Polybrominated diphenyl ethers (PBDEs) are added to plastics, polyurethane foam, paints, and synthetic fabrics as a flame retardant. Recently, concerns have arisen about possible health impacts of PBDE exposure because studies have revealed rising PBDE levels in the tissues of humans and wildlife (Hites 2004; Law et al. 2003). The chemical structure of PBDEs resembles that of polychlorinated biphenyls (PCBs), and PBDEs may act similarly as disruptors of the hypothalamic-pituitary-thyroid axis (Birnbaum and Staskal 2004; Tomy et al. 2004; Zhou et al. 2002). In rodents, neurogenesis in the brain is induced by T3 (Uchida et al. 2005), and THs stimulate stem cell proliferation and neuronal differentiation in the olfactory system of mammals and fish (Lema and Nevitt 2004; Paternostro and Meisami 1994). Nevertheless, it remains unclear whether exposure to PBDEs impacts TH-mediated neural development (Porterfield 2000).

In the present study, we used teleost fish as an animal model for investigating the influence of PBDEs on neurogenesis and brain development. Teleost fish show cell proliferation and neural differentiation in the brain throughout adult life (Adolf et al. 2006; Lema et al. 2005; Zupanc et al. 2005), and the extent of neurogenesis in the adult fish brain greatly exceeds that in mammals (Carey et al. 2002). Embryonic exposure of zebrafish (Danio rerio) to PBDE-47 has been found to lead to cardiac and morphologic defects that appear to be caused by a primary effect on neural function (Lema et al. 2007). Whether such neural and behavioral impacts of PBDE exposure result from disruption of TH signaling during brain development, however, has yet to be examined.

We tested the hypothesis that dietary exposure to PBDEs affects TH-regulated gene transcription in the brain of zebrafish (Danio rerio). The mechanism by which PBDEs depress TH expression and TH-regulated pathways in the brain may be particularly sensitive to disruption by PBDE flame retardants.

Polybrominated diphenyl ethers (PBDEs) are implicated as disruptors of the hypothalamic-pituitary-thyroid axis. Animals exposed to PBDEs may show reduced plasma thyroid hormone (TH), but it is not known whether PBDEs impact TH-regulated pathways in target tissues.

Research

**Dietary Exposure to 2,2′,4,4′-Tetrabromodiphenyl Ether (PBDE-47) Alters Thyroid Status and Thyroid Hormone–Regulated Gene Transcription in the Pituitary and Brain**

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**BACKGROUND:** Polybrominated diphenyl ether (PBDE) flame retardants have been implicated as disruptors of the hypothalamic-pituitary-thyroid axis. Animals exposed to PBDEs may show reduced plasma thyroid hormone (TH), but it is not known whether PBDEs impact TH-regulated pathways in target tissues.

**OBJECTIVE:** We examined the effects of dietary exposure to 2,2′,4,4′-tetrabromodiphenyl ether (PBDE-47)—commonly the most concentrated PBDE in human tissues—on plasma TH levels and on gene transcripts for glycoprotein hormone α-subunit (GPHα) and thyrotropin β-subunit (TSHβ) in the pituitary gland, the autoinduced TH receptors α and β in the brain and liver, and the TH-responsive transcription factor basic transcription element-binding protein (BTEB) in the brain.

**METHODS:** Breeding pairs of adult fathead minnows (Pimephales promelas) were given dietary PBDE-47 at two doses (2.4 μg/pair/day or 12.3 μg/pair/day) for 21 days.

**RESULTS:** Minnows exposed to PBDE-47 had depressed plasma thyroxine (T4), but not T3, TSHβ, and on gene transcripts for glycoprotein hormone α-subunit (GPHα) and thyrotropin β-subunit (TSHβ) in the pituitary gland, the autoinduced TH receptor α and β in the brain and liver, and the TH-responsive transcription factor basic transcription element-binding protein (BTEB) in the brain.

