

Distribution of Sex Steroid Hormone Receptors in the Brain of an African Cichlid Fish, *Astatotilapia burtoni*

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ABSTRACT

Sex steroid hormones released from the gonads play an important role in mediating social behavior across all vertebrates. Many effects of these gonadal hormones are mediated by nuclear steroid hormone receptors, which are crucial for integration in the brain of external (e.g., social) signals with internal physiological cues to produce an appropriate behavioral output. The African cichlid fish *Astatotilapia burtoni* presents an attractive model system for the study of how internal cues and external social signals are integrated in the brain as males display robust plasticity in the form of two distinct, yet reversible, behavioral and physiological phenotypes depending on the social environment. In order to better understand where sex steroid hormones act to regulate social behavior in this species, we have determined the distribution of the androgen receptor,

estrogen receptor alpha, estrogen receptor beta, and progesterone receptor mRNA and protein throughout the telencephalon and diencephalon and some mesencephalic structures of *A. burtoni*. All steroid hormone receptors were found in key brain regions known to modulate social behavior in other vertebrates including the proposed teleost homologs of the mammalian amygdalar complex, hippocampus, striatum, preoptic area, anterior hypothalamus, ventromedial hypothalamus, and ventral tegmental area. Overall, there is high concordance of mRNA and protein labeling. Our results significantly extend our understanding of sex steroid pathways in the cichlid brain and support the important role of nuclear sex steroid hormone receptors in modulating social behaviors in teleosts and across vertebrates. *J. Comp. Neurol.* 518:3302–3326, 2010.

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INDEXING TERMS: estrogen receptor; androgen receptor; progesterone receptor; hypothalamus; social behavior network; mesolimbic reward system

Sex steroid hormones—androgens, estrogens, and progestins—are ubiquitous in all vertebrates and modulate a variety of neural processes and behavior such as reproduction, aggression, learning, and memory (Hull and Dominguez, 2007; Westberg and Eriksson, 2008; Luine, 2008; Galea et al., 2008). Each of these sex steroid hormones modulate these processes through specific receptors in dedicated neural circuits that are well characterized in many species of birds and mammals (Ball and Balthazart, 2004; Dulac and Kimchi 2007). Within these neural circuits, gonadal hormones can have both organizational and activational effects. Classically, steroid hormones organize the brain during development and then activate the structures organized in development later in life (Phoenix et al., 1959; Young et al., 1964; McEwen, 1980). However, the relative extent to which organizational or activational effects shape an organism's brain and behavior can vary considerably across species. This is well illustrated by considering two types of polymorphic

systems: one in which the male phenotypes are fixed throughout their adult life and another in which males switch between reproductive morphs throughout the adult lifespan (Knapp, 2004). Organizational effects appear strongest in fixed phenotypic systems, whereas activational effects of steroid hormones and their receptors are more substantial in plastic phenotypic systems (Moore, 1991; Thompson and Moore, 1992). Thus, to understand the role of steroid hormones and their receptors in actively modulating complex behavior, a model

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system that is behaviorally plastic is advantageous. Here we characterize the distribution of androgen receptors, estrogen receptors, and the progesterone receptor in the brain of the African cichlid fish, *Astatotilapia burtoni*, which has become an established model system for the study of hormonal and environmental modulation of phenotypic and neural plasticity (Hofmann, 2003; Robinson et al., 2008).

Stimuli in the (social) environment are transduced by sensory systems and can have both immediate and long-term effects on brain processes and behavior. The modulation of gene expression levels constitutes one key channel for affecting such long-term changes (Aubin-Horth and Renn, 2009). In addition to internal physiological cues, production of social behavior requires an integration of external cues in the brain where signals are processed and behavioral decisions implemented by dedicated brain circuits. Steroid hormones are excellent candidates for integrating environmental inputs into gene expression changes, which then in turn can alter neural circuit function and properties (Ball and Balthazart, 2004). Changes in external signals, such as altering day length or social environment, can influence the effects of hormones on behavior (Trainor et al., 2007; Goymann, 2009). However, gonadal hormones can also have rapid nongenomic effects that can play an important role in behavior (Ramage-Healey and Bass, 2006; Mani et al., 2009).

Each gonadal hormone is associated with one or more conserved nuclear receptor that mediates enduring effects of the hormone by influencing gene transcription. Upon ligand binding, receptors dimerize and act cooperatively with coactivators and other DNA-binding proteins to interact with regulatory sequences in promoter regions called hormone response elements (Tetel, 2009). The specificity of action of steroid hormone receptors is due to specificity of the receptor to both its ligand and its DNA response element as well as the spatial and temporal expression of the steroid hormone receptor itself. The distribution of androgen and estrogen receptors in the brain has been studied in several teleost species including goldfish, the oyster toadfish, zebrafish, midshipman, sea bass and Atlantic croaker (androgen receptor: Fine et al., 1996; Gelinas and Callard, 1997; Forlano et al., 2009; estrogen receptors: Menuet et al., 2002; Hawkins et al., 2005; Forlano et al., 2005; Muriach et al., 2008). The neural distribution of the progesterone receptor has been studied in zebrafish, although only a few brain regions are described (Hanna et al., 2010). Surprisingly, little is known about the distribution of these receptors in the brains of teleosts with plastic behavioral phenotypes, even though this information would give us a better understanding of which brain regions may be sites of modulation of neural and behavioral plasticity by gonadal hormones.

Abbreviations

An	Anterior thalamic nucleus	mPGn	Medial preglomerular nucleus
AC	Anterior commissure	nLT	Nucleus of the lateral torus
aTn	Anterior tuberal nucleus	OB	Olfactory bulb
Cn	Central nucleus of the inferior lobe	OPT	Optic tract
CP	Central posterior thalamic nucleus	OT	Optic tectum
D	Dorsal (pallial) part of the telencephalon	P	Pituitary
Dc	Central part of D	PAG	Periaqueductal gray
Dc-2	Subdivision of Dc	PGCn	Preglomerular commissural nucleus
Dd	Dorsal part of D	PN	Prethalamic nucleus
DH	Dorsal hypothalamus	POA	Preoptic area
DI	Lateral part of D	PPd	Dorsal periventricular pretectal nucleus
Dld	Dorsal part of DI	PPr	Rostral periventricular pretectal nucleus
Dlg	Granular part of DI	pTGN	Preglomerular tertiary gustatory nucleus
Dlv	Ventral part of DI	PVO	Paraventricular organ
Dlvv	Ventral part of Dlv	ST	Semicircular torus
Dm	Medial part of D	TPp	Periventricular nucleus of the posterior tuberculum
Dm-1,2,3	Subdivisions of Dm	V	Ventral (subpallial) division of the telencephalon
Dm2c	Caudal part of Dm-2	Vc	Central part of V
Dn	Diffuse nucleus of the inferior lobe	Vd	Dorsal nucleus of V
Dp	Posterior part of D	Vdc	Caudal part of Vd
Dx	Unassigned part of D	Vdr	Rostral part of Vd
E	Entopeduncular nucleus	VH	Ventral hypothalamus
Gn	Glomerular nucleus	Vi	Intermediate part of V
H	Habenula	VI	Lateral part of V
HC	Horizontal commissure	VM	Ventromedial thalamic nucleus
IL	Inferior lobe	Vp	Postcommissural nucleus of V
LHn	Lateral hypothalamic nucleus	vPPn	Ventral portion of the periventricular pretectal nucleus
IPGn	Lateral preglomerular nucleus	Vs	Supracommissural nucleus of V
LR	Lateral recess	Vsl	Lateral part of Vs
LT	Longitudinal torus	Vsm	Medial part of Vs
LZ	Limited zone of the diencephalon	vTn	Ventral tuberal nucleus
MB	Mammillary body	Vv	Ventral part of V

The African cichlid, *A. burtoni*, is an excellent model system to study the mechanisms by which gonadal hormones modulate neural and behavioral plasticity. In this species, males display robust phenotypic plasticity in the form of two distinct phenotypes. Dominant males are colorful, reproductively active, and defend territories where they court and spawn with females. Subordinate males have cryptic coloration, are reproductively suppressed, and school with females. This species presents an attractive model system for the study of activational effects of hormones and their receptors as individuals are “plastic” and change from one phenotype to another depending on the immediate social environment (Hofmann and Fernald, 2001). The social behavior of these fish is complex, yet stereotyped and easily quantified, adding to their potential as a model system (Fernald and Hirata, 1977a,b). Additionally, in *A. burtoni* we can investigate the interaction between an individual and its social environment, as both social and hormonal status can exert profound influences on neural circuitry and behavior (Hofmann, 2003).

The influence of social status and behavioral plasticity on steroid hormone levels, especially androgens, has been studied extensively in *A. burtoni*. Dominant males have significantly higher circulating levels of both androgens (testosterone and 11-ketotestosterone) and estradiol than subordinate males (Parikh et al., 2006a; Greenwood et al., 2008; Munchrath and Hofmann, in prep.). Fernald (1976) showed that exogenous testosterone increased aggressive displays in dominant males, although it remains unclear whether this effect was mediated by androgen receptors or by estrogen receptors via aromatase. There are also physiological consequences to a change in social status, as after social defeat androgen levels will decrease in dominant males within 24 hours (Parikh et al., 2006b). Importantly, the expression of androgen and estrogen receptors varies within these social phenotypes. Burmeister et al. (2007) measured the levels of androgen and estrogen receptor mRNA in gross brain dissections in *A. burtoni* and found that in the anterior portion of the brain (which comprised the entire telencephalon and a portion of the POA), dominant males had higher levels of AR α , AR β , ER β a, and ER β b mRNA compared with subordinate males. Yet despite the potentially important role of steroid hormones in modulating behavioral plasticity and social dominance in this species, knowledge of the detailed distribution of sex steroid hormone receptors in the brain is lacking.

Based on insights in mammals, birds, and teleosts, there are two neural networks that seem to regulate social behavior and/or encode the salience of (social) stimuli. Many studies indicate that the “reward system” (including but not limited to the midbrain dopaminergic system) is the neural network where evaluations of stimu-

lus salience are made (Deco and Rolls, 2005; Wickens et al., 2007). The neural substrate of social behaviors has been described by Newman (1999) as “social behavior network” in mammals, and has been expanded to reptiles, birds, and teleosts (Newman, 1999; Crews, 2003; Goodson, 2005). The core nodes of Newman’s network are involved in multiple forms of social behavior, are reciprocally connected, and—by definition—contain sex steroid hormone receptors. Although the brain regions involved in the dopaminergic reward system and Newman’s social behavior network are well studied in mammals, homologizing these brain areas with structures in the teleost brain has been controversial (Nieuwenhuys et al., 1998; Northcutt, 2008). However, a consensus is emerging from developmental, neurochemical, hodological, and lesion studies that provides support for at least partial homologies for most of the relevant areas in the teleost brain (Rink and Wullimann, 2001, 2002; Portavella et al., 2002; Wullimann and Mueller, 2004; Northcutt, 2006, 2008; Bruce and Braford, 2009).

The main aim of this study was to test the hypothesis that the androgen receptor (AR), estrogen receptor alpha (ER α), estrogen receptor beta (ER β), and the progesterone receptor (PR) are widely distributed throughout fore- and midbrain of a teleost with plastic behavioral phenotypes. We also predicted that these steroid receptors are expressed in brain regions important for the regulation of social behavior and evaluation of stimulus salience in the African cichlid fish *A. burtoni*.

MATERIALS AND METHODS

Animals

Astatotilapia burtoni from a wild-caught stock population were kept in aquaria under conditions mimicking their natural environment (Fernald and Hirata, 1977b): pH 8.0, 28°C water temperature, and 12h:12h light:dark cycle with 10 minutes each dusk and dawn periods. Gravel substrate and terracotta shelters provided the substrate that facilitates the establishment and maintenance of territories necessary for reproduction (Fernald and Hirata, 1977a). Fish were fed every day with cichlid flakes (Arcata Pet Supplies). The animals chosen for this study were dominant and subordinate males as described by Fernald (1976), who had been in their respective social states for at least 4 weeks. Dominant males were identified as aggressively defending a territory within the tank, courting females, and displaying bright color and an eye bar. Subordinate males were identified by absence of a territory, schooling with the females, fleeing from territorial males, and lack of bright body coloration and eye bar. All work was carried out in compliance with the

Institutional Animal Care and Use Committee at the University of Texas at Austin.

Where possible the neuroanatomical nomenclature of Fernald and Shelton (1985) for the diencephalon and mesencephalon and Burmeister et al. (2009) for the telencephalon was followed. However, for the prethalamic nucleus (PN), we adopted the nomenclature of Meader (1934), although this region has been identified as the anterior preglomerular nucleus (aPGn) in Fernald and Shelton (1985). This was done to avoid confusion of functionally different regions in percomorphs and cyprinids (Braford and Northcutt, 1983; Yamamoto and Ito, 2005, 2008; Northcutt, 2006). For the central nucleus of the inferior lobe we followed the nomenclature according to Ahrens and Wullimann (2002) and Yang et al. (2007). The nomenclature for the periaqueductal gray was used according to Forlano et al. (2001). Parvocellular, magnocellular, and gigantocellular portions of the preoptic area were identified as described in Braford and Northcutt (1983) based on cell size and location.

Cloning of the *A. burtoni* PR full cDNA

With the exception of the PR, sequences for all *A. burtoni* sex steroid hormone receptors were available in GenBank (see below). In order to obtain the *A. burtoni* PR sequence, we designed primers against the Nile tilapia, *Oreochromis niloticus*, PR mRNA (GenBank accession number AB110982) and cloned a 359-bp fragment of the *A. burtoni* PR from whole brain cDNA. (See Table 1 for information on primer sequences.) The remainder of the full-length sequence corresponding to the 5' and 3' end of the coding

region and the 5' and 3' untranslated region was cloned by RACE (ClonTech, Palo Alto, CA) according to the manufacturer's instructions. The entire sequence has been submitted in GenBank (accession number FJ605735).

