garden dormouse (*Eliomys quercinusl*). J. Comp. Neurol., 293:340–346.

Ichimiya, Y., Emson, P.C., and Shaw, F.D. (1988) Localization of vasopressin mRNA-containing neurons in the hypothalamus of the monkey. Brain Res., 464:81–85.

Kawata, M., and Sano, Y. (1982) Immunohistochemical identification of the oxytocin and vasopressin neurons in the hypothalamus of the monkey (*Macaca fuscata*). Anat. Embryol., 165:151–167.

Koolhass, J.M., van den Brink, T.H.C., Roozendaal, B., and Boorsma, F. (1990) Medial amygdala and aggressive behavior: Interaction between testosterone and vasopressin. Aggressive Behav., 16:223–229.

Miller, M.A., Urban, J.A., and Dorsa, D.M. (1989a) Steroid dependency of vasopressin neurons in the bed nucleus of the stria terminalis by in situ hybridization. Endocrinology, 125:2335–2340.

Miller, M.A., Vician, L., Clifton, D.K., and Dorsa, D.M. (1989b) Sex differences in vasopressin neurons in the bed nucleus of the stria terminalis by in situ hybridization. Peptides, 10:615–619.

Miller, M.A., De Vries, G.J., Al-Shamma, H.A., and Dorsa, D.M. (1992) Decline of vasopressin immunoreactivity and mRNA levels in the bed nucleus of the stria terminalis following castration. J. Neurosci., 12:2881–2887.

Sofroniew, M.V., and Weindl, A. (1980) Identification of parvocellular vasopressin and neurophysin neurons in the suprachiasmatic nucleus of a variety of mammals including primates. J. Comp. Neurol., 193:659–675.

Sofroniew, M.V., and Weindl, A. (1981) Central nervous system distribution of vasopressin, oxytocin, and neurophysin. In: Endogenous Peptides and Learning and Memory Processes. J.L. Martinex, R.A. Jensen, R.B. Mesing, H. Rigter, and J.L. McGaugh, eds. Academic Press, New York, pp. 327–369.

Stephan, H., Baron, G., and Schwerdtfeger, W.K. (1980) The Brain of the Common Marmoset (*Callithrix jacchus*). Springer-Verlag, Berlin.

Stevenson, M.F., and Rylands, A.B. (1988) The marmosets, genus Callithrix. In: Ecology and Behavior of Neotropical Primates, Vol. 2. R.A. Mittermeier, A.B. Rylands, A.F. Coimbra-Filho, and G.A.B. da Fonseca, eds. World Wildlife Fund, Washington, DC, pp. 131–222.

Sukhov, R.R., Walker, L.C., Rance, N.E., Price, D.L., and Young, W.S., III (1993) Vasopressin and oxytocin gene expression in the human hypothalamus. J. Comp. Neurol., 337:295–306.

Ueda, S., Kawata, M., and Sano, Y. (1983) Identification of serotonin- and vasopressin immunoreactivities in the suprachiasmatic nucleus of four mammalian species. Cell Tissue Res., 234:237–248.

Valtin, H. (1987) Physiological effects of vasopressin on the kidney. In: Vasopressin, Principles and Properties. D.M. Gash and G.J. Boer, eds. Plenum, New York, pp. 389–433.

van Leeuwen, F.W., and Caffé, A.R. (1983) Vasopressin-immunoreac-

tive cell bodies in the bed nucleus of the stria terminalis of the rat. Cell Tissue Res., 228:525–534.

van Leeuwen, F.W., Caffé, A.R., and De Vries, G.J. (1985) Vasopressin cells in the bed nucleus of the stria terminalis of the rat: Sex difference and the influence of androgens. Brain Res., 325:391–394.

Wang, Z.X., and De Vries, G.J. (1995) Androgen and estrogen effects on vasopressin messenger RNA expression in the medial amygdaloid nucleus in male and female rats. J. Neuroendocrinol., 7:827–831.

Wang, Z.X., Ferris, C.F., and De Vries, G.J. (1994) The role of septal vasopressin innervation in paternal behavior in prairie voles (*Microtus ochrogaster*). Proc. Natl. Acad. Sci. U. S. A., 91:400–404.

Wang, Z.X., Toloczko, D., Young, L.J., Moody, K., Newman, J.D., and Insel, T.R. (1996a) Vasopressin pathways in the brain of common marmosets (*Callithrix jacchus*): Studies with immunocytochemistry, in situ hybridization and receptor autoradiography. Soc. Neurosci. Abs., 22:1556.

Wang, Z.X., Zhou, L., Hulihan, T.J., and Insel, T.R. (1996b) Immunoreactivity of central vasopressin and oxytocin pathways in microtine rodents: A quantitative comparative study. J. Comp. Neurol., 366: 726–737.

Williams, J.R., Insel, T.R., Harbaugh, C.R., and Carter, C.S. (1994) Oxytocin administered centrally facilitates formation of a partner preference in female prairie voles (*Microtus ochrogaster*). J. Neuroendocrinol., 6:247–250.

Winslow, J.T., Hastings, N., Carter, C.S., Harbaugh, C.R., and Insel, T.R. (1993) A role for central vasopressin in pair bonding in monogamous prairie voles. Nature, 365:545–548.

Zhou, L., Blaustein, J.D., and De Vries, G.J. (1994) Distribution of androgen receptor immunoreactivity in vasopressin- and oxytocin-immunoreactive neurons in the male rat brain. Endocardinology, 134:2622–2627.