**CONCLUSIONS:** Our results indicate that dietary exposure to PBDE-47 alters TH signaling at multiple levels of the hypothalamic-pituitary-thyroid axis and provide evidence that TH-responsive pathways in the brain may be particularly sensitive to disruption by PBDE flame retardants.

**KEY WORDS:** basic transcription element-binding protein, brain, endocrine disruption, PBDE-47, polybrominated diphenyl ethers, thyroid hormone, thyroid hormone receptor, thyroid-stimulating hormone, thyrotropin, Environment Health Perspectives 116:1694–1699 (2008). doi:10.1289/ehp.11570 available via http://dx.doi.org/ [Online 1 August 2008]

In the vertebrate brain, THs play key roles in regulating neural development and functioning (Koibuchi and Chini 2000; König and Neto 2002). THs influence neurogenesis by modulating the proliferation of neural progenitor cells, influencing dendritic and synaptic formation, and regulating myelination (Gould and Butcher 1989; Porterfield and Hendrich 1993). In rodents, neurogenesis in the brain is induced by T3 (Uchida et al. 2005), and THs stimulate stem cell proliferation and neuronal differentiation in the olfactory system of mammals and fish (Lema and Nevitt 2004; Paternostro and Meisami 1994). Nevertheless, it remains unclear whether exposure to PBDEs impacts TH-mediated neural development (Porterfield 2000).

In the present study, we used teleost fish as an animal model for investigating the influence of PBDEs on neurogenesis and brain development. Teleost fish show cell proliferation and neural differentiation in the brain throughout adult life (Adolf et al. 2006; Lema et al. 2005; Zupanc et al. 2005), and the extent of neurogenesis in the adult fish brain greatly exceeds that in mammals (Carey et al. 2002). Embryonic exposure of zebrafish (Danio rerio) to PBDE-47 has been found to lead to cardiac and morphologic defects that appear to be caused by a primary effect on neural function (Lema et al. 2007). Whether such neural and behavioral impacts of PBDE exposure result from disruption of TH signaling during brain development, however, has yet to be examined.

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transcripts in target tissues in the adult fathead minnow (*Pimephales promelas*). The fathead minnow is a teleost model for assessing the toxic and endocrine-disrupting effects of chemical pollutants (Ankley and Villeneuve 2006), and oral exposure to the PBDE congener 2.2′,4,4′-tetrabromodiphenyl ether (PBDE-47) impaired reproductive activity in this species (Muirhead et al. 2006). We exposed adult minnows to a dietary source of PBDE-47, typically the most concentrated PBDE congener in humans and wildlife (Hites 2004; Schecter et al. 2005). We then examined the effects of PBDE-47 exposure on plasma T₄ and T₃ status and mRNA levels for thyrotropin β-subunit (TSHβ) and glycoprotein hormone α-subunit (GPHα) in the pituitary. We also examined how PBDE-47 affected key target tissues for THs by quantifying transcripts for the autoinduced TRα and TRβ genes in the brain and liver, and by quantifying brain mRNA for basic transcription element-binding protein (BTEB), a TH-responsive transcription factor that regulates neural differentiation (Cayrou et al. 2002; Denver et al. 1999).

**Materials and Methods**

**Animals and housing.** Adult fathead minnows (*Pimephales promelas*) were obtained from Environmental Consulting & Testing (Superior, WI). Minnows were maintained at the Battelle Pacific Northwest Division in Sequim, Washington, under a 16 hr:8 hr light:dark photoperiod with water quality parameters of 24–26°C, 6.6–7.4 mg/L dissolved oxygen, and 8.1–8.3 pH for the duration of the experiment. All animals were solved oxygen, and 8.1–8.3 pH for the duration of the experiment. All animals were treated humanely and with regard for alleviation of suffering, in accordance with guidelines of the Battelle Institutional Animal Care and Use Committee.