In situ hybridization (ISH)

Dominant ($n = 8$) and subordinate ($n = 8$) males were sacrificed and their brains rapidly dissected, fresh frozen in O.C.T. (Optimal Cutting Temperature Compound, Tissue-Tek, Torrance, CA) on a block of dry ice and stored at -80°C . Brains were then sectioned on a cryostat at $20\ \mu\text{m}$ and thaw-mounted onto Super-Frost Plus slides (Erie Scientific, Portsmouth, NH) in six series that were stored at -80°C for at least 6 weeks until processing for ISH. Each of the six steroid hormone receptors was analyzed in each individual. Sections were fixed in cold 4% paraformaldehyde (pH 7.2) for 10 minutes and washed in $1\times$ phosphate-buffered saline (PBS; pH 7.4). The sections were then incubated in 0.1 M triethanolamine (TEA) (pH 8.0) for 10 minutes followed by 15 minutes in freshly prepared TEA/0.25% acetic anhydride, rinsed in $2\times$ SSC, dehydrated in increasing ethanol series, air-dried, and stored at -80°C . Riboprobes were reverse-transcribed in the presence of fluorescein-labeled UTP (Roche, Indianapolis, IN) using a T7/SP6 Maxiscript in vitro transcription kit (Ambion, Austin, TX) to produce antisense or sense fluorescein-labeled probes. All probes were designed to include the ligand-binding domain of each receptor. (See Table 2 for primer information.) The template used to make the AR α probe was 646 bp in length (GenBank accession number: AF121257); the AR β probe was 516 bp in length (GenBank accession number: AY082342); the ER α probe was 788 bp in length (GenBank accession number: AY422089); the ER β a probe was 670 bp in length (GenBank accession number: DQ862128); the ER β b probe was 665 bp in length (GenBank accession number: DQ862129); the PR probe was 359 bp in length (GenBank accession FJ605735). Slides were then warmed to room temperature, air-dried, and preequilibrated in hybridization buffer (50% formamide, $5\times$ SSC, $5\times$ Denhardt's solution, 125 mg/mL Baker's yeast tRNA, 250 mg/mL denatured herring sperm DNA) for 2 hours at 65°C . Sections were then incubated in

TABLE 1.
Primer Information for Cloning the Progesterone Receptor

PR cloning reaction	Primer sequence
PR cloning, forward primer	5'-GCACCTGATCTGATTCTTAGCCAG
PR cloning, reverse primer	5'-GCCTGGATGAAGGTAACCAACAG
Outer 5'-RACE	5'-GGCATCCATGAGTTTGGTGGAGGTGG
Nested 5'-RACE	5'-TTTGAATAGCCTTGGTCAGCTCCCG
Outer 3'-RACE	5'-CAAATGAAGGAGAAGGGCATCGTGG
Nested 3'-RACE	5'-CCCAGCGATTCTACCACCTACCAAC

TABLE 2.
Primer Information for In Situ Hybridization Probe Template

Gene	Forward primer	Reverse primer
Androgen receptor alpha	5'-AATGTGTTTATGAACCCACGC	5'-TCTTCCGCTCAGTTTGTCCG
Androgen receptor beta	5'-CGGCGGCTTTTCATCACC	5'-AGTTGGAGTTGGGATAAAG
Estrogen receptor alpha	5'-GAAGATGAACCAACCTAC	5'-TGCCTTGAGTCTCTGAAC
Estrogen receptor beta-a	5'-GCCAAGAAGATTCCAGGGTTTG	5'-TCCAGGTATTTGAAGTCCCG
Estrogen receptor beta-b	5'-AACCCAGAGTTCATTTCCC	5'-TACACCAGCACCGCATTCTTCC
Progesterone receptor	5'-GCACCTGATCTGATTCTTAGCCAG	5'-GCCTGGATGAAGGTAACCAACAG

TABLE 3.
Antibody Details

1°	Antigen	Supplier	Source	IHC dilution	Type
PR	Chicken PR purified from oviduct	Abcam (ab2767)	Mouse	1:500	Monoclonal
AR	Human AR: MEVQLGLGRVYPRPPSKTYRGC	Millipore (06-680)	Rabbit	1:250	Polyclonal
ER α	Rat ER α : TYYPPEAEGFPNTI	Millipore (06-935)	Rabbit	1:1,000	Polyclonal
ER β	Human ER β : CSPAESKSKESQNPQSQ	Invitrogen (51-7700)	Rabbit	1:250	Polyclonal

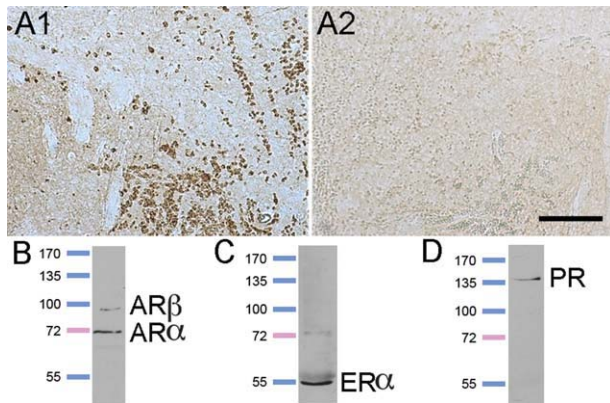


Figure 1. Confirmation of antibody specificity. **A:** Immunohistochemical staining with an ER β antibody shows distinct cell labeling (**A1**) and this staining is completely blocked when the antibody is preabsorbed with the original antigen prior to immunohistochemical procedure (**A2**). Western blot was used to confirm specificity of the AR (**B**), ER α (**C**), and PR (**D**) antibodies against *A. burtoni* whole brain extract. Scale bar = 100 μ m. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

riboprobe overnight at the same temperature. Experimental slides were exposed to antisense fluorescein-labeled probe, whereas control slides were incubated with sense fluorescein-labeled probe. Additional control slides were treated with RNase before hybridization with antisense probe. After the overnight hybridization, slides were processed for detection of mRNA by nonradioactive, nonfluorescent detection. After RNase A treatment at 37°C, sections were washed in a decreasing series of SSC and equilibrated in 150 mM NaCl/100 mM Tris (pH 7.5) at room temperature before incubation in 1:1,000 anti-fluo-

rescein-alkaline phosphatase Fab fragments (Roche) in 0.5% Tween 20/PBS for 2 hours at room temperature. Sections were then washed in 100 mM Tris (pH 7.5). Chromogenic product was formed using BM Purple (Roche) at room temperature until desired darkness was achieved and was terminated simultaneously for all slides within a gene group. Slides were then washed, dehydrated in an ethanol series ending in xylene, and coverslipped with Permount (Fisher Scientific, Pittsburgh, PA).

Immunohistochemistry (IHC)

Dominant ($n = 4$) and subordinate ($n = 4$) males were sacrificed and their brains rapidly dissected and incubated in 4% paraformaldehyde in 1 \times PBS; pH 7.4 at 4°C overnight. Brains were then washed in 1 \times PBS and cryoprotected in 30% sucrose in 1 \times PBS overnight at 4°C before embedding in O.C.T. (Tissue-Tek) and storing at -80°C . Brains were then sectioned on a cryostat at 20 μ m and thaw-mounted onto Super-Frost Plus slides (Erie Scientific) in five series that were stored at -80°C until processing for IHC.

Sections were removed from -80°C and air-dried before being fixed in chilled 4% paraformaldehyde in 1 \times PBS, pH 7.4, for 10 minutes. Sections were then rinsed in PBS and incubated in 3% hydrogen peroxide in PBS for 20 minutes. After washing in PBS, antigen retrieval was performed by incubating in boiling citrate buffer (10 mM citric acid, 0.05% Tween 20, pH 6.0). After two minutes the boiling citrate buffer was replaced two times and incubated for 5 minutes each, followed by a PBS wash. After blocking for 1 hour in blocking solution (5% normal goat serum and 0.3% Triton X-100 in PBS), sections were incubated in primary antibody (AR 1:250, PR 1:500, ER α 1:1,000, ER β 1:250, see Table 3 for antibody details) in PBS with 2% normal goat serum and 0.3% Triton X-100 at

Figure 2. Distribution of AR mRNA and protein in the telencephalon. Representative sections of the telencephalon are presented as the first image in each panel with AR protein shown as dots on the right side of the brain and AR α mRNA shown as gray shading on the left and AR β mRNA as gray shading on the right. The density of dots indicating protein corresponds to the density of cells positive for AR-immunoreactivity. The degree of shading for mRNA corresponds to the density of expression. The micrographs in the top panel show AR α and AR β mRNA (**A2,A3**) and AR protein (**A4**) in the olfactory bulb. Micrographs in the second panel show labeling of AR α and AR β mRNA (**B2,B3**) and AR protein (**B4**) in Vv. The third panel shows micrographs of AR α and AR β mRNA (**C2,C3**) and AR protein (**C4**) in Dc. The fourth panel shows micrographs of AR α and AR β mRNA (**D2,D3**) and AR protein (**D4**) in Vdc and Vsm. The bottom panel shows AR protein in gigantocellular (**E2**), magnocellular (**E3**), and parvocellular (**E4**) cells in the POA. Scale bars = 100 μ m except E2–E4 = 20 μ m. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

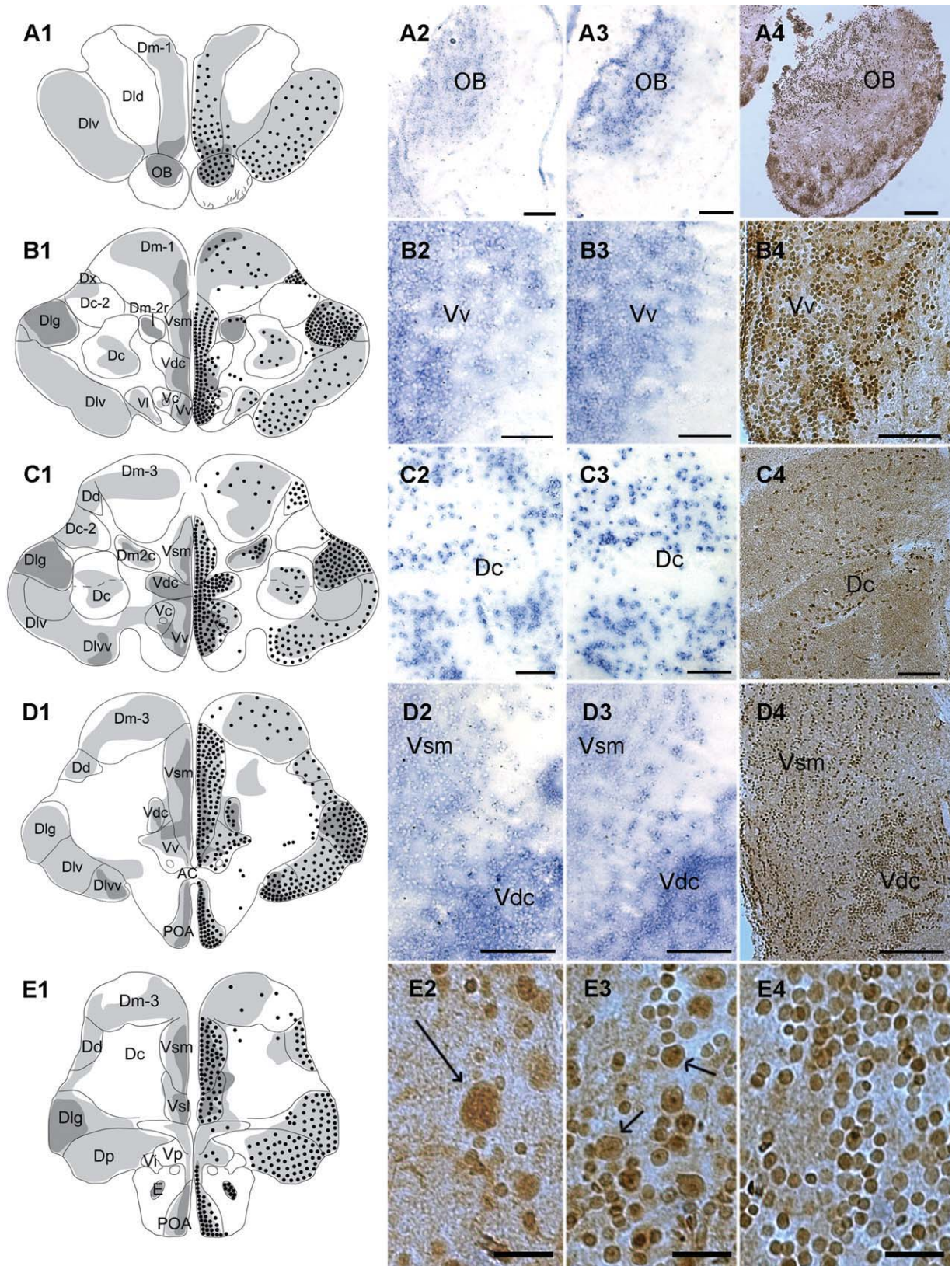


Figure 2

room temperature overnight. Sections were then rinsed, incubated for 2 hours in a biotinylated goat anti-mouse (PR) or anti-rabbit (AR, ER α , ER β) secondary antibody (Vector Laboratories, Burlingame, CA), rinsed again, and, after treatment with the ABC peroxidase staining kit (Vector Laboratories) according to the manufacturer's instructions, immunoreactivity was visualized using 3,3'-diaminobenzidine (DAB) substrate (Vector Laboratories). Sections were then dehydrated and coverslipped with Permount (Fisher Scientific, Itasca, IL). For control sections, all procedures were the same except that primary antibody was omitted. All antibodies used in this study were obtained from commercial suppliers, as summarized in Table 3, along with information on antigen, source, and dilution.

Western blot characterization of AR, ER α , and PR antibodies

In order to determine whether these antibodies would bind specifically to the cichlid antigens, we extracted protein from whole brain using a Mammalian Cell Lysis kit (Sigma, St. Louis, MO) according to the manufacturer's instructions. Whole brain protein extract was run on a sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) gel in replicate, in which one-half of the gel used for downstream Western blotting and the other half exposed to Coomassie stain to verify protein presence. Whole brain extract on the gel was transferred onto a nitrocellulose membrane overnight. The membrane was then blocked in 5% dry milk in wash buffer (0.5% Triton X-100, 0.1% Tween-20 in 1 \times Tris-buffered saline [TBS], incubated in primary antibody [1:1,000 AR, 1:5,000 ER α , or 1:2,000 PR in 1 \times TBS and 2% NaN₃] for 1 hour, washed five times for 3 minutes each in wash buffer, and then incubated in either goat-anti-mouse horseradish peroxidase (HRP)-conjugated antibody (PR) or goat-anti-rabbit HRP-conjugated antibody (AR, ER α ; Southern Biotechnology, Birmingham, AL) in blocking solution for 30 minutes. After washing five times for 3 minutes each with wash buffer, the membrane was exposed to HRP substrate (Immobilon Western, Millipore, Bedford, MA) and exposed to film for 2 minutes. Using the AR antibody, two

bands were visualized putatively representing AR α and AR β at the predicted sizes of 90 kD and 78 kD, respectively (Fig. 1B). Using the ER α antibody, one large band was visualized near 55 kD, near the expected size of the teleost ER α (Fig. 1C). The predicted size of the teleost ER β is near 75 kD. Using the PR antibody, one large band was visualized near 140 kD, the putative size of the teleost PR (Fig. 1D). As can sometimes be the case with immunoblotting, the ER β antibody did not provide a signal on the Western blot. We found, however, that preabsorption of the ER β antibody with 10 μ g per mL of original antigen for 1 hour at room temperature prior to immunohistochemistry blocked all signal (Fig. 1A). This result does not rule out that the ER β antiserum might still crossreact with another protein in the brain. However, all antisera used in this study, including the one against ER β , showed high concordance with mRNA expression patterns as determined by *in situ* hybridization, indicating specificity.

