

Original Article

Cite this article: Liu C *et al* (2021). Serotonin and early life stress interact to shape brain architecture and anxious avoidant behavior – a TPH2 imaging genetics approach. *Psychological Medicine* **51**, 2476–2484. <https://doi.org/10.1017/S0033291720002809>

Received: 24 August 2019
Revised: 21 April 2020
Accepted: 18 July 2020
First published online: 28 September 2020


Key words:

Amygdala; early life stress; frontal cortex; punishment sensitivity; serotonin

Author for correspondence:

Benjamin Becker,
E-mail: ben_becker@gmx.de

Serotonin and early life stress interact to shape brain architecture and anxious avoidant behavior – a TPH2 imaging genetics approach

Congcong Liu¹, Lei Xu¹, Jialin Li¹, Feng Zhou¹, Xi Yang¹, Xiaoxiao Zheng¹, Meina Fu¹, Keshuang Li¹, Cornelia Sindermann², Christian Montag^{1,2}, Yina Ma³, Dirk Scheele^{4,5}, Richard P. Ebstein^{6,7}, Shuxia Yao¹, Keith M. Kendrick¹ and Benjamin Becker¹ 

¹The Clinical Hospital of the Chengdu Brain Science Institute, School of Life Science and Technology, MOE Key Laboratory for Neuroinformation, University of Electronic Science and Technology of China, 611731 Chengdu, China; ²Department of Molecular Psychology, Institute of Psychology and Education, Ulm University, 89081 Ulm, Germany; ³State Key Laboratory of Cognitive Neuroscience and Learning, IDG/McGovern Institute of Brain Research, Beijing Normal University, 100875 Beijing, China; ⁴Division of Medical Psychology, Department of Psychiatry and Psychotherapy, University Hospital Bonn, 53105 Bonn, Germany; ⁵Department of Psychiatry, School of Medicine & Health Sciences, University of Oldenburg, 26129 Oldenburg, Germany; ⁶School of Management, Zhejiang University of Technology, 310023 Hangzhou, China and ⁷China Center for Behavior Economics and Finance, South Western University of Finance and Economics (SWUFE), 611130, Chengdu, China

Abstract

Background. Early life stress has been associated with emotional dysregulations and altered architecture of limbic-prefrontal brain systems engaged in emotional processing. Serotonin regulates both, developmental and experience-dependent neuroplasticity in these circuits. Central serotonergic biosynthesis rates are regulated by Tryptophan hydroxylase 2 (*TPH2*) and transgenic animal models suggest that *TPH2*-gene associated differences in serotonergic signaling mediate the impact of aversive early life experiences on a phenotype characterized by anxious avoidance.

Methods. The present study employed an imaging genetics approach that capitalized on individual differences in a *TPH2* polymorphism (703G/T; rs4570625) to determine whether differences in serotonergic signaling modulate the effects of early life stress on brain structure and function and punishment sensitivity in humans ($n = 252$).

Results. Higher maltreatment exposure before the age of 16 was associated with increased gray matter volumes in a circuitry spanning thalamic-limbic-prefrontal regions and decreased intrinsic communication in limbic-prefrontal circuits selectively in TT carriers. In an independent replication sample, associations between higher early life stress and increased frontal volumes in TT carriers were confirmed. On the phenotype level, the genotype moderated the association between higher early life stress exposure and higher punishment sensitivity. In TT carriers, the association between higher early life stress exposure and punishment sensitivity was critically mediated by increased thalamic-limbic-prefrontal volumes.

Conclusions. The present findings suggest that early life stress shapes the neural organization of the limbic-prefrontal circuits in interaction with individual variations in the *TPH2* gene to promote a phenotype characterized by facilitated threat avoidance, thus promoting early adaptation to an adverse environment.