**Bioencapsulation of PBDE-47 in Artemia shrimp.** We obtained PBDE-47 from ChemServices (> 99% purity; West Chester, PA). A stock solution of PBDE-47 was prepared by dissolving 10.0 mg/mL in hexane. One milliliter of stock solution was added to a 1-L Erlenmeyer flask, the hexane evaporated, and approximately 15,000 adult brine shrimp (*Artemia franciscana*) added and incubated overnight to bioencapsulate the PBDE-47 (Muirhead et al. 2006). Before dosing minnows with the bioencapsulated brine shrimp, aliquots of the *Artemia* were assayed for PBDE-47 concentration using gas chromatography.

**PBDE-47 exposure.** We placed minnows in 38-L aquaria with one adult male and one adult female per aquarium. Each aquarium contained a 10.2-cm diameter clay pot that was split longitudinally to provide spawning substrate. Before beginning PBDE-47 exposure, the breeding pairs for all treatments (n = 9–11 pairs per treatment) were fed clean, frozen *Artemia* (San Francisco Bay Brand, Newark, CA) diluted 1:1 with sterile filtered seawater (¬ 0.5 g wet weight/mL ad libitum twice daily for 7 days, during which time we checked the spawning substrate every morning to confirm that each pair was reproducively active.

Following this 7-day period, minnows were fed PBDE-47 bioencapsulated *Artemia* (1 mL) twice daily for 21 days. Minnow pairs were given PBDE-47 either as a low dose (2.38 ± 0.63 μg PBDE-47/pair/day) or a high dose (12.30 ± 3.61 μg PBDE-47/pair/day). We selected these doses based on previous PBDE exposures with this species (Muirhead et al. 2006). A third, control group of minnow pairs continued to be fed *Artemia* not bioencapsulated with PBDE-47. We monitored spawning activity daily for the duration of PBDE-47 exposure, as described above.

After 21 days of PBDE-47 exposure, minnows were euthanized with tricaine methanesulfonate (Argent Chemical, Redmond, WA), and body mass (grams) and fork length (millimeters) were measured. Plasma was collected, and the pituitary gland, brain, and liver were dissected and frozen rapidly in liquid nitrogen, although the liver was first weighed to determine liver somatic index (LSI). We also dissected one gonad and immersed it in Bouin’s fixative for histologic analysis. After removal of the digestive tract, the remaining carcass of each animal was frozen to quantify body burdens of PBDE-47. All tissues were stored at −80°C.

T₄ and T₃ radioimmunoassays. Plasma concentrations of T₄ and T₃ were measured by radioimmunoassay as described previously (Dickhoff et al. 1982) using anti–L-T₄ (1:4,000) or anti–L–T₃ antiserum (1:10,000) (Accurate Chemical & Scientific Corp., Westbury, NY) and 125I-labeled T₄ or T₃ (Perkin-Elmer, Waltham, MA). The intraassay coefficient of variation was 4.1% for the T₄ assay and 5.4% for the T₃ assay. All samples were run in single assays. Given the small body size of fathead minnows, only the larger male sex provided sufficient plasma to quantify both T₄ and T₃ from the same individual. For that reason, we assayed T₃ in males only.

**Cloning of cDNA for BTEB.** We first identified and sequenced the cDNA for BTEB from the brain of fathead minnow using primers designed for zebrafish BTEB (GenBank accession no. AY793999 (National Center for Biotechnology Information 2008)). First strand cDNA was amplified in a 50-μL polymerase chain reaction (PCR) containing 2 μg of total RNA from the brain under the thermal profile: 94°C for 2 min, followed by 30 cycles of 94°C for 30 sec, 50°C for 30 sec, and 72°C for 90 sec, and ending with 72°C for 10 min. The cDNA was purified and sequenced to provide a 151-bp partial sequence, which was used to design primers (see Supplemental Material, Table 1 (available online at http://www.ehponline.org/members/2008/11570/suppl.pdf)) to obtain the full length BTEB sequence (SMART RACE cDNA Amplification Kit; BD Biosciences, Palo Alto, CA). The full-length cDNA sequence for fathead minnow BTEB is available online (GenBank accession no. EF432310 (National Center for Biotechnology Information 2008)).