Photomicroscopy

Brightfield optics were used to visualize immunohistochemical staining throughout the brain at low (5 \times) and high magnification (10 \times). Photographs were taken with a digital camera (AxioCam MRc, Zeiss) attached to a Zeiss AxioImager.A1 AX10 microscope (Zeiss) using the AxioVision (Zeiss) image acquisition and processing software. Images were compiled and brightness- and contrast-enhanced in Adobe Photoshop CS3 (San Jose, CA).

RESULTS

Sex steroid receptors are widely distributed throughout the male cichlid fore- and midbrain. In the following, we present a distribution map along with representative photomicrographs of representative brain areas for each steroid hormone receptor separately. For each representative section of the map, the nomenclature is displayed on the left side while protein signal as determined by immunohistochemistry is represented by dots on the right side. The density of dots representing protein indicates qualitatively the density of cells positive for the protein of

Figure 3. Distribution of AR mRNA and protein in the diencephalon and mesencephalon. Representative sections of the diencephalon and some mesencephalic structures are depicted in the left column with AR protein represented by dots on the right, AR α mRNA as gray shading on the left, and AR β mRNA as gray shading on the right. The density of dots indicating protein corresponds to the density of cells positive for AR-immunoreactivity. The degree of shading for mRNA corresponds to the density of expression. Micrographs in the top row show AR α and AR β mRNA (A2,A3) and AR protein (A4) in the ventral tuberal nucleus. Micrographs in the second row show AR α and AR β mRNA (B2,B3) and AR protein (B4) in the anterior tuberal nucleus. The third panel contains micrographs showing AR α and AR β mRNA (C2,C3) and AR protein (C4) patterns in the periventricular nucleus of the posterior tuberculum. The fourth panel contains micrographs showing AR α and AR β mRNA (D2,D3) and AR protein (D4) in the semicircular torus (ST). The bottom panel shows micrographs of AR α and AR β mRNA (E2,E3) and AR protein (E4) patterns in the periaqueductal gray. Scale bars = 100 μ m. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

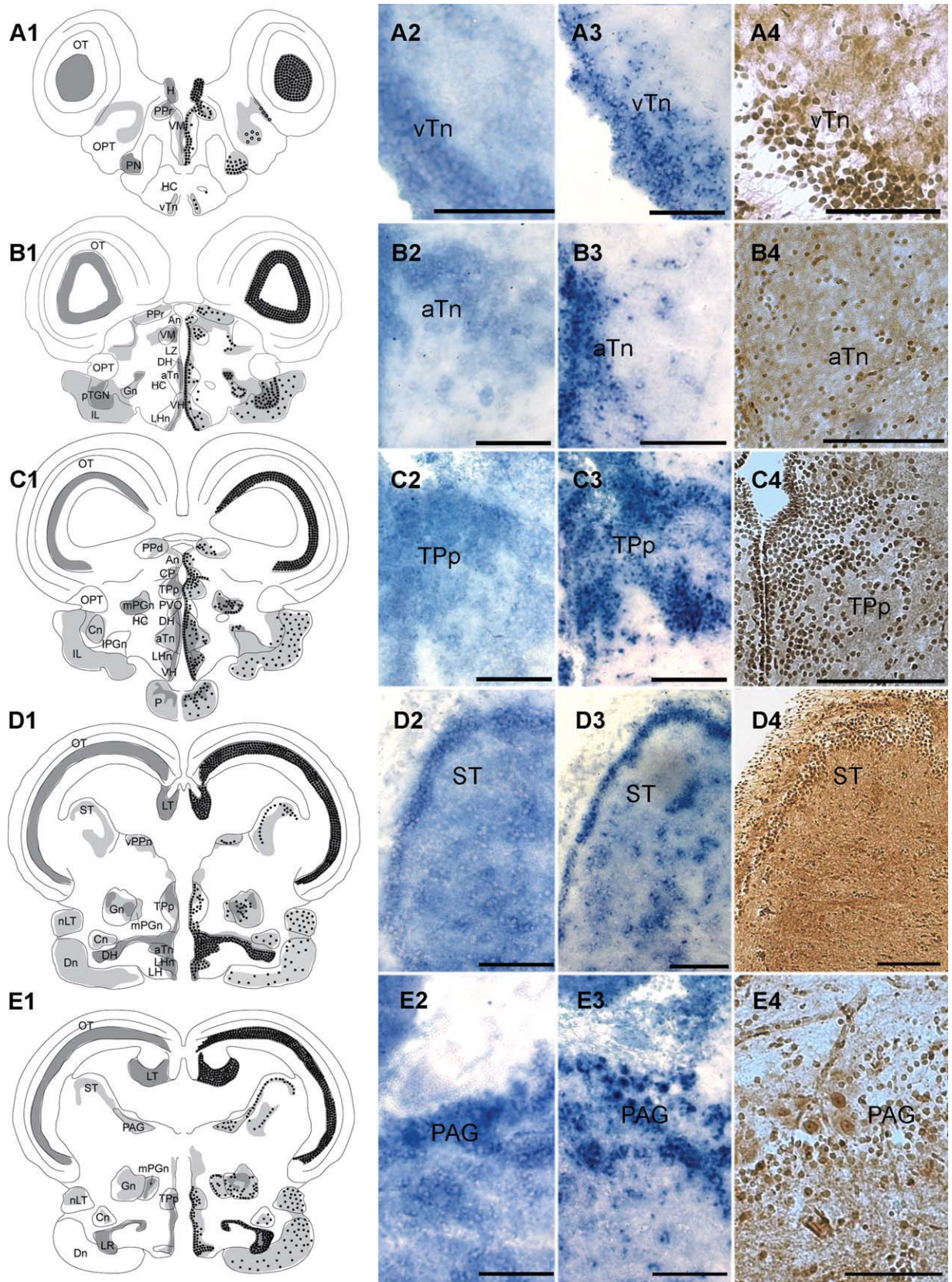


Figure 3

interest. The degree of shading qualitatively represents the density of mRNA expression in that region. Unless specifically stated, all descriptions of protein-immunoreactivity refer to nuclear staining. In the maps for PR and ER α , mRNA is shown as gray shading on the right half of each representative section. Since teleosts have two subtypes of the AR (AR α and AR β) and ER β (ER β a and ER β b), the alpha subtypes are displayed on the left portion of each representative section while the beta subtype is depicted on the right. The antibodies available for either AR or ER β do not allow us to distinguish these subtypes via IHC. The general patterns shown here are representative of both dominant and subordinate males (notwithstanding possible quantitative differences, which we do not investigate here). Overall, the mRNA detection via in situ hybridization and protein immunohistochemistry staining showed high congruence. Control slides that include omitting antibody for immunohistochemistry and hybridizing with sense probes for in situ hybridization showed no specific signal.

Androgen receptor

Robust expression of both AR β and AR α mRNA and AR protein is seen throughout the telencephalon, diencephalon, and mesencephalic structures of *A. burtoni* (Fig. 2). In general, AR α and AR β show similar patterns of expression and consistently overlap with AR protein immunoreactivity.

Telencephalon

Strong signal for AR α and AR β mRNA and AR protein is found in discrete parts of the dorsal and ventral telencephalon (Fig. 2). There is robust expression of AR protein and mRNA of both subtypes in the granule cell layer of the olfactory bulb (OB, Fig. 2A). However, AR-immunoreactivity is also seen in the glomeruli, although mRNA is not expressed here. In the dorsal telencephalon there is signal of mRNA of both subtypes and AR-immunoreactive cells including the central, lateral, medial, and posterior parts (Dc, DI, Dm, and Dp, respectively). Subdivisions within these regions with heavy staining are the granular part of DI and the ventral part of the ventral DI (DIg and DIv). AR staining is nearly absent in the dorsal part of DI (DI_d). There are two distinct cell groups in Dc with light

staining (Fig. 2C). The patterns of AR subtypes within the dorsal telencephalon vary, with AR β staining being more restricted than AR α . Region Dx has AR protein but only AR β staining. In the rostral part of Dd only AR β mRNA is expressed, but in the more caudal regions of Dd both subtypes are present. Within the ventral telencephalon there is staining of both AR subtypes and AR-immunoreactive cells within the ventral, central, dorsal, and supracommissural parts (Vv, Vc, Vd, and Vs, respectively; Fig. 2B–E). There is good overlap between staining of both subtypes of AR and protein immunoreactivity in the ventral telencephalon with the exception of Vdc, which has more AR α mRNA than AR β . Finally, AR protein and mRNA of both subtypes are present in the entopeduncular nucleus (E).

The preoptic area (POA) has very heavy staining of AR mRNA subtypes and AR protein. The teleost POA has three cell populations that play distinct roles in modulating behavior (Greenwood et al., 2008): parvocellular, magnocellular, and gigantocellular neurons. AR protein immunoreactivity was observed in each of these cell groups (Fig. 2E2–4).

Diencephalon and mesencephalon

The pattern of both AR subtype mRNA expression and cell-immunoreactivity for AR show extensive overlap, similar to patterns seen in the telencephalon, although the diencephalic AR patterns are more diffuse than those seen in the telencephalon (Fig. 3). Perhaps the most striking pattern seen in the diencephalon and some mesencephalic structures is the intense mRNA staining and protein immunoreactivity of the optic tectum (OT) and longitudinal torus (LT). Caudal to the POA, AR α and AR β mRNA hybridization and AR protein immunoreactivity is found in the habenula (H) and the ventromedial thalamic nucleus (VM). Several periventricular pretecal nuclei show AR staining including the rostral, dorsal, and ventral regions (PPr, PPd, and vPPn, respectively). AR protein and mRNAs are present within the prethalamic nucleus (PN), which lies ventrolateral to VM. AR mRNA and protein is abundant in the anterior ventral hypothalamic nuclei including the ventral and anterior tuberal regions (vTn and aTn, respectively; Fig. 3A,B) and the periventricular hypothalamic regions including

Figure 4. Distribution of ER α mRNA and protein in the telencephalon. Representative sections of the telencephalon are presented as the first image in each panel with ER α protein shown as dots and mRNA shown as shading on the right side of the brain. The density of dots indicating protein corresponds to the density of cells positive for ER α -immunoreactivity. The degree of shading for mRNA corresponds to the density of expression. The micrographs in the top panel show ER α mRNA (A2) and ER α protein (A3) in the olfactory bulb. Micrographs in the second panel show labeling of ER α mRNA (B2) and protein (B2) in Vv. The third panel shows micrographs of ER α mRNA (C2) and protein (C3) in Dc. The fourth panel shows micrographs of ER α mRNA (D2) and protein (D3) in Vdc and Vsm. The bottom panel shows ER α protein in gigantocellular (E2), magnocellular (E3), and parvocellular (E4) cells in the POA. Scale bars = 100 μ m except E2–E4 = 20 μ m. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

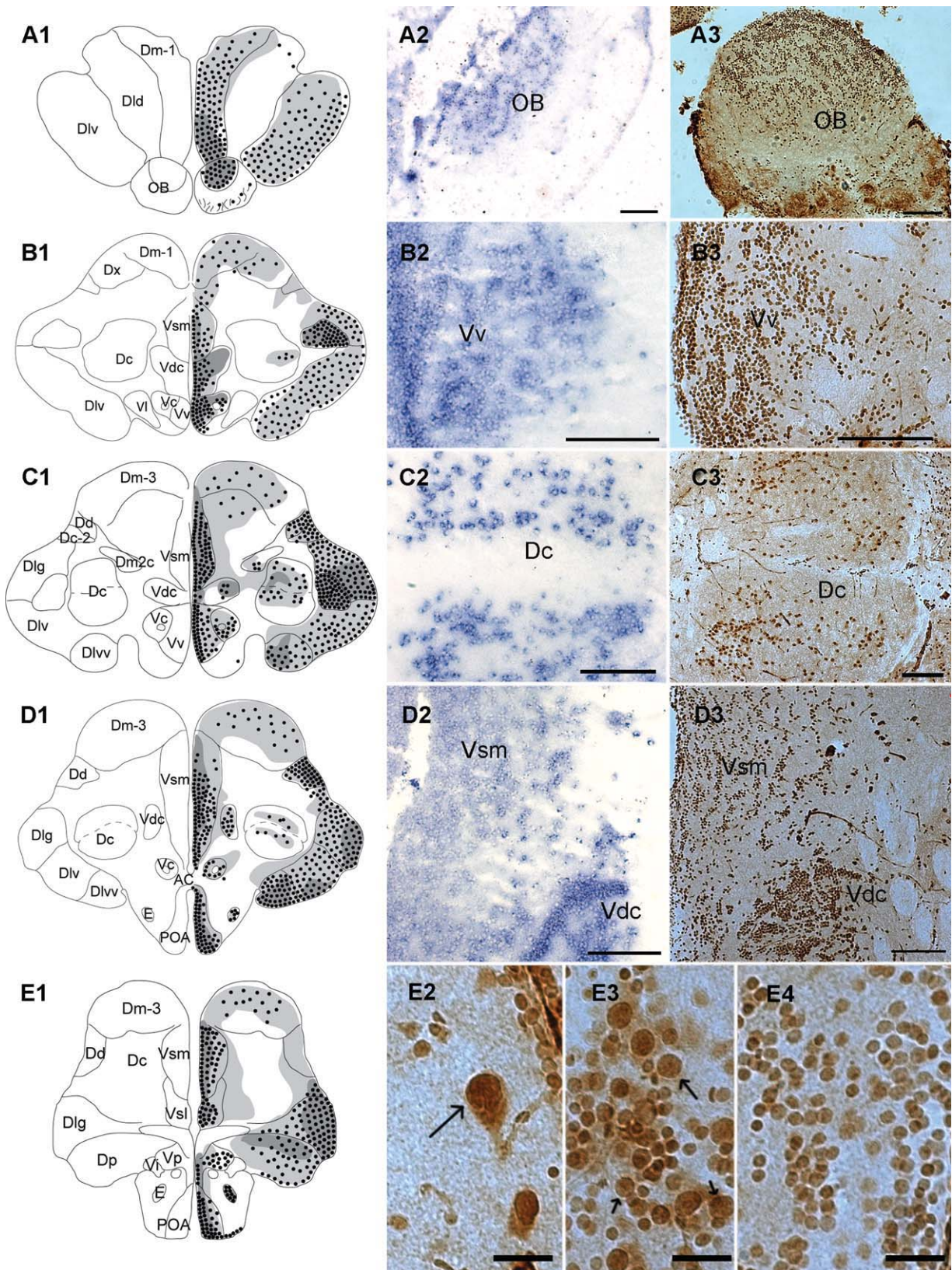


Figure 4

the ventral hypothalamus (VH), lateral hypothalamic nucleus (LHn), and the dorsal hypothalamus (DH). Lateral to these regions, staining is also found within the inferior lobe including the central (Cn) and diffuse nuclei (Dn). Abundant AR expression is found throughout the extent of the periventricular nucleus of the posterior tuberculum (TPp; Fig. 3C) and the thalamic region, central posterior thalamic nucleus (CP). A weak signal of both AR mRNA subtypes and light protein immunoreactivity is found within the glomerular nucleus (Gn). AR staining is also present within the lateral torus (nLT). Both mRNA and protein are expressed within the semicircular torus (ST, Fig. 3D) and the periaqueductal gray (PAG; Fig. 3E). In the caudal diencephalon the preglomerular commissural nucleus (PGCn) and the mammillary body (MB) also contain both AR mRNAs and protein (not shown). Finally, strong signal of AR protein and mRNA of both subtypes is found within the pituitary (Fig. 3C1).