Introduction

Early life stress (ELS) has been associated with strongly increased prevalence rates for psychiatric disorders and emotional dysregulations in adulthood. Converging evidence from animal and human studies suggest an association between ELS and lasting alterations in the structural and functional organization of the brain, particularly in limbic systems engaged in threat and anxiety processing, including the amygdala-hippocampal complex, and frontal systems engaged in emotion regulation (Teicher, Samson, Anderson, & Ohashi, 2016).

On the behavioral level, considerable variations in the long-term sequelae of ELS have been reported. For instance, longitudinal data suggest that the majority of individuals with severe ELS exhibits cognitive and emotional dysfunctions in adulthood, whereas a significant minority remained unaffected (Sonuga-Barke *et al.*, 2017), suggesting that innate factors such as genetic variations may temper the long-term trajectory of ELS. Initial studies that combined candidate gene approaches with neuroimaging reported that specific single-nucleotide polymorphisms (SNPs) of genes involved in neuroplasticity and stress reactivity (brain derived neurotrophic factor, oxytocin receptor) may confer differential susceptibility to the detrimental

impact of aversive childhood experiences on the brain, i.e. differential reductions of limbic volumes following ELS exposure (Dannlowski et al., 2016; van Velzen et al., 2016).

Serotonin regulates both, neuromaturation during sensitive periods and learning-related neuroplasticity (Lesch & Waider, 2012) suggesting that innate differences in central serotonergic signaling may modulate the long-term effects of ELS. Central serotonin biosynthesis is regulated by the rate-limiting enzyme tryptophan hydroxylase (*TPH*), with the second isoform *TPH2* being exclusively expressed in central serotonin neurons (Zhang, Beaulieu, Sotnikova, Gainetdinov, & Caron, 2004).

Individual differences in the *TPH2* encoding gene have been linked to variations in both, serotonin synthesis rates in limbic and prefrontal systems (Booij et al., 2012; Furmark et al., 2016; Ottenhof, Sild, Levesque, Ruhe, & Booij, 2018;) and behavioral variations in emotional reactivity and regulation (Gutknecht et al., 2007; Laas et al., 2017; Reuter, Kuepper, & Hennig, 2007). Initial studies employing genetic imaging approaches furthermore reported that *TPH2* variants affect emotional reactivity in limbic regions and regulatory control in frontal regions (Canli, Congdon, Gutknecht, Constable, & Lesch, 2005; Canli, Congdon, Todd Constable, & Lesch, 2008; Kennedy et al., 2012; Reuter et al., 2008).

Transgenic animal models that capitalized on the selective effects of the *TPH2* isoform on central serotonin (e.g. in a mouse model with a mutated *TPH2* knock-in human polymorphism resulting in reduced brain 5-HT levels) suggest that congenital *TPH2*-associated serotonergic deficiency mediates the impact of early aversive experiences on anxious behavior in adulthood (Sachs et al., 2013), possibly due to serotonergic modulation of synaptic plasticity in limbic-prefrontal circuits that underpin emotional learning (Lesch & Waider, 2012). In humans, *TPH2* SNP rs4570625 (−703 G/T) variations modulate the impact of ELS on emotional behavior, such that T-allele carriers exhibited increased threat attention in infancy (Forssman et al., 2014) and elevated stress-reactivity in adulthood (Mandelli et al., 2012).

Despite accumulating evidence suggesting that *TPH2* genetics interact with early aversive experience to shape a phenotype characterized by anxious behavior, the brain systems that mediate this association have not been determined in humans.

To determine interactive effects of ELS and the *TPH2* SNP rs4570625 (−703 G/T) polymorphism on brain structure and function and their relationship to anxious-avoidant behavior in adulthood a sample of healthy subjects ($n = 252$) underwent *TPH2* rs4570625 genotyping and brain structural and functional magnetic resonance imaging (MRI). ELS exposure was retrospectively assessed by self-report, anxious behavior was assessed using a scale related to the Behavioral Inhibition System (BIS, Gray, 1987). The BIS appears particularly suitable given that it (1) specifically measures reactivity towards stimuli that are associated with a high probability of punishment and shapes anxious-avoidant behavior, and, (2) has been associated with the septo-hippocampal-amygdala system (Gray & McNaughton, 2000) and – in humans – prefrontal systems engaged in threat detection and emotion regulation (Fung, Qi, Hassabis, Daw, & Mobbs, 2019). Based on previous findings suggesting that (a) ELS is associated with brain structural and functional changes in limbic-frontal circuits and that (b) *TPH2* genetic variations are linked with serotonergic neurotransmission in these circuits [albeit with little direct evidence for the functional role of these SNPs (Ottenhof et al., 2018)] and (c) brain serotonin levels modulate experience-dependent synaptic plasticity in limbic-frontal circuits,