**Real-time quantitative reverse-transcribed PCR assays.** We extracted total RNA from the pituitary gland using the MiniPrep RNase Kit (Qiagen, Inc., Valencia, CA) and from the brain and liver using Tri-Reagent (Molecular Research Center, Cincinnati, OH). Extracted RNA was quantified (Nanodrop Technologies, Wilmington, DE) and diluted to 15 ng/μL. Total RNA was reverse-transcribed (RT) in 15-μL reactions containing 3.0 μL 5x buffer and 1.5 μL dithiothreitol (DTT; Invitrogen, Carlsbad, CA), 0.75 μL deoxyribonucleotide triphosphate (dNTP) and 0.255 μL random hexamer (Promega, Madison, WI), 0.3 μL RNAse inhibitor (20 U/μL; Applied Biosystems, Foster City, CA), 0.1875 μL Superscript II reverse transcriptase (Invitrogen), 6.0375 μL ddH₂O (nuclease-free water; Sigma, St. Louis, MO), and 3.0 μL of total RNA template (15 ng/μL) under a profile of 25°C for 10 min, 48°C for 60 min, and 95°C for 5 min.

Primers and probes for real-time quantitative RT-PCR assays were designed for TSHβ (GenBank accession no. DQ677879 (Lema et al. 2008), GPβHs (DQ256072), TRa (DQ074645), TRβ (AY533142) and BTEB (EF432310) from fathead minnow using Primer Express software (ABI). All primers and probes were synthesized by Integrated DNA Technologies (Corvallis, IA) [see Supplemental Material, Table 2 (available online at http://www.ehponline.org/members/2008/11570/suppl.pdf)]. Quantitative RT-PCR reactions (25 μL) contained 12.5 μL Master Mix (ABI Universal MasterMix Reagent), 0.5 μL forward primer, 0.5 μL reverse primer, 0.5 μL probe, 8.0 μL nuclelease-free H₂O, and 3.0 μL of reverse-transcribed cDNA template. Reactions were run on an ABI 7700 Sequence Detector under a profile of 50°C for 2 min, 95°C for 10 min, and then 40–45 cycles of 95°C for 15 sec and 60°C for 1 min. All samples for each gene were run on a single 96-well plate. For each gene, we tested for DNA contamination by analyzing a total RNA sample that was not reverse-transcribed, and each run included duplicate samples lacking cDNA template. We used serial dilutions of total RNA from the experiment as a standard curve. Standard curve samples were run in triplicate, but samples themselves were not duplicated. We also quantified expression for 18S (Universal 18S;
sons between the control and each treatment -test compari-
t Bonferroni-corrected pairwise compari-
We used chi-square tests to compare the distri-
cant effect of treatment was found, pairwise compari-
GPH
plasma T
0 to 237.6 μg.
curves prepared for PBDE-47 ranged from
mode with a split ratio of 8:1. Standard
analyzed on a Hewlett-Packard 5890 GC
experimental fish. The hexane extracts were
fractions encompassing observed levels in
carcasses fortified with PBDE-47 at concen-
cency of PBDE-47 was 90–95% in blank
ferred to a GC-ECD autosampler vial and
(5 min). The hexane layer was then trans-
ferred to a GC-ECD autosampler vial and
diluted 1:10 with hexane. Extraction effi-
ciency of PBDE-47 was 90–95% in blank
carcasses fortified with PBDE-47 at concen-
trations encompassing observed levels in
experimental fish. The hexane extracts were
analyzed on a Hewlett-Packard 5890 GC
(Agilent Technologies, Santa Clara, CA)
equipped with a DB-5 30-m, 0.25 μM capil-
ary column and operated in split injection
mode with a split ratio of 8:1. Standard
curves prepared for PBDE-47 ranged from
0 to 237.0 μg.
Statistical analyses. We used two-factor
analysis of variance (ANOVA) models to
examine the effects of treatment and sex on
plasma T4, mRNA levels for TSHβ and
GPHx in the pituitary, TRα and TRβ in the
brain and liver, and BTEB in the brain.
Samples that exceeded three standard devia-
tions were considered outliers and excluded from
analysis. We used a one-factor ANOVA model
to test for effects on plasma T3. When a signifi-
cant effect of treatment was found, pairwise com-
parisons were made using Dunnett’s tests.
We used chi-square tests to compare the distri-
bution of gonadal stages between treatments.
Bonferroni-corrected pairwise t-test compari-
sions between the control and each treatment
PBDE dosing levels (Figure 3B; *p = 0.001).
There was no difference in brain TRβ tran-
scription levels between sexes.
Dietary PBDE-47 exposure also altered
mRNA abundance for the TH-regulated tran-
scription factor BTEB, although this effect
differed between sexes (Figure 3C; *p = 0.029).
In males, BTEB transcript was reduced in both
the low and high PBDE-47 exposures. Females
had lower levels of BTEB transcript than males
(*p = 0.0008), but expression in females was not affected by PBDE exposure.