Estrogen receptor alpha

ER α mRNA staining and protein immunoreactivity are found throughout the telencephalon, diencephalon, and some mesencephalic structures overall showing a high degree of overlap.

Telencephalon

An abundance of ER α is present within the dorsal and ventral telencephalon (Fig. 4). There is a pronounced expression of both mRNA and protein within the granule layer of the olfactory bulb (OB, Fig. 4A). ER α protein is also found within the glomeruli, although mRNA expression is not seen here. Within the dorsal telencephalon, ER α is present in Dc, Dd, DI, and Dm, with the strongest ER α mRNA signal and densest cell-immunoreactivity found in Dd and DIv. There is very little staining in DI. There are two distinct cell groups within Dc that have light staining of both mRNA and protein (Fig. 4C). Within the ventral telencephalon, ER α mRNA and protein is present within the posterior part (Vp) as well as Vc, Vd, Vp, Vs, and Vv (Fig. 5B–E). Interestingly, ER α mRNA and protein are absent within VI, making it the only steroid hormone

receptor absent within this part of V. Regions with the heaviest staining for mRNA and highest density of immunoreactive cells are in Vdc, the medial part of Vs (Vsm), and Vv.

Within the POA there was heavy staining of ER α mRNA and a high population of ER α -immunoreactive cells. ER α was present within all three POA cell subtypes: parvocellular, magnocellular, and gigantocellular (Fig. 4E2–4). Finally, ER α mRNA and protein are also present within the entopeduncular nucleus (E).

Diencephalon and mesencephalon

Compared to ER α patterns found in the telencephalon, mRNA and protein patterns are more diffuse in the diencephalon and mesencephalic structures, and similar to the distributions found for the AR subtypes. ER α mRNA and protein continue to show high concordance in these more caudal regions (Fig. 5). Caudal to the POA the VM has abundant ER α mRNA and protein presence. Plentiful ER α staining of both mRNA and protein was also seen in the habenula (H). Ventrolateral to VM, ER α protein and mRNA is abundant within the prethalamic nucleus (PN). Within the periventricular pre-tectal nuclei, ER α is found within the PPr, PPd, and vPPn. In the anterior ventral hypothalamic nuclei, ER α is found within both the vTn and aTn (Fig. 5A,B) as well as in the DH, VH, and LHn. Interestingly, there is intense expression of ER α mRNA as well as ER α protein immunoreactivity in the OT and the LT, similar to that seen with AR. ER α is highly expressed throughout the TPp (Fig. 5C) and in the thalamic nuclei, CP. Staining is also found lateral to these regions in the inferior lobe including the Cn and Dn. Dorsal to Cn and Dn, the nLT also contains ER α mRNA and protein. Light mRNA and protein staining is found within the Gn. Dorsal and lateral to the thalamus, ER α mRNA and protein is present in ST (Fig. 5D). The PAG also contains ER α mRNA and protein (Fig. 5E). Caudally in the diencephalon, the mammillary body (MB) and preglomerular commissural nucleus (PGCn) both express ER α mRNA and protein (not shown). Finally, the pituitary shows intense expression

Figure 5. Distribution of ER α mRNA and protein in the diencephalon and mesencephalon. Representative sections of the diencephalon and some mesencephalic structures are depicted in the left column with ER α protein represented by dots and mRNA as gray shading. The density of dots indicating protein corresponds to the density of cells positive for ER α -immunoreactivity. The degree of shading for mRNA corresponds to the density of expression. Micrographs in the top row show ER α mRNA (A2) and protein (A3) in the ventral tuberal nucleus. Micrographs in the second row show ER α mRNA (B2) and protein (B3) in the anterior tuberal nucleus. The third panel contains micrographs showing ER α mRNA (C2) and protein (C3) patterns in the periventricular nucleus of the posterior tuberculum. The fourth panel contains micrographs showing ER α mRNA (D2) and protein (D3) in the semicircular torus (ST). The bottom panel shows micrographs of ER α mRNA (E2) and protein (E3) patterns in the periaqueductal gray (PAG). Scale bars = 100 μ m. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

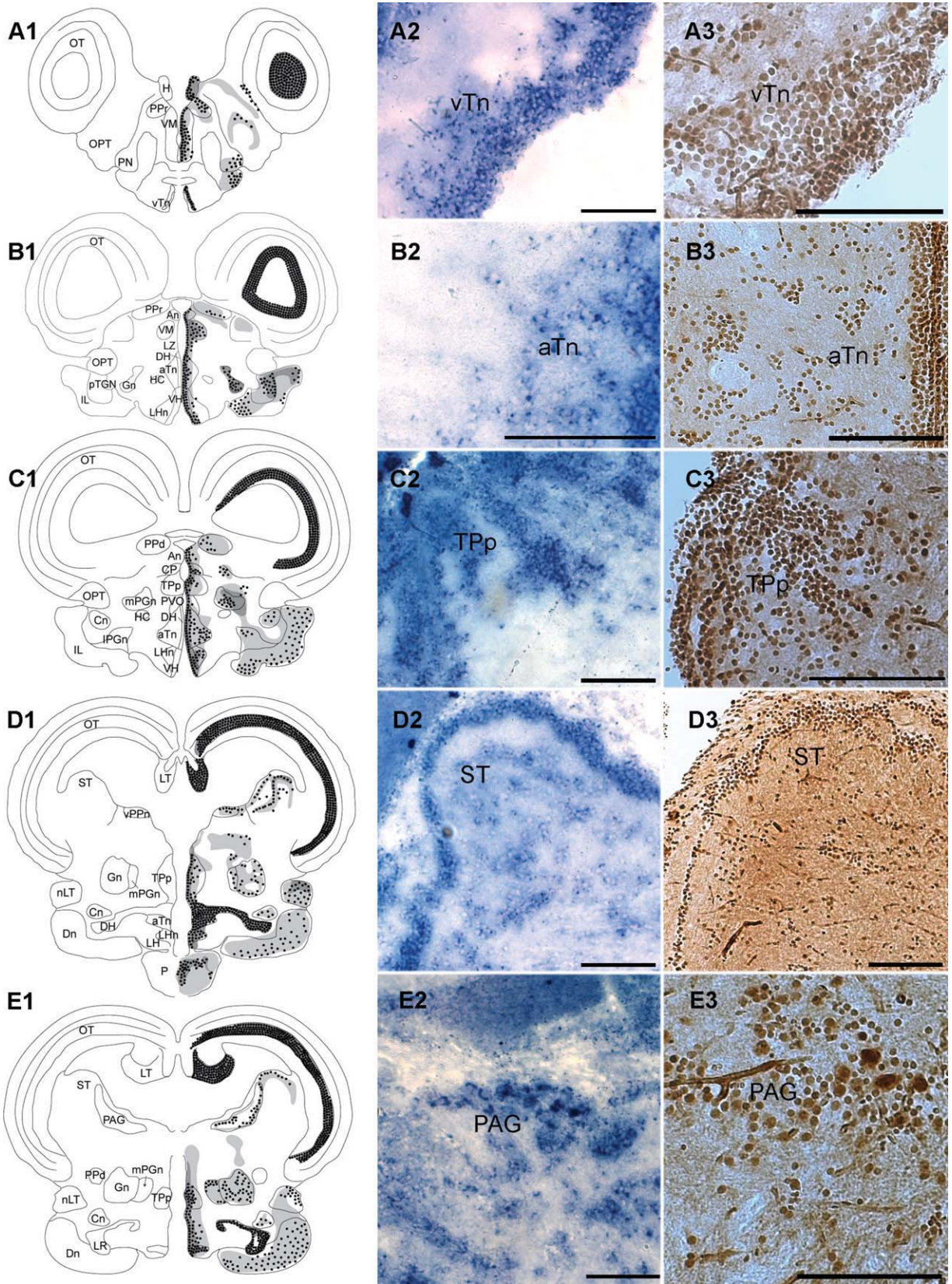


Figure 5

of ER α mRNA and heavy staining of protein immunoreactivity.

Estrogen receptor beta

ER β is abundant throughout the telencephalon, diencephalon, and mesencephalon. Staining of the ER β mRNA subtypes, ER β α and ER β β , largely overlap, but the ER β β subtype appears more widespread in the telencephalon compared to ER β α . While the other sex steroid hormone receptors in the study are very similar in distribution, ER β patterns appear the most different from the other sex steroid receptors. Additionally, the ER β antibody showed either cytosolic or nuclear staining in discrete brain regions. This is similar to ER staining patterns in mammals, where nuclear and/or cytosolic staining is seen throughout development in the pituitary and in adult epithelial cells (Pasqualini et al., 1999; Flynn et al., 2008). These different staining patterns are represented in the distribution maps (Figs. 6, 7) by open circles (cytosolic) or filled circles (nuclear).

Telencephalon

ER β α and ER β β mRNA and protein are found in discrete nuclei of the dorsal and ventral telencephalon (Fig. 6). Interestingly, ER β cell immunoreactivity differed in nuclear or cytosolic staining in discrete brain regions. Overall, there was very consistent overlap of protein immunoreactivity and mRNA detection of both subtypes. Strong mRNA hybridization of both mRNA subtypes and high levels of protein immunoreactivity are seen in the granule cell layer of the olfactory bulb (OB, Fig. 6A). ER β protein is also found within fibers of the glomeruli, although mRNA expression is not found here. In the dorsal telencephalon, ER β protein and both ER β α and ER β β mRNA subtypes are present within Dc, DI, and Dm. Within these dorsal regions, DIg has the highest density of immunoreactive cells. ER β is the only steroid receptor expressed abundantly in DId; PR is present, yet very sparse (see below). This staining is most likely ER β β , as there is ER β β mRNA staining in this region but not ER β α mRNA (Fig. 6A1). Two distinct cell groups positive for ER β form within

Dc (Fig. 6C). The staining in both DId and Dc is cytosolic, suggesting that ER β is not affecting gene transcription within these regions. Within DI, DIg has an abundance of ER β compared to DIv. Within the ventral telencephalon, ER β protein and mRNA subtypes are present within Vc, Vd, Vs, and Vv (Fig. 6B–E). While the pattern of cellular localization in the dorsal telencephalon differs between brain regions, all immunoreactive cells within the ventral telencephalon had predominantly nuclear staining. Finally, ER β protein and mRNA of both subtypes are present in the entopeduncular nucleus (E).

ER β protein and mRNA was also present within the POA, although staining patterns were more restricted within the POA regions compared to the distributions of AR, ER α , and PR in the POA. In some individuals, ER β was more abundant within the dorsal portion of the parvocellular POA than the ventral region. ER β immunoreactivity was also observed in magnocellular and gigantocellular cells (Fig. 6E). Interestingly, within the gigantocellular cells the ER β staining pattern is different from that of the other nuclear hormone receptors in this study, as there appear to be aggregates of protein surrounding the nucleus (Fig. 6E2). These receptors may be inactivated in that they remain in cytosolic aggregates rather than translocate to the nucleus to modulate gene transcription.