we hypothesized that (1) the impact of ELS on the structural and functional organization of limbic-prefrontal circuits varies as a function of *TPH2* rs4570625 genetic differences and (2) ELS-associated neuroplastic changes in this circuitry determine variations in anxious-avoidant behavior during early adulthood.

In line with previous studies on the effects of ELS on brain structure (e.g. Teicher et al., 2016) we furthermore expected a negative association between ELS and brain structure independent of genotype. Given the lack of previous studies on general effects of variations in *TPH2* on brain structure, no specific hypotheses in this respect were formulated. Based on recent meta-analytic evidence on the low robustness of interaction effects between candidate gene variants and ELS on complex behavioral traits (Border et al., 2019; Culverhouse, Saccone, & Bierut, 2018), we included an independent dataset to test the robustness of the findings observed in the discovery sample (see recommendations in Carter et al., 2017).

Methods

Participants

$N = 252$ healthy subjects (age range 18–29 years) served as discovery sample. In the context of problematic effect size determination in genetic imaging studies (Avinun, Nevo, Knodt, Elliott, & Hariri, 2018; Carter et al., 2017) sample size was based on previous studies (Dannlowski et al., 2016; van Velzen et al., 2016). In line with recent recommendations a replication sample was included (Carter et al., 2017). An independent sample from a study examining *TPH2* genotype and acute tryptophan depletion served as replication dataset (<https://clinicaltrials.gov/ct2/show/NCT03549182>, ID NCT03549182). The dataset included early life stress and brain structural assessments in healthy male *TPH2* rs4570625 homozygotes (TT, GG), data from $n = 51$ placebo-treated subjects served as replication dataset (details online Supplementary Information and Supplementary Table S1). In both samples, participants with current or a history of medical, neurological/psychiatric disorders, regular use of psychotropic substances and MRI contraindications were excluded. The study was approved by the local ethics committee and in accordance with the latest revision of the Declaration of Helsinki. Written informed consent was obtained.

The discovery data represent part of the Chengdu Gene Brain Behavior Project that aims at determining behavioral and genetic associations in a large healthy cohort. The project incorporates studies focusing on the genetic and neural correlates of trait autism (Li et al., 2019; Montag et al., 2017) as well as determining interactions between early life stress exposure and *TPH2* genetics. The variables examined for the latter research aim have been pre-specified in line with the study hypotheses. All variables, data exclusion and sample sizes are completely reported.

Childhood experience, perceived stress and punishment sensitivity

Levels of ELS exposure were assessed using the Childhood Trauma Questionnaire (CTQ) (Bernstein et al., 2003) which consists of 25 retrospective self-report items spanning five types of aversive childhood experiences. In accordance with previous studies (e.g. Dannlowski et al., 2016), CTQ total score were used. Current stress (during the last months) was assessed using the Perceived Stress Scale (PSS, Cohen, Kamarck, and Mermelstein,

1983). The Sensitivity to Punishment scale (SPS, Sensitivity to Punishment and Sensitivity to Reward Questionnaire, Torrubia, Avila, Moltó, and Caseras, 2001) was administered to assess individual differences in behavioral inhibition. Individuals with high punishment sensitivity experience high levels of anxiety and avoid potential dangers (Gray, 1987). Cronbach's α in the present sample demonstrated good internal consistency (0.847 CTQ; 0.834 PSS; 0.844 SPS). CTQ scores were non-normally distributed ($p < 0.001$, Shapiro–Wilk).