TR transcripts in the liver. LSI was greater
in females than in males and was elevated 38%
in males exposed to the high dose of PBDE-47
(*p = 0.009; see Supplemental Material, Table 3
available online at http://www.ehponline.org/
members/2008/11570/suppl.pdf)]. Transcript
levels for TRα and TRβ in the liver were not
altered by PBDE-47 [see Supplemental
Material, Figure 1 (available online at http://
www.ehponline.org/members/2008/11570/
suppl.pdf)]. Male minnows, however, had
greater levels of TRβ mRNA in the liver than
females (*p < 0.0001). TRα mRNA levels did
not vary between the sexes.

Gonad staging and reproductive behavior. Male
minnows exposed to PBDE-47 had fewer
mature spermatozoa and more primary
spermatocytes and spermatids compared with
control males (low dose vs. control:
χ2 = 17.78, *p = 0.001; high dose vs. control: χ2 = 57.22, 
p < 0.001; see Supplemental Material, Table 4

Figure 1. Exposure to PBDE-47 depressed circulating concentrations of total T4 in males and females (A), but had no effect on total T3 in males (B). *p < 0.05 compared with control.

Figure 2. Dietary exposure to PBDE-47 altered relative transcripts levels for TSHβ (A) and GPHx (B) in the
pituitary gland. Transcript levels are expressed relative to template RNA levels. *p < 0.05 compared with control.
PBDE-47 also reduced brain mRNA levels of elevated levels, plasma levels of T3 may also be although, if PBDE exposure occurs at greatly current study, these effects on T4 generally Hallgren et al. 2001). As was observed in the sexes and elevated TR B and TR A were tissue specific. Transcripts for both TR are at both exposure doses. The effects of PBDE-47 on TH receptor mRNA abundance were tissue specific. Transcripts for both TRα and TRβ in the liver were unaffected by PBDE-47. In the brain, however, PBDE exposure reduced mRNA for TRβ in both sexes and elevated TRα mRNA in females. PBDE-47 also reduced brain mRNA levels of the TH-regulated transcription factor BTEB in males only.

The reduction in T4 observed in both sexes is consistent with previous studies showing that PBDE mixtures and single congeners can depress plasma T4 (Fernie et al. 2005; Hallgren et al. 2001). As was observed in the current study, these effects on T4 generally occur in the absence of any change in T3; although, if PBDE exposure occurs at greatly elevated levels, plasma levels of T3 may also be reduced (Zhou et al. 2001). The mechanism by which PBDEs depress T4 is not clear. Some researchers have hypothesized that the decreased T4 is caused by displacement of T4 from transport proteins (Hamers et al. 2006; Meerts et al. 2000), but quantitative structural-activity binding models indicate weak affinity of PBDE-47 to transthyretin (TTR), although the hydroxylated form of PBDE-47, 6-OH-PBDE-47, has greater affinity (Harju et al. 2007). An experimental study using recombinant sea bream TTR likewise found that PBDE-47 has lower affinity for teleost TTR than either T3 or T4 whereas the affinity of 6-OH-PBDE-47 is greater than that of the endogenous hormones (Morgado et al. 2007). Hydroxylated PBDEs such as 6-OH-PBDE-47 are produced metabolically from parent compounds (Mörcck et al. 2003), and metabolic conversion of PBDE-47 may have occurred in the minnows. TTR, however, is generally not the dominant TH transport protein in fish, and binding of PBDEs to thyroxin-binding protein and serum albumin has yet to be examined.