Diencephalon and mesencephalon

ER β staining in the diencephalon and mesencephalon is more diffuse than in the telencephalon, but more widespread than the other steroid hormone receptors in this study (Fig. 7). There continues to be high overlap between staining patterns of the ER β mRNA subtypes and ER β protein immunoreactivity. Caudal to the POA, ER β protein and mRNA of both subtypes are present within the VM. The prethalamic nucleus (PN), which lies ventrolateral to VM, also contains ER β protein and mRNA of both subtypes. The habenula (H) also shows heavy staining of ER β mRNA and protein. ER β α and ER β β mRNA and protein are also found within the OT and the LT. In the anterior ventral hypothalamus, ER β is present within the vTn and aTn (Fig. 7A,B). ER β is also

Figure 6. Distribution of ER β mRNA and protein in the telencephalon. Representative sections of the telencephalon are presented as the first image in each panel with ER β protein shown as dots on the right side of the brain and ER β α mRNA shown as gray shading on the left and ER β β mRNA as gray shading on the right. Open circles denote cytosolic staining while closed circles indicate nuclear localization. The density of dots indicating protein corresponds to the density of cells positive for ER β -immunoreactivity. The degree of shading for mRNA corresponds to the density of expression. The micrographs in the top panel show ER β α and ER β β mRNA (A2,A2) and ER β protein (A4) in the olfactory bulb. Micrographs in the second panel show labeling of ER β α and ER β β mRNA (B2,B3) and ER β protein (B4) in Vv. The third panel shows micrographs of ER β α and ER β β mRNA (C2,C3) and ER β protein (C4) in Dc. The fourth panel shows micrographs of ER β α and ER β β mRNA (D2,D3) and ER β protein (D4) in Vdc and Vsm. The bottom panel shows ER β protein in gigantocellular (E2), magnocellular (E3), and parvocellular (E4) cells in the POA. Scale bars = 100 μ m except E2–E4 = 20 μ m. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

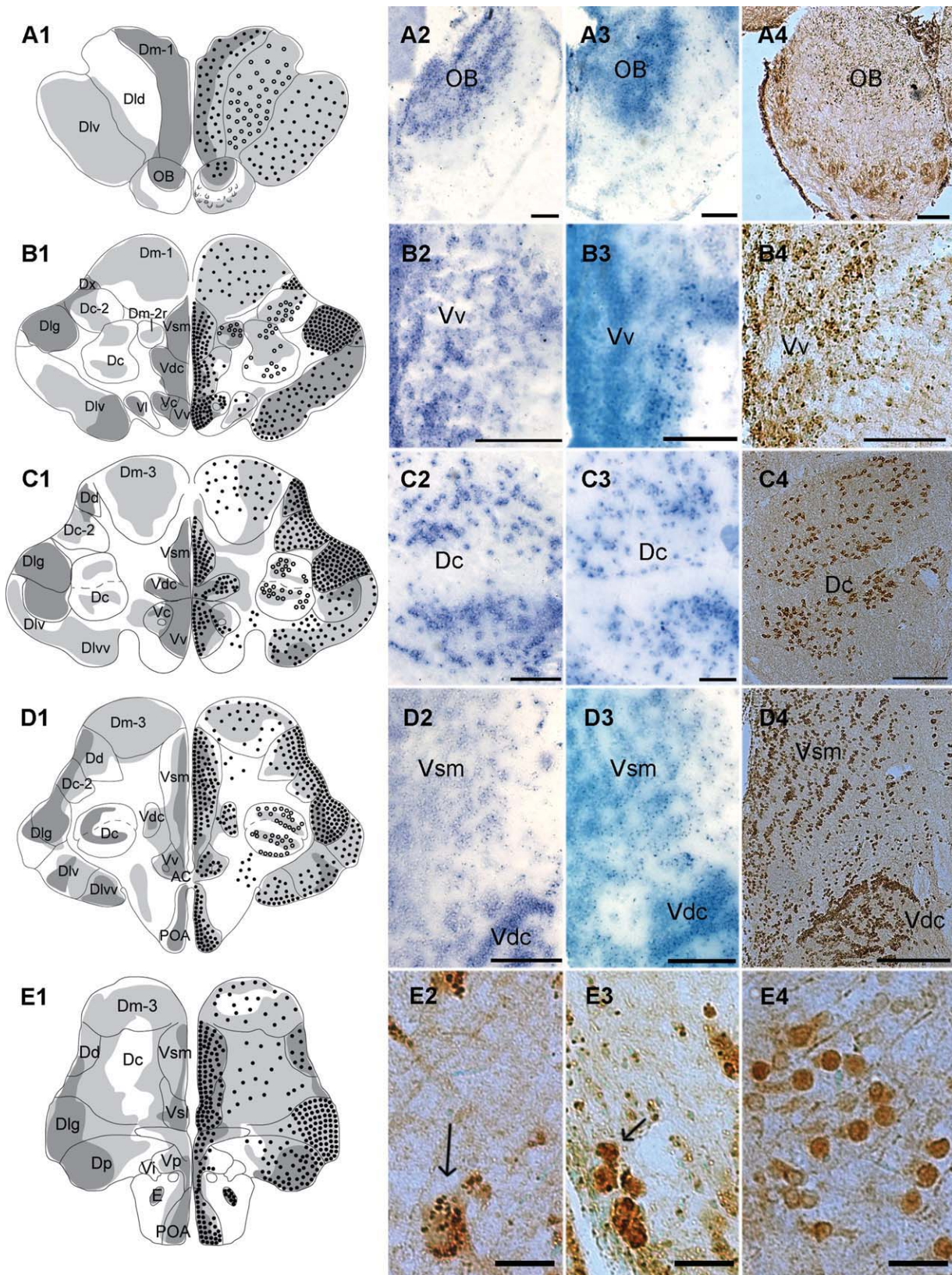


Figure 6

present within the DH, LHn, and VH, and in the periventricular pretectal nuclei PPr, PPd, and vPPn. The thalamic nucleus, CP, also shows ER β staining. The TPp shows staining of both ER β mRNA subtypes and protein (Fig. 7C). The inferior lobe also contains ER β in the Cn and Dn nuclei. Staining of ER β a and ER β b mRNAs and protein-immunoreactive cells was observed within Gn and nLT. ER β mRNA and protein is present in the ST (Fig. 7D) and ventromedial to the ST, the PAG also contains ER β mRNA and protein (Fig. 7E). ER β mRNAs and protein are also found in the caudal diencephalic nuclei, mammillary body (MB, not shown) and preglomerular commissural nucleus (PGCn, not shown). Finally, in the pituitary ER β a and ER β b mRNAs are present throughout, whereas ER β protein immunoreactivity is more heterogeneous.

Progesterone receptor

To our knowledge, we present here the first detailed description of PR in the telencephalon, diencephalon, and mesencephalon of any teleost, although preoptic and hypothalamic regions have recently been described in zebrafish (Hanna et al., 2010). PR is abundant in the telencephalon and diencephalon, and mRNA and protein show high congruence.

Telencephalon

An abundance of PR is found within distinct regions of the dorsal and ventral telencephalon (Fig. 8). There is robust staining of PR mRNA and protein within the granule cell layer of the olfactory bulb (OB, Fig. 8A). Like the other steroid hormone receptors, PR protein is found within the glomeruli, but mRNA is not expressed here. Within the dorsal telencephalon, PR protein and mRNA was present in Dc, Dd, DI, and Dm, and more sparsely in DId. The heaviest staining for mRNA and highest density of immunoreactive cells is found within DIg. PR mRNA and protein cluster into two distinct groups within Dc (Fig. 8C). Within the ventral telencephalon, PR protein and mRNA are present within Vc, Vd, Vs, and Vv (Fig. 8B–E). Regions with the

highest density of PR immunoreactive cells are the Vv and Vsm.

There is a very strong PR mRNA signal and a very high density of PR-immunoreactive cells within the POA. PR is found within parvocellular, magnocellular, and gigantocellular cells (Fig. 8E). Finally, the entopeduncular nucleus (E) contains both PR mRNA expression and protein immunoreactivity.

Diencephalon and mesencephalon

PR mRNA and protein is generally more diffuse in the diencephalon and mesencephalon compared to the telencephalon (Fig. 9). As with patterns seen in the telencephalon, mRNA and protein patterns show high concordance. One of the most striking staining patterns is the robust mRNA and protein signal in the OT and LT, similar to the other sex steroid receptors. Caudal to the POA, PR mRNA and protein is found within the VM. Ventrolateral to VM, the prethalamic nucleus (PN) contains both PR protein and mRNA. The habenula also contains PR mRNA and protein. Within the periventricular pretectal nuclei, PR is present within PPr, PPd, and vPPn. PR mRNA and protein signal is abundant within the anterior ventral hypothalamic nuclei, including the vTn and aTn (Fig. 9A,B) and the DH, VH and LHn. PR mRNA and protein is consistently found throughout the TPp (Fig. 9C) and in the thalamic CP. PR staining is also present within the semicircular torus ST (Fig. 9D) and PAG (Fig. 9E). The lateral torus (nLT) contains both mRNA and protein. In the ventral lateral portion of the hypothalamus, staining is found in the inferior lobe including the Cn and Dn. Light staining of PR protein and mRNA is also found in Gn. More caudally in the diencephalon, mammillary body (MB) and preglomerular commissural nucleus (PGCn) also contain PR mRNA and protein (not shown). Finally, PR mRNA and protein are abundant within the pituitary.

DISCUSSION

We have shown here for males of the African cichlid fish, *A. burtoni*, that steroid hormone receptors are widely

Figure 7. Distribution of ER β mRNA and protein in the diencephalon and mesencephalon. Representative sections of the diencephalon and some mesencephalic structures are depicted in the left column with ER β protein represented by dots on the right, ER β a mRNA as gray shading on the left, and ER β b mRNA as gray shading on the right. Open circles denote cytosolic staining while closed circles indicate nuclear localization. The density of dots indicating protein corresponds to the density of cells positive for ER β -immunoreactivity. The degree of shading for mRNA corresponds to the density of expression. Micrographs in the top row show ER β a and ER β b mRNA (A2,A3) and ER β protein (A4) in the ventral tuberal nucleus. Micrographs in the second row show ER β a and ER β b mRNA (B2,B3) and AR protein (B4) in the anterior tuberal nucleus. The ovoid structure in B2 is a fiber tract that appears alongside the aTn. The third panel contains micrographs showing ER β a and ER β b mRNA (C2,C3) and ER β protein (C4) patterns in the periventricular nucleus of the posterior tuberculum. The fourth panel contains micrographs showing ER β a and ER β b mRNA (D2,D3) and ER β protein (D4) in the semicircular torus (ST). The bottom panel shows micrographs of ER β a and ER β b mRNA (E2,E3) and ER β protein (E4) patterns in the periaqueductal gray (PAG). Scale bars = 100 μ m. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

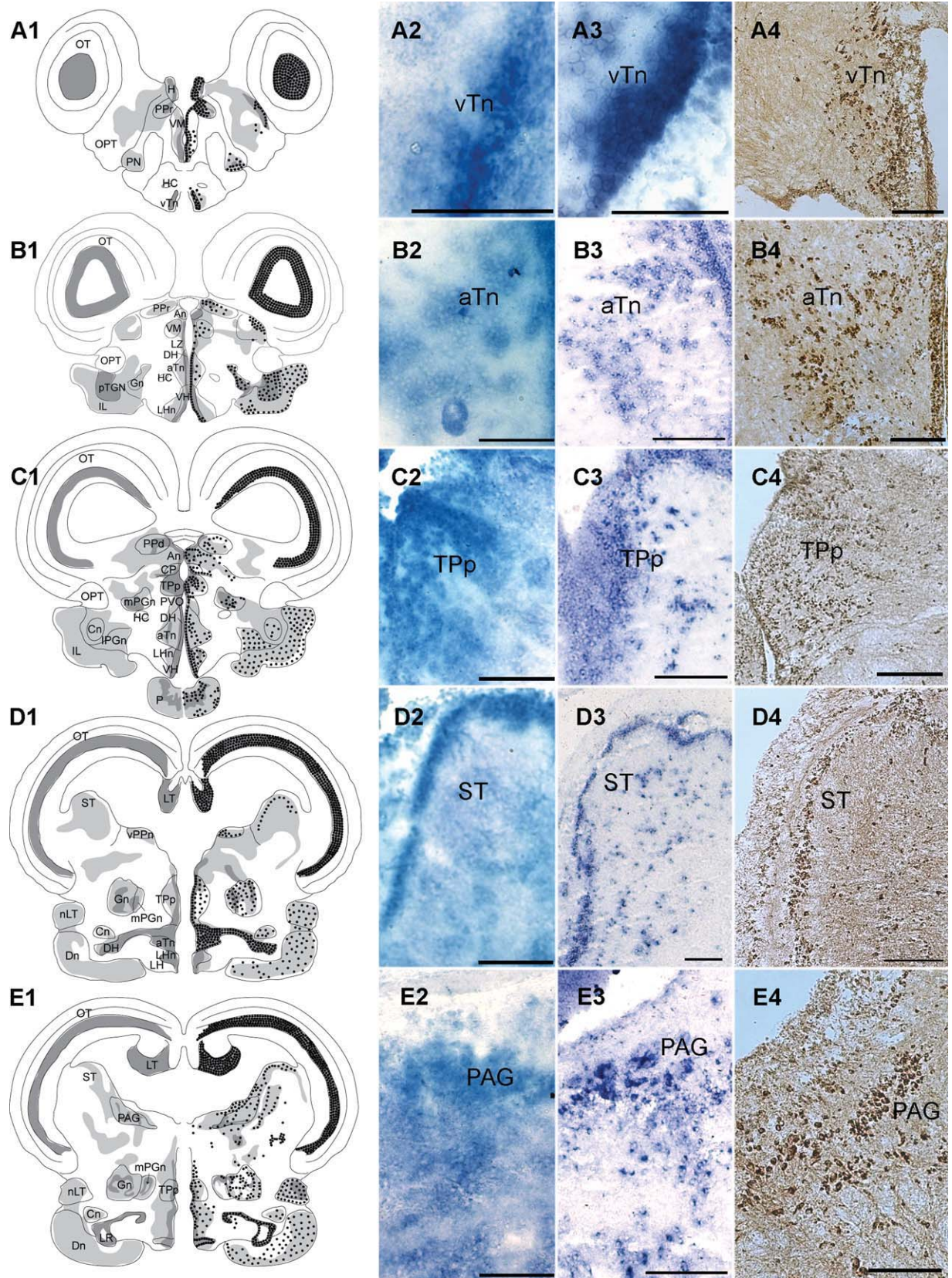


Figure 7

distributed throughout the telencephalon and diencephalon, and have elucidated which regions of the brain are likely targets of sex steroid modulation. We find excellent correspondence between mRNA expression patterns and protein immunoreactivity of each sex steroid hormone receptor. Further, we find sex steroid hormone receptors in neural circuits that are known across vertebrates to modulate social behaviors and/or process the salience/rewarding properties of a stimulus. There is remarkable overlap in the presence of all steroid hormone receptors within many brain nuclei. Variation occurs in the pallial area Dld, where only ER β and PR are expressed (the latter quite sparsely), and in subpallial area VI, which lacks ER α expression. Areas Vp and Dd lack expression of AR α and AR β , respectively. Interestingly, the subpallial area VI, which contains sex steroid receptors in midshipman fish (Forlano et al., 2010), is the only fore- and midbrain region examined where we did not find a single sex steroid hormone receptor. Finally, while all sex steroid hormones were abundant in the granule layer of the OB, only protein was found in the glomerular layer. This discrepancy could be due to sensitivity in mRNA staining or that the protein is translocated to other regions away from the source of translation.

In the following we compare the findings presented here for the cichlid fish *A. burtoni* with previously published results in other species of teleosts as well as tetrapods. Variation within and across species could possibly result from differences in sex and reproductive state in addition to evolutionary divergence and issues related to homology of brain structures. It is important to note, however, that—as a consequence of organizational and/or activational control—variation in sex steroid receptor expression (between sexes; among fixed or plastic alternative phenotypes; or across seasons) typically manifests itself as quantitative differences in expression level, and not qualitatively as presence or absence (Godwin and Crews, 1995; Burmeister et al., 2007). Finally, discrepancies could also result from differences in the techniques used, as most previous studies only detected mRNA and the signal of the expression can vary based on development times.