Genotyping and MRI data

Genomic DNA was purified from buccal cells using a MagNA Pure96 robot (Roche Diagnostics, Mannheim), sample probes were designed by TIB MolBiol (Berlin, Germany). Genotyping was conducted by real-time polymerase chain reaction (RT-PCR) and subsequent high-resolution melting on a Cobas Z480 Light Cycler (Roche Diagnostics, Mannheim, Germany) according to the manufacturer's instructions. MRI data acquisition was conducted on a 3.0 Tesla GE MR750 system (General Electric Medical System, Milwaukee, WI, USA) using standard acquisition parameters and procedures. Following initial quality assessments, the data were preprocessed using validated procedures in SPM12 (<http://www.fil.ion.ucl.ac.uk/spm/>), see *Supporting Information*.

Analysis: genotype \times ELS effects on brain structure and functional connectivity

Due to the non-normal distribution of CTQ scores (distribution visualized in Fig. S2), non-parametric permutation tests were employed to examine the effect of *TPH2* rs4570625 genotype and ELS on brain structure and function (Permutation Analysis of Linear Models, PALM) (Winkler, Ridgway, Webster, Smith, & Nichols, 2014). Gray matter (GM) volumes and functional connectivity maps were entered into a single full factorial model respectively, with genotype group as a between-subject factor (TT *v.* TG *v.* GG). CTQ scores were entered as covariate (dimensional model), including the crucial CTQ times group interaction term. In line with previous genetic imaging studies examining interactions between candidate genes and ELS on the brain (Dannlowski et al., 2013; Frodl et al., 2014; van Velzen et al., 2016), age, gender, education years, and for brain structure total intracranial volume, and for resting-state mean framewise displacement were included as covariates. Based on the results of the brain structural analysis we further explored whether regions showing *TPH2* genotype and ELS effects on brain structure additionally exhibit altered intrinsic functional interactions with other brain regions. To this end, seed-to-whole-brain voxel-wise connectivity maps were computed using standard protocols (Resting-State fMRI Data Analysis Toolkit; REST; <http://www.restfmri.net>, *Supporting Information*).

Statistical significance was determined using permutation-based inferences (10 000 permutations) and $p_{FWE} < 0.05$ using threshold-free cluster enhancement (TFCE) to control for multiple comparisons (within a gray matter mask, spm grey.nii > 0.3). In line with a previous study (Birn, Roeber, & Pollak, 2017), relative effects of current stress on the brain were determined by recomputing the analyses and substituting CTQ with PSS scores.

Associations with anxious avoidant behavior

Associations between anxious avoidant behavior, ELS and brain structure or function (extracted gray matter and functional connectivity estimates from 5 mm-radius spheres centered at the peak coordinates of interaction clusters) were next examined. The moderation effect of the *TPH2* rs4570625 genotype on the association of CTQ with sensitivity to punishment was explored using a moderation analysis (PROCESS, Preacher and Hayes, 2004) estimating whether the interaction between the predictor (CTQ) and moderator (genotype) could predict the dependent variable (SPS scores). Next associations between ELS-associated brain structural or functional changes and the behavioral phenotype were explored using non-parametric correlation analyses (PALM, 10 000 permutations). Finally, a mediation analysis tested whether brain structural changes mediated effects of ELS on anxious avoidant behavior (punishment sensitivity) within genotype groups [bootstrapping with 10 000 permutations, bias-corrected 95% confidence intervals (CIs) to test the significance of indirect effects, Preacher and Hayes, 2008].

Replication procedure

Gray matter volumes from regions identified in the discovery sample were extracted from the MRI data of the replication sample and subjected as dependent variables to partial correlation analyses with CTQ scores as an independent variable (covariates: age, total intracranial volume).