Our data show that the PBDE-induced reduction in peripheral T3 is accompanied by changes in pituitary mRNAs for TSH. TSH is composed of an α- and β-subunit with each subunit synthesized separately. The GPH α-subunit of TSH is identical to that of follicle-stimulating hormone (FSH) and luteinizing hormone (LH), so it is TSH’s β-subunit that determines the hormone’s functional specificity. In the present study, TSHβ mRNA was elevated in both sexes by the low PBDE dose, and transcript for GPHβ was depressed in both sexes at the high dose. The elevation in TSHβ mRNA at the lower dose is consistent with reduced negative feedback on the pituitary from the decline in circulating T4. At the higher PBDE dose, however, alternative regulatory mechanisms or toxic effects may occur. Supporting this idea, the testes of PBDE-47–exposed males in the high dose had fewer spermatozoa. A similar decline in spermatozoa was observed in fathead minnows given an oral dose of 28.7 μg PBDE-47/pair/day (Murhead et al. 2006), suggesting that PBDE exposures at high doses may impact gametogenesis and pituitary feedback from gonadal steroids.

Although the mechanism responsible for the PBDE-induced decline in circulating T4 cannot be discerned from alterations in pituitary mRNA levels alone, the reduced pituitary GPHβ transcript may cause a reduction in bioactive TSH protein production and a decline in TH biosynthesis.

To test whether PBDE-47 exposure affects TH-mediated gene transcripts in target tissues, we quantified mRNAs for TRα and TRβ in the brain and liver. TRs act as ligand-activated transcription factors by inducing or repressing the transcription of genes containing thyroid response elements (TREs). The genes for TRs themselves contain TREs, so that transcripts for TRα and TRβ are autoinduced by T3 (Lema SC, Dickey JT, Schulz IR, Swanson P, unpublished data; Liu et al. 2000). This autoinduction means that TR transcripts are markers for assessing TH-induced activation of gene transcripts in target tissues (Opitz et al. 2006). In fish and other vertebrates, distinct expression patterns of the TRα and TRβ isoforms suggest that TRs have tissue-specific and developmental state-specific functions (Forrest et al. 1990; Yamano and Miwa 1998). Indeed, in neural development, the α and β receptors play distinct roles (Forrest et al. 2002). Studies with in vitro cell culture have shown that TRα regulates stem cell proliferation, whereas TRβ mediates differentiation of these newly proliferated cells into neurons (Jones et al. 2003; Lebel et al. 1994; Letouulé et al. 1995).

In the present study, found that dietary PBDE-47 exposure did not affect TR transcripts in the liver, but it decreased mRNA levels for TRβ by 15–22% in the brain of males and females at both doses and elevated TRα transcripts by 37% in females at the high dose. These changes in TR transcript expression may result from the PBDE-induced T4 decline or via interactions between PBDE-47 and TRs or their corepressors. It is important to note, however, that transcripts for both TRs are similarly autoinduced by T3 in the brain and liver in both sexes in adult fathead minnows (Lema SC, Dickey JT, Schulz IR, Swanson P, unpublished data). That PBDE-47 exposure altered