Neuroanatomical distribution of sex steroid hormones compared with other teleosts

Androgen receptor

AR is widely distributed throughout the *A. burtoni* telencephalon and diencephalon, and mRNA and protein patterns show very high congruence. AR α and AR β mRNA expression patterns have previously been examined in this species (Harbott et al., 2007), although only in telencephalon and hypothalamic areas. Additionally, the present study for the first time determined AR protein distribution in a percomorph fish. The brain regions positive for AR α and AR β expression in this present study are consistent with those reported in Harbott et al. (2007).

The wide distribution pattern of AR protein and the mRNA subtypes shows high overlap with mRNA distributions described for the midshipman (Forlano et al., 2010) and zebrafish (Gorelick et al., 2008) and protein distributions described in goldfish (Gelinas and Callard, 1997). The studies in zebrafish and midshipman did not distinguish between AR α and AR β mRNA subtypes. As in *A. burtoni*, AR protein is expressed within the olfactory bulb of goldfish, but mRNA was not detected within the olfactory bulb of midshipman or zebrafish. Within the dorsal telencephalon (D), the central (Dc) and lateral (DI) subdivisions contain AR protein in goldfish, only DI contains AR mRNA in zebrafish, and Dc and medial subdivision of D (Dm) contain AR mRNA in the midshipman, while *A. burtoni* show mRNA of both subtypes and AR protein in these regions. Comparing *A. burtoni* with these three species, only *A. burtoni* shows AR presence within the posterior division of D (Dp). Within the ventral telencephalon (V), AR protein is found within the goldfish dorsal (Vd) and lateral (VI) subdivisions of V, and AR mRNA is present within the supracommissural (Vs), postcommissural (Vp), dorsal (Vd), and intermediate (Vi) subdivisions of V in the midshipman. Unexpectedly, no subpallial areas were reported to contain AR in zebrafish. Both AR protein and mRNA subtypes are expressed within all of the ventral telencephalon regions previously reported in the other teleost species with the exception of Vi. Surprisingly, AR is not found within the ventral subdivision in the ventral telencephalon (area Vv) of the above teleost species,

Figure 8. Distribution of PR mRNA and protein in the telencephalon. Representative sections of the telencephalon are presented as the first image in each panel with PR protein shown as dots and mRNA shown as shading. The density of dots indicating protein corresponds to the density of cells positive for PR-immunoreactivity. The degree of shading for mRNA corresponds to the density of expression. The micrographs in the top panel show PR mRNA (A2) and PR protein (A3) in the olfactory bulb. Micrographs in the second panel show labeling of PR mRNA (B2) and protein (B2) in Vv. The third panel shows micrographs of PR mRNA (C2) and protein (C3) in Dc. The fourth panel shows micrographs of PR mRNA (D2) and protein (D3) in Vdc and Vsm. The bottom panel shows PR protein in gigantocellular (E2), magnocellular (E3), and parvocellular (E4) cells in the POA. Scale bars = 100 μ m except E2–E4 = 20 μ m. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

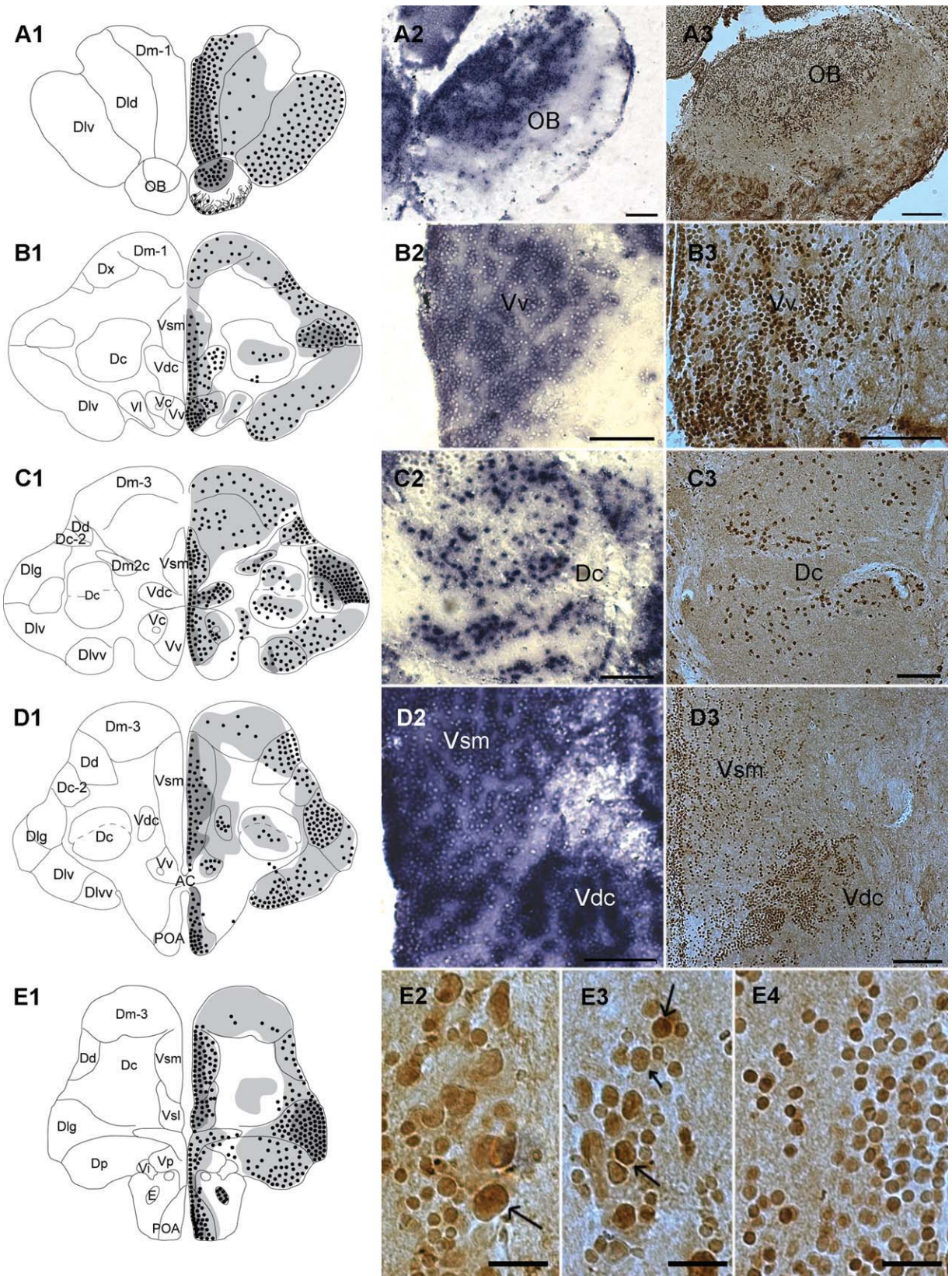


Figure 8

although we find robust expression and protein presence in this region in the present study, consistent with previous studies of AR in *A. burtoni* (Harbott et al., 2007). AR mRNA of both subtypes and protein is found in the preoptic area of *A. burtoni*, zebrafish, midshipman, and goldfish. We also found an abundance of AR in the optic tectum, tuberal nuclei, and hypothalamic regions, consistent with the previous reports in goldfish, zebrafish, and the midshipman.

Estrogen receptor alpha

ER α is also widely distributed throughout the *A. burtoni* telencephalon and diencephalon, much more so than previously published distributions in other teleost species, although most of these studies describe mRNA only and not protein. ER α mRNA distributions have been described in the midshipman (Forlano et al., 2005), Atlantic croaker (Hawkins et al., 2005), rainbow trout (Menuet et al., 2001), zebrafish (Menuet et al., 2002), and eelpout (Andreassen et al., 2003). In general, ER α is consistently found within the ventral regions of the ventral telencephalon (Vv), the preoptic area, and the hypothalamus; however, comparing across teleosts is difficult as many of these studies report only neuroendocrine regions of the brain, with the exception of the midshipman (Forlano et al., 2005). Unlike the midshipman, ER α is found within the lateral portion of the dorsal telencephalon (D1) and the dorsal and caudal regions of the ventral telencephalon (Vd and Vc) in *A. burtoni*. *A. burtoni* and the midshipman have very similar distribution patterns of ER α in ventral hypothalamus, thalamus, and brainstem regions including the periaqueductal gray.

Estrogen receptor beta

ER β is widely distributed throughout the *A. burtoni* telencephalon and diencephalon, where the ER β b mRNA subtype appears to be more widespread than ER β a. Distribution of ER β a and ER β b mRNA subtypes have been described in the Atlantic croaker (Hawkins et al., 2005), sea bass (Muriach et al., 2008), and zebrafish (Menuet et al., 2002), although to our knowledge no studies have examined protein distribution. Studies in sea bass and zebrafish have described ER β

mRNA expression patterns in the POA, hypothalamus, and posterior tuberculum, in which both ER β subtypes are expressed, similar to *A. burtoni*. In contrast to the Atlantic croaker, where ER β b, and not ER β a, is expressed in the posterior tuberculum, both *A. burtoni* and zebrafish express both subtypes within this region. Our results contrast with those from sea bass, where ER β a was expressed in the ventral telencephalon and the POA, but ER β b expression was restricted to the POA.

Progesterone receptor

We have cloned a single PR mRNA transcript from *A. burtoni* and found no evidence for additional PR genes. The Japanese eel likely has two PR subtypes from two different genes (Ikeuchi et al., 2002). However, other ray-finned fishes such as zebrafish, stickleback, and medaka (which all have sequenced genomes available) appear to only have one (Hanna et al., 2010), suggesting either a possible gene duplication in the lineage leading to eels (Anguilliformes) or the deletion of the gene at the base of euteleosts. It is thus unlikely that *A. burtoni* has more than one PR gene.

As with the other sex steroid receptors, we found that PR mRNA and protein have exceptional concordance and are widely distributed throughout the telencephalon and diencephalon. The distribution of PR mRNA and protein in the hypothalamus and preoptic area has been recently described in zebrafish (Hanna et al., 2010). PR is expressed in the same regions of the telencephalon in both zebrafish and *A. burtoni*. The only region of the ventral telencephalon (V) described by Hanna et al. (2010) was the postcommissural subdivision of the V (Vp), which expresses PR, similar to *A. burtoni*. Regions of the zebrafish brain in the dorsal telencephalon (D) were the medial, lateral, and posterior divisions of D (Dm, Dl, and Dp), in which PR is abundant in both species. In the diencephalon of both zebrafish and *A. burtoni*, PR was also expressed in the periventricular nucleus of the posterior tuberculum (TPp) and in the thalamic central posterior nucleus (CP). Finally PR is expressed in the zebrafish dorsal, ventral, and lateral periventricular hypothalamic areas (DH, VH, and LHn, respectively) and in the anterior tuberal nucleus (aTn), similar to *A. burtoni*.

Figure 9. Distribution of progesterone receptor mRNA and protein in the diencephalon and mesencephalon. Representative sections of the diencephalon and some mesencephalic structures are depicted in the left column with PR protein represented by dots and mRNA as gray shading. The density of dots indicating protein corresponds to the density of cells positive for PR-immunoreactivity. The degree of shading for mRNA corresponds to the density of expression. Micrographs in the top row show PR mRNA (A2) and protein (A3) in the ventral tuberal nucleus. Micrographs in the second row show PR mRNA (B2) and protein (B3) in the anterior tuberal nucleus. The third panel contains micrographs showing PR mRNA (C2) and protein (C3) patterns in the periventricular nucleus of the posterior tuberculum. The fourth panel contains micrographs showing PR mRNA (D2) and protein (D3) in the semicircular torus (ST). The bottom panel shows micrographs of PR mRNA (E2) and protein (E3) patterns in the periaqueductal gray (PAG). Scale bars = 100 μ m. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