Data availability statement

The data that support the findings of the present study are openly available in the repository of the Open Science Framework at <https://osf.io/DG8V3/>, doi 10.17605/OSF.IO/DG8V3.

Results

Sample and genotyping

A total of 229 right-handed Han Chinese (age $M = 21.55 \pm 2.31$, 115 females) were included in the final analysis (exclusion online Supplementary Fig. S1). Genotyping for *TPH2* rs4570625 yielded $n = 71$ TT homozygotes, $n = 107$ TG heterozygotes, and $n = 51$ GG homozygotes. Allele frequencies did not deviate from those expected according to the Hardy-Weinberg Equilibrium ($\chi^2_{(1)} = 0.735$, $p = 0.391$) and were in the expected distribution for Han Chinese populations (see https://www.ncbi.nlm.nih.gov/snp/rs4570625#frequency_tab). Previous studies on the *TPH2* rs4570625 were mostly conducted in Caucasian populations with a rare occurrence of the T-allele. In contrast the present examined was conducted in a Han Chinese population which allowed us to separately examine TG and TT carriers. Genotype groups had comparable socio-demographics and CTQ scores ($ps > 0.36$), however, PSS scores were significantly higher in TT compared to TG carriers ($F_{(2,226)} = 4.89$, $p = 0.008$, partial $\eta^2 = 0.041$) Post hoc test revealed that PSS in TT homozygotes was significantly higher than in TG heterozygotes ($t_{(176)} = 3.10$, $p = 0.002$, Cohen's $d = 0.47$) (\times Table 1).

Interactive effects of *TPH2* \times ELS on brain structure

No significant main effects of ELS and genotype were found. Examining interactions of ELS \times genotype revealed effects in

Table 1. Sample characteristics ($n = 229$) stratified according to *TPH2* rs4570625

	TT ($n = 71$)	TG ($n = 107$)	GG ($n = 51$)	p Value	Total sample
Age, Years	21.55 ± 2.48	21.46 ± 2.24	21.76 ± 2.27	0.74 ^a	21.55 ± 2.31
Gender (M/F)	32/39	56/51	26/25	0.63 ^b	114/115
Education, Years	15.55 ± 2.09	15.69 ± 1.84	15.78 ± 1.84	0.79 ^a	15.67 ± 1.91
CTQ	38.08 ± 9.22	37.92 ± 10.65	38.45 ± 9.10	0.95 ^a	38.09 ± 9.85
PSS	26.18 ± 5.51	23.61 ± 5.38	24.55 ± 5.21	0.008 ^a	24.62 ± 5.47
SPS	11.11 ± 4.81	10.21 ± 4.49	10.96 ± 3.79	0.363 ^a	10.66 ± 4.45

CTQ, Childhood Trauma Questionnaire; F, female; M, male; PSS, Perceived Stress Scale; SPS, Sensitivity to Punishment scale. Mean and standard deviations (\pm s.d.) are displayed.

^a F tests.

^b χ^2 tests.

a broad thalamic-limbic-frontal network, including a cluster spanning the bilateral thalamus, parahippocampal gyrus, hippocampus, and amygdala ($k = 2609$, $p_{FWE-TFCE} < 0.05$), a cluster spanning the bilateral ventromedial frontal cortex (vmPFC) ($k = 1575$, $p_{FWE-TFCE} < 0.05$), and additional clusters located in the left dorsolateral prefrontal cortex (DLPFC) ($k = 201$, $p_{FWE-TFCE} < 0.05$), right ($k = 335$, $p_{FWE-TFCE} < 0.05$) as well as left ($k = 181$, $p_{FWE-TFCE} < 0.05$) dorsal anterior cingulate cortex (dACC) (Fig. 1, details online Supplementary Table S2). Post-hoc analyses by means of extracted parameter estimates from the significant interaction clusters revealed pronounced effects of ELS on gray matter volume in TT homozygotes, whereas associations in TG heterozygotes and GG homozygotes failed to reach significance. In TT homozygotes, higher stress exposure during childhood specifically associated with increased gray matter