![Figure 3. Dietary PBDE-47 exposure elevated mRNA levels for TRα in females (A), and reduced mRNA levels for TRβ in both sexes (B). PBDE-47 exposure also reduced gene transcripts for BTEB in the brain of male, but not female, minnows (C). Transcript levels are normalized to 18S.](image-url)
TR transcripts in the brain only, and TRα in a sex-specific pattern, suggests that PBDE-47 or its metabolites act directly on TR gene transcription mechanisms in target tissues (see also Schirks et al. 2007). Moreover, this finding exemplifies how impacts of PBDEs on gene transcripts do not conform to the expectations predicted by general hypothyroidism and demonstrates that these PBDE-induced effects cannot be generalized across tissues or sexes. Although the mechanism for PBDE-47’s impacts on TR gene transcription remains unclear, recent evidence indicates that PBDEs 47, 99, and 209 interact with the mouse pregnant X receptor (pXR) and its human counterpart, the nuclear steroid and xenobiotic receptor (SXR) (Pacyniak et al. 2007). The SXR interacts with the corepresser SMRT (silencing mediator for retinoid and thyroid receptors) (Takehita et al. 2002), and PBDE-induced impacts on SXR might contribute to changes in TR gene transcription.

Even though the mechanism by which PBDE-47 alters brain TR transcripts is unresolved, our results clearly provide new evidence that dietary intake of PBDEs may impact TH-mediated neural development. In support of this idea, PBDE-47 exposure reduced transcript levels for the TH-regulated gene BTEB in the male minnow brain by as much as 53% but did not affect that of females. BTEB encodes a zinc-fingered transcription factor that binds GC-box domains to facilitate or inhibit TH-mediated gene transcription. In mammals, T₃ up-regulation of BTEB is specific to neurons (Denver et al. 1999), and in Xenopus, BTEB is responsive to T₃ in brain and other tissues (Furlow and Kanamori 2002; Hooper et al. 2002). Studies in which BTEB expression has been blocked or induced have revealed that BTEB mediates T₃-induced neuronal differentiation and neurite branching via TH activation of TRβ (Cayrou et al. 2002; Denver et al. 1999). The T₃-induced BTEB protein also binds the promoter of the TRβ gene to regulate its autoexpression by THs (Bagamasbad et al. 2008).

Whether the PBDE-induced change in BTEB transcript observed here translates to altered neurogenesis is not clear. Cell proliferation and neural differentiation occur throughout the adult fish brain (Lema et al. 2007; Zapanc et al. 2005), and BTEB transcript is regulated by T₃ in the brain of adult fathead minnows (Lema SC, Dickey JT, Schultz IR, Swanson P, unpublished data). Still, it is not known if BTEB regulates neurogenesis during this telost life stage as it does during mammalian development. There is, however, accumulating evidence in mammals that THs regulate adult neurogenesis (Desouza et al. 2005; Fernandez et al. 2004; Tekuma et al. 2002). In adult rats, for instance, exogenous TH increases immunoreactivity for the cell proliferation marker Ki-67 in the subventricular zone of the brain (Giardino et al. 2000). Taken together, these studies suggest that THs may influence neurogenesis in adults as they do in embryonic and neonatal life.

In summary, our results provide evidence that oral PBDE-47 exposure affects the thyroid axis at several levels by depressing peripheral levels of T₄, altering pituitary transcripts for TSHβ and GPHα, and changing brain mRNA levels for the TH-responsive genes TRα, TRβ, and BTEB. Taken together, these results provide evidence that oral intake of the brominated flame retardant PBDE-47 can impact TH-regulated gene transcription in the pituitary gland and brain, and they illustrate how PBDE-induced changes in TH-regulated transcripts do not conform to the effects predicted by general hypothyroidism. Given these findings, it becomes crucial to ask whether these changes in TH-mediated mRNA levels translate into health consequences for humans or wildlife (Birnbaum and Staskal 2004; McDonal 2002). PBDEs are lipophilic and bioaccumulate, and several studies have shown rising PBDE contaminants in the tissues of invertebrates, fish, birds, and marine mammals, as well as in the breast milk, blood, and tissues of humans (Hites 2004; Law et al. 2003; Schecter et al. 2003, 2005). The PBDE-induced changes in TH-regulated genes transcripts seen here indicate that neurogenesis and brain development may be impacted by PBDE exposure, and they highlight the need for future investigations into how PBDEs influence TH-mediated neural function.

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