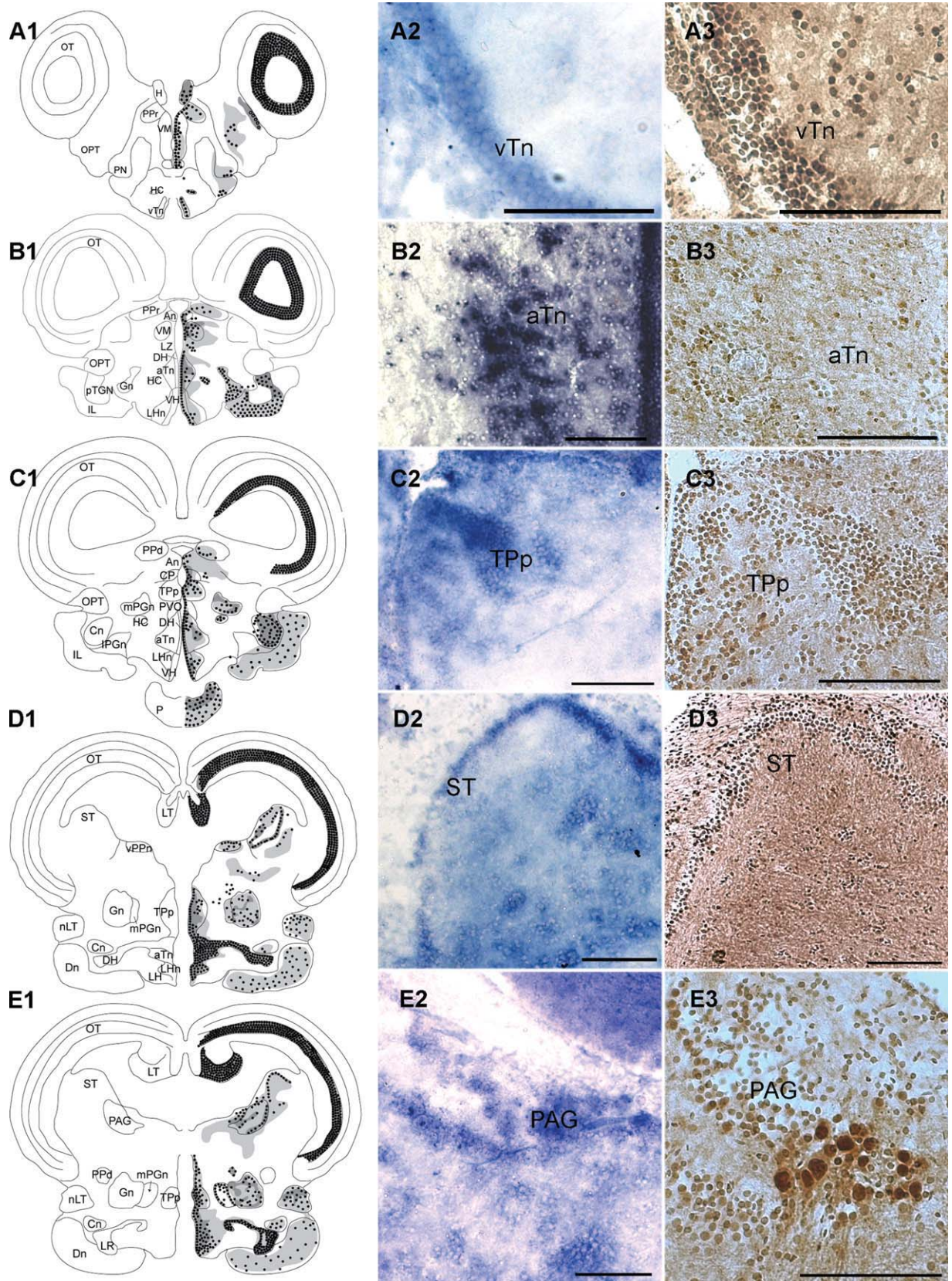


Figure 9

Functional considerations of sex steroid hormone receptors in the teleost brain

Various lesion and stimulation studies have pointed to the POA as a brain region that regulates aggressive and reproductive behaviors in teleosts, consistent with findings in other vertebrates (Wheeler and Crews, 1978; de Jonge et al., 1989). Electrical stimulation of the POA increases courtship behavior and decreases aggressive displays in *Lepomis* sunfish males (Demski and Knigge, 1971). It is obviously advantageous to a male to decrease aggressive displays while courting a female (Miller, 1963). Ablation of the POA decreases the spawning reflex in male killifish, *Fundulus heteroclitus* (Macey et al., 1974). We have found all sex steroid hormone receptors within all three cell groups (parvocellular, magnocellular, and gigantocellular) in the POA (Figs. 2E, 4E, 6E, 8E). Previous work by Greenwood et al. (2008) in *A. burtoni* has suggested that these three cell groups may differentially regulate social dominance, as dominant males have higher AVT expression in the gigantocellular subregion compared to subordinate males. However, subordinate males have higher AVT expression in the parvocellular portion, while AVT expression in the magnocellular portion does not differ with social status. Future studies utilizing quantitative in situ hybridization for sex steroid receptors in the different subpopulations of the POA will provide us insight into whether these receptors are differently modulating social dominance in a region-specific manner.

Also functionally important as a social signal to some male teleost fish, including *A. burtoni*, is the production of body coloration. Compared with subordinate males, dominant *A. burtoni* males show bright nuptial coloration and also have higher levels of circulating testosterone (Parikh et al., 2006a; Greenwood et al., 2008). Functional studies of the neural control of coloration have shown that electrical stimulation of the ventral ST evokes agonistic color responses in *Lepomis* sunfish males (Demski, 1969). We have shown here that all sex steroid hormone receptors are present within the ST, including the androgen receptors, which supports the hypothesis that gonadal hormones also play a role in generating and regulating teleost fish color patterns.

Comparison of sex steroid hormone distributions to tetrapods

The structure of the teleost brain has long been a source of confusion for neuroanatomists, but as evidence accumulated that the brain develops via eversion of the neural tube, rather than inversion as in tetrapods and other nonteleost fishes, much progress has been made in the mapping of the teleost brain and assigning these

brain regions putative homologies (Yamamoto et al., 2007). Homologies between brain regions in teleosts and other vertebrates are emerging not only through developmental studies, but also through lesion, neurochemistry, hodology studies (Rink and Wullimann, 2001, 2002; Portavella et al., 2002; Wullimann and Mueller, 2004; Northcutt, 2006, 2008; Bruce and Braford, 2009). Understanding these (partial) homology relationships across vertebrates will be necessary for reconstructing the evolution of two neural circuits that are considered crucial in the regulation of social behavior and the evaluation of rewarding stimuli, respectively: Newman's social behavior network (Newman, 1999) and the mesolimbic dopaminergic system (Wise, 2002). The homologies suggested here for relating various fore- and midbrain regions in teleosts and tetrapods are based on a multitude of considerations, and should thus still be considered tentative.

The social behavior network that was originally described in mammals has now been expanded to other vertebrate classes (Crews, 2003; Goodson, 2005). The brain regions in the network contain mostly hypothalamic regions, mediate social behavior, and express steroid hormone receptors. The nodes of this network include the preoptic area (POA), anterior hypothalamus, ventromedial hypothalamus, medial amygdala (MeAMY) and bed nucleus of the stria terminalis (BNST), periaqueductal gray, and the lateral septum (LS). These regions contain steroid hormone receptors in every vertebrate class studied including reptiles (Young et al., 1994; Moga et al., 2000; Tang et al., 2001; Rosen et al., 2002), amphibians (Meglio et al., 1987; Guerriero et al., 2005), birds (Sterling et al., 1987; Balthazart et al., 1998; Foidart, 1999; Belle and Lea, 2001), and mammals (Kato et al., 1994; Osterlund et al., 1998; Murphy et al., 1999; Roselli et al., 2001; Zhang et al., 2002; Holmes et al., 2008). The only exceptions seem to be in the periaqueductal gray, where ER is absent in reptiles and PR is absent in birds. The putative homologs of these brain regions in teleosts are the supra-commissural region of the ventral telencephalon (Vs) as the homolog of the MeAMY/BNST (Northcutt, 1995), the ventral and lateral nuclei of the ventral telencephalon (Vv and Vl) as the homolog of the lateral septum (Wullimann and Müller, 2004), the POA as the homolog to the mammalian medial preoptic area (Moore and Lowry, 1998), the ventral tuberal region as the homolog to the anterior hypothalamus (Kittelberger et al., 2006), the anterior tuberal region as the homolog of the ventromedial hypothalamus (Forlano et al., 2005), and the PAG as the mammalian periaqueductal gray (Forlano et al., 2001). We have shown here that steroid hormone receptors are expressed in each of these brain regions in *A. burtoni*, providing neurochemical evidence in support of these suggested homologies in the social behavior network,

although further manipulative and behavioral studies are still necessary.

The midbrain dopaminergic system consists of the ventral tegmental area, which projects to many forebrain nuclei in what has been described as the “reward” system and is important for reinforcing learned behavior (Young and Wang, 2004). Regions that receive input from this dopaminergic system include the basolateral amygdala, hippocampus, nucleus accumbens, ventral pallidum, striatum, BNST, and the lateral septum. Most of these brain nuclei contain steroid hormone receptors in reptiles (Young et al., 1994; Moga et al., 2000; Tang et al., 2001), amphibians (di Meglio et al., 1987; Guerriero et al., 2005), birds (Sterling et al., 1987; Balthazart et al., 1998; Foidart et al., 1999; Belle and Lea, 2001), and mammals (Kato et al., 1994; Osterlund et al., 1998; Murphy et al., 1999; Zhang et al., 2002; Holmes et al., 2008). However, there are some exceptions, as PR is not present (or has not been reported) within the avian amygdaloid complex or in the VTA; ER is not present (or has not been reported) within the nucleus accumbens, striatum, VTA, or amygdaloid complex of reptiles, and AR is not present (or has not been reported) in the VTA of reptiles or within the striatum of mammals. The putative teleost homologs to these forebrain nuclei are more contentious than those of the social behavior network. The putative homologs are as follows: the medial division of the dorsal telencephalon (Dm) as a putative homolog to the mammalian lateral amygdala (Portavella et al., 2002; Northcutt, 2006), the lateral region of the dorsal telencephalon (DI) as a putative homolog to the mammalian hippocampus (Portavella, 2004; Northcutt, 2006), the ventral region of the ventral telencephalon (Vv) is a putative homolog to the mammalian nucleus accumbens (Northcutt, 1995; Braford, 2009), the dorsal and central regions of the ventral telencephalon (Vc/Vd) is a putative homolog to the vertebrate striatum (Wullimann and Rink, 2002), the postcommissural region of the ventral telencephalon (Vp) is a putative homolog to the basal amygdala (Nieuwenhuys and Meek, 1990), and the posterior tuberculum (TPp) has been suggested to be at least functionally equivalent (Rink and Wullimann, 2001) or, more recently, in fact homologous to the ventral tegmental area (Luo et al., 2008). We report here that AR, ER α , ER β , and PR are within all of these regions in *A. burtoni*, suggesting that steroid hormones may play an important role in modulating these neural systems involved in evaluating the salience of social and other stimuli.

CONCLUSIONS

We have demonstrated that AR, ER α , ER β , and PR are expressed in brain regions that putatively regulate social

behavior and evaluation of stimulus salience in a teleost brain. These findings suggest that steroid hormones may play an important role in the regulation of complex social behavior, behavioral plasticity, and the evaluation of a rewarding stimulus in *A. burtoni*. Building on this foundation, future work will use quantitative detection methods and pharmacological manipulations to further dissect the role steroid hormone receptors may play in regulating the remarkable plasticity of social behavior in this species either on their own or in concert with neuropeptide pathways and aminergic modulation.

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LITERATURE CITED

- Ahrens K, Wullimann MF. 2002. Hypothalamic inferior lobe and lateral torus connections in a percomorph teleost, the red cichlid (*Hemichromis lifalili*). *J Comp Neurol* 449: 43–64.
- Andreassen TK, Skjoedt K, Anglade I, Kah O, Korsgaard B. 2003. Molecular cloning, characterisation, and tissue distribution of oestrogen receptor alpha in eelpout (*Zoarces viviparus*). *Gen Comp Endocrinol* 132:356–368.
- Aubin-Horth N, Renn SC. 2009. Genomic reaction norms: using integrative biology to understand molecular mechanisms of phenotypic plasticity. *Mol Ecol* 18:3763–3780.
- Ball GF, Balthazart J. 2004. Hormonal regulation of brain circuits mediating male sexual behavior in birds. *Physiol Behav* 83:329–346.
- Balthazart J, Ball GF. 2007. Topography in the preoptic region: differential regulation of appetitive and consummatory male sexual behaviors. *Front Neuroendocrinol* 28: 161–178.
- Balthazart J, Foidart A, Houbart M, Prins GS, Ball GF. 1998. Distribution of androgen receptor-immunoreactive cells in the quail forebrain and their relationship with aromatase immunoreactivity. *J Neurobiol* 35:323–340.
- Bass AH, Grober MS. 2001. Social and neural modulation of sexual plasticity in teleost fish. *Brain Behav Evol* 57: 293–300.
- Braford MR, Northcutt RG. 1983. Organization of the diencephalon and pretectum of ray-finned fishes. In: David RG, Northcutt RG, editors. *Fish neurobiology*, vol. 2. Ann Arbor: University of Michigan Press. p 117–163.
- Belle MD, Lea RW. 2001. Androgen receptor immunolocalization in brains of courting and brooding male and female ring doves (*Streptopelia risoria*). *Gen Comp Endocrinol* 124:173–187.
- Bruce LL, Braford MR. 2009. Evolution of the limbic system. In: Squire LR, editor. *Encyclopedia of neuroscience*, vol. 4. Oxford: Academic Press. p 43–55.
- Burmeister SS, Kailasanath V, Fernald RD. 2007. Social dominance regulates androgen and estrogen receptor gene expression. *Horm Behav* 51:164–170.

- Burmeister SS, Munshi RG, Fernald RD. 2009. Cytoarchitecture of a cichlid fish telencephalon. *Brain Behav Evol* 74: 110–120.
- Crews D. 2003. The development of phenotypic plasticity: where biology and psychology meet. *Dev Psychobiol* 43: 1–10.
- Crews D. 2005. Evolution of neuroendocrine mechanisms that regulate sexual behavior. *Trends Endocrinol Metab* 16: 354–361
- de Jonge FH, Louwerse AL, Ooms MP, Evers P, Endert E, van de Poll NE. 1989. Lesions of the SDN-POA inhibit sexual behavior of male Wistar rats. *Brain Res Bull* 23:483–492.
- Deco G, Rolls ET. 2005. Attention, short-term memory, and action selection: a unifying theory. *Prog Neurobiol* 76: 236–256.
- Demski LS. 1969. Behavioral effects of electrical stimulation of the brain in free-swimming bluegills (*Lepomis macrochirus*). PhD Diss., University of Rochester, New York.
- Demski LS, Knigge KM. 1971. The telencephalon and hypothalamus of the bluegill (*Lepomis macrochirus*): evoked feeding, aggressive and reproductive behavior with representative frontal sections. *J Comp Neurol* 143:1–16.
- di Meglio M, Morrell JI, Pfaff DW. 1987. Localization of steroid-concentrating cells in the central nervous system of the frog *Rana esculenta*. *Gen Comp Endocrinol* 67: 149–154.
- Dulac C, Kimchi T. 2007. Neural mechanisms underlying sex-specific behaviors in vertebrates. *Curr Opin Neurobiol* 17: 675–683.
- Fernald RD. 1976. The effect of testosterone on the behavior and coloration of adult male cichlid fish (*Haplochromis burtoni*, Günther). *Horm Res* 7:172–178.
- Fernald RD, Hirata NR. 1977a. Field study of *Haplochromis burtoni*: quantitative behavioral observations. *Anim Behav* 25:964–975.
- Fernald RD, Hirata NR. 1977b. Field study of *Haplochromis burtoni*: habitats and co-habitants. *Environ Biol Fishes* 2: 299–308.
- Fernald RD, Shelton LC. 1985. The organization of the dienkephalon and the preteum in the cichlid fish, *Haplochromis burtoni*. *J Comp Neurol* 238:202–217.
- Fine ML, Chen FA, Keefer DA. 1996. Autoradiographic localization of dihydrotestosterone and testosterone concentrating neurons in the brain of the oyster toadfish. *Brain Res* 709:65–80.
- Flynn JM, Dimitrijevic SD, Younes M, Skliris G, Murphy LC, Cammarata PR. 2008. Role of wild-type estrogen receptor-beta in mitochondrial cytoprotection of cultured normal male and female human lens epithelial cells. *Am J Physiol Endocrinol Metab* 295:E637–647.
- Foidart A, Lakaye B, Grisar T, Ball GF, Balthazart J. 1999. Estrogen receptor-beta in quail: cloning, tissue expression and neuroanatomical distribution. *J Neurobiol* 40:327–342.
- Forlano PM, Deitcher DL, Myers DA, Bass AH. 2001. Anatomical distribution and cellular basis for high levels of aromatase activity in the brain of teleost fish: aromatase enzyme and mRNA expression identify glia as source. *J Neurosci* 21:8943–8955.
- Forlano PM, Deitcher DL, Bass AH. 2005. Distribution of estrogen receptor alpha mRNA in the brain and inner ear of a vocal fish with comparisons to sites of aromatase expression. *J Comp Neurol* 483:91–113.
- Forlano PM, Marchaterre M, Deitcher DL, Bass AH. 2010. Distribution of androgen receptor mRNA expression in vocal, auditory and neuroendocrine circuits in a teleost fish. *J Comp Neurol* 518:493–512.
- Galea LA, Uban KA, Epp JR, Brummelte S, Barha CK, Wilson WL, Lieblich SE, Pawluski JL. 2008. Endocrine regulation of cognition and neuroplasticity: our pursuit to unveil the complex interaction between hormones, the brain, and behaviour. *Can J Exp Psychol* 62:247–260.
- Gelinas D, Callard GV. 1997. Immunolocalization of aromatase- and androgen receptor-positive neurons in the goldfish brain. *Gen Comp Endocrinol* 106:155–168.
- Godwin J, Crews D. 1995. Sex differences in estrogen and progesterone receptor messenger ribonucleic acid regulation in the brain of little striped whiptail lizards. *Neuroendocrinology* 62:293–300.
- Goodson JL. 2005. The vertebrate social behavior network: evolutionary themes and variations. *Horm Behav* 48: 11–22.
- Gorelick DA, Watson W, Halpern ME. 2008. Androgen receptor gene expression in the developing and adult zebrafish brain. *Dev Dyn* 237:2987–2995.
- Goymann W. 2009. Social modulation of androgens in male birds. *Gen Comp Endocrinol* 163:149–157.
- Greenwood AK, Wark AR, Fernald RD, Hofmann HA. 2008. Expression of arginine vasotocin in distinct preoptic regions is associated with dominant and subordinate behaviour in an African cichlid fish. *Proc Biol Sci* 275: 2393–2402.
- Guerrero G, Prins GS, Birch L, Ciarcia G. 2005. Neurodistribution of androgen receptor immunoreactivity in the male frog, *Rana esculenta*. *Ann N Y Acad Sci* 1040:332–336.
- Hanna RN, Daly SC, Pang Y, Anglade I, Kah O, Thomas P, Zhu Y. 2010. Characterization and expression of the nuclear progesterin receptor in zebrafish gonads and brain. *Biol Reprod* 82:112–122.
- Harbott LK, Burmeister SS, White RB, Vagell M, Fernald RD. 2007. Androgen receptors in a cichlid fish, *Astatotilapia burtoni*: structure, localization, and expression levels. *J Comp Neurol* 504:57–73.
- Hawkins MB, Godwin J, Crews D, Thomas P. 2005. The distributions of the duplicate oestrogen receptors ER-beta a and ER-beta b in the forebrain of the Atlantic croaker (*Micropogonias undulatus*): evidence for subfunctionalization after gene duplication. *Proc Biol Sci B* 272:633–641.
- Hofmann HA. 2003. Functional genomics of neural and behavioral plasticity. *J Neurobiol* 54:272–282.
- Holmes MM, Goldman BD, Forger NG. 2008. Social status and sex independently influence androgen receptor expression in the eusocial naked mole-rat brain. *Horm Behav* 54:278–285.
- Hull EM, Dominguez JM. 2007. Sexual behavior in male rodents. *Horm Behav* 52:45–55.
- Ikeuchi T, Todo T, Kobayashi T, Nagahama Y. 2002. A novel progesterone receptor subtype in the Japanese eel, *Anguilla japonica*. *FEBS Lett* 510:77–82.
- Kato J, Hirata S, Nozawa A, Yamada-Mouri N. 1994. Gene expression of progesterone receptor isoforms in the rat brain. *Horm Behav* 28:454–463.
- Kittelberger JM, Land BR, Bass AH. 2006. Midbrain periaqueductal gray and vocal patterning in a teleost fish. *J Neurophysiol* 96:71–85.
- Knapp R. 2004. Endocrine mediation of vertebrate male alternative reproductive tactics: the next generation of studies. *Integr Comp Biol* 43:658–668.
- Luine VN. 2008. Sex steroids and cognitive function. *J Neuroendocrinol* 20:866–872.
- Luo GR, Chen Y, Li XP, Liu TX, Le WD. 2008. Nr4a2 is essential for the differentiation of dopaminergic neurons during zebrafish embryogenesis. *Mol Cell Neurosci* 39: 202–210.
- Macey MJ, Pickford GE, Peter RE. 1974. Forebrain localization of the spawning reflex response to exogenous neurohypophysial hormones in the killifish, *Fundulus heteroclitus*. *J Exp Zool* 190:269–280.

- Mani SK, Portillo W, Reyna A. 2009. Steroid hormone action in the brain: cross-talk between signalling pathways. *J Neuroendocrinol* 21:243–247.
- McEwen BS. 1980. Gonadal steroids and brain development. *Biol Reprod* 22:43–48.
- Meader RG. 1934. The optic system of the teleost, *Holocentrus*. I. The primary optic pathways and the corpus geniculatum complex. *J Comp Neurol* 60:361–407.
- Menuet A, Anglade I, Flouriot G, Pakdel F, Kah O. 2001. Tissue-specific expression of two structurally different estrogen receptor alpha isoforms along the female reproductive axis of an oviparous species, the rainbow trout. *Biol Reprod* 65:1548–1557.
- Menuet A, Pellegrini E, Anglade I, Blaise O, Laudet V, Kah O, Pakdel F. 2002. Molecular characterization of three estrogen receptor forms in zebrafish: binding characteristics, transactivation properties, and tissue distributions. *Biol Reprod* 66:1881–1892.
- Miller HC. 1963. The behavior of the pumpkinseed sunfish *Lepomis gibbosus* (Linnaeus), with notes on the behavior of other species of *Lepomis* and the pigmy sunfish, *Elassoma evergladei*. *Behaviour* 22:88–151.
- Moga MM, Geib BM, Zhou D, Prins GS. 2000. Androgen receptor-immunoreactivity in the forebrain of the eastern fence lizard (*Sceloporus undulatus*). *Brain Res* 879:174–182.
- Moore MC. 1991. Application of organization-activation theory to alternative male reproductive strategies: a review. *Horm Behav* 25:154–179.
- Moore FL, Lowry CA. 1998. Comparative neuroanatomy of vasotocin and vasopressin in amphibians and other vertebrates. *Comp Biochem Physiol C Pharmacol Toxicol Endocrinol* 119:251–260.
- Muriach B, Carrillo M, Zanuy S, Cerdá-Reverter JM. 2008. Distribution of estrogen receptor 2 mRNAs (Esr2a and Esr2b) in the brain and pituitary of the sea bass (*Dicentrarchus labrax*). *Brain Res* 1210:126–141.
- Murphy AZ, Shupnik MA, Hoffman GE. 1999. Androgen and estrogen (alpha) receptor distribution in the periaqueductal gray of the male rat. *Horm Behav* 36:98–108.
- Newman SW. 1999. The medial extended amygdala in male reproductive behavior. A node in the mammalian social behavior network. *Ann N Y Acad Sci* 877:242–257.
- Nieuwenhuys R, Meek J. 1990. The telencephalon of sarcopterygian fishes. In: Jones EG, Peters A, editors. *Cerebral cortex*, vol. 8A. Comparative structure and evolution of cerebral cortex. Part I. New York: Plenum Press. p 75–106.
- Nieuwenhuys R, ten Donkelaar HJ, Nicholson E. 1998. *The central nervous system of vertebrates*. Berlin: Springer.
- Northcutt RG. 1995. The forebrain of gnathostomes: in search of a morphotype. *Brain Behav Evol* 46:275–318.
- Northcutt RG. 2006. Connections of the lateral and medial divisions of the goldfish telencephalic pallium. *J Comp Neurol* 494:903–943.
- Northcutt RG. 2008. Forebrain evolution in bony fishes. *Brain Res Bull* 75:191–205.
- Osterlund M, Kuiper GG, Gustafsson JA, Hurd YL. 1998. Differential distribution and regulation of estrogen receptor-alpha and -beta mRNA within the female rat brain. *Brain Res Mol Brain Res* 54:175–180.
- Parikh VN, Clement TS, Fernald RD. 2006a. Androgen level and male social status in the African cichlid, *Astatotilapia burtoni*. *Behav Brain Res* 166:291–295.
- Parikh VN, Clement TS, Fernald RD. 2006b. Physiological consequences of social descent: studies in *Astatotilapia burtoni*. *J Endocrinol* 190:183–190.
- Pasqualini C, Guivarch D, Boxberg YV, Nothias F, Vincent JD, Vernier P. 1999. Stage- and region-specific expression of estrogen receptor alpha isoforms during ontogeny of the pituitary gland. *Endocrinology* 140:2781–2789.
- Phoenix C, Goy R, Gerall A, Young W. 1959. Organizing action of prenatally administered testosterone propionate on the tissues mediating mating behavior in the female guinea pig. *Endocrinology* 65:369–382.
- Portavella M, Vargas JP, Torres B, Salas C. 2002. The effects of telencephalic pallial lesions on spatial, temporal, and emotional learning in goldfish. *Brain Res Bull* 57:397–399.
- Remage-Healey L, Bass AH. 2006. A rapid neuromodulatory role for steroid hormones in the control of reproductive behavior. *Brain Res* 1126:27–35.
- Rink E, Wullimann MF. 2001. The teleostean (zebrafish) dopaminergic system ascending to the subpallium (striatum) is located in the basal diencephalon (posterior tuberculum). *Brain Res* 889:316–330.
- Rink E, Wullimann MF. 2002. Connections of the ventral telencephalon and tyrosine hydroxylase distribution in the zebrafish brain (*Danio rerio*) lead to identification of an ascending dopaminergic system in a teleost. *Brain Res Bull* 57:385–387.
- Robinson GE, Fernald RD, Clayton DF. 2008. Genes and social behavior. *Science* 322:896–900.
- Roselli CE, Klosterman S, Resko JA. 2001. Anatomic relationships between aromatase and androgen receptor mRNA expression in the hypothalamus and amygdala of adult male cynomolgus monkeys. *J Comp Neurol* 439:208–223.
- Rosen G, O'Bryant E, Matthews J, Zacharewski T, Wade J. 2002. Distribution of androgen receptor mRNA expression and immunoreactivity in the brain of the green anole lizard. *J Neuroendocrinol* 14:19–28.
- Sterling RJ, Gasc JM, Sharp PJ, Renoir JM, Tuohimaa P, Baulieu EE. 1987. The distribution of nuclear progesterone receptor in the hypothalamus and forebrain of the domestic hen. *Cell Tissue Res* 248:201–205.
- Tang YZ, Piao YS, Zhuang LZ, Wang ZW. 2001. Expression of androgen receptor mRNA in the brain of *Gekko gekko*: implications for understanding the role of androgens in controlling auditory and vocal processes. *J Comp Neurol* 438:136–147.
- Tetel MJ. 2009. Nuclear receptor coactivators: essential players for steroid hormone action in the brain and in behaviour. *J Neuroendocrinol* 21:229–237.
- Thompson CW, Moore MC. 1992. Behavioral and hormonal correlates of alternative reproductive strategies in a polygynous lizard: tests of the relative plasticity and challenge hypotheses. *Horm Behav* 26:568–585.
- Trainor BC, Lin S, Finy MS, Rowland MR, Nelson RJ. 2007. Photoperiod reverses the effects of estrogens on male aggression via genomic and nongenomic pathways. *Proc Natl Acad Sci U S A* 104:9840–9845.
- Westberg L, Eriksson E. 2008. Sex steroid-related candidate genes in psychiatric disorders. *J Psychiatry Neurosci* 33:319–330.
- Wheeler JM, Crews D. 1978. The role of the anterior hypothalamus-preoptic area in the regulation of male reproductive behavior in the lizard, *Anolis carolinensis*: lesion studies. *Horm Behav* 11:42–60.
- Wickens JR, Budd CS, Hyland BI, Arbuthnott GW. 2007. Striatal contributions to reward and decision making: making sense of regional variations in a reiterated processing matrix. *Ann N Y Acad Sci* 1104:192–212.
- Wise RA. 2002. Brain reward circuitry: insights from unsensed incentives. *Neuron* 36:229–240.
- Wullimann MF, Mueller T. 2004. Teleostean and mammalian forebrains contrasted: Evidence from genes to behavior. *J Comp Neurol* 475:143–162.

- Wullimann MF, Rink E. 2002. The teleostean forebrain: a comparative and developmental view based on early proliferation, Pax6 activity and catecholaminergic organization. *Brain Res Bull* 57:363–370.
- Yamamoto N, Ito H. 2005. Fiber connections of the anterior preglomerular nucleus in cyprinids with notes on telencephalic connections of the preglomerular complex. *J Comp Neurol* 491:212–233.
- Yamamoto N, Ito H. 2008. Visual, lateral line, and auditory ascending pathways to the dorsal telencephalic area through the rostralateral region of the lateral preglomerular nucleus in cyprinids. *J Comp Neurol* 508:615–647.
- Yamamoto N, Ishikawa Y, Yoshimoto M, Xue HG, Bahaxar N, Sawai N, Yang CY, Ozawa H, Ito H. 2007. A new interpretation on the homology of the teleostean telencephalon based on hodology and a new eversion model. *Brain Behav Evol* 69:96–104.
- Yang CY, Xue HG, Yoshimoto M, Ito H, Yamamoto N, Ozawa H. 2007. Fiber connections of the corpus glomerulosum pars rotunda, with special reference to efferent projection pattern to the inferior lobe in a percomorph teleost, tilapia (*Oreochromis niloticus*). *J Comp Neurol* 501:582–607.
- Young LJ, Wang Z. 2004. The neurobiology of pair bonding. *Nat Neurosci* 7:1048–1054.
- Young WC, Goy RW, Phoenix CH. 1964. Hormones and sexual behavior. *Science* 143:212–218.
- Young LJ, Lopreato GF, Horan K, Crews D. 1994. Cloning and in situ hybridization analysis of estrogen receptor, progesterone receptor, and androgen receptor expression in the brain of whiptail lizards (*Cnemidophorus uniparens* and *C. inornatus*). *J Comp Neurol* 347:288–300.
- Zhang JQ, Cai WQ, Su BY, Zhou de S. 2002. Immunocytochemical localization of estrogen receptor beta in the rat brain. *Shi Yan Sheng Wu Xue Bao* 35:15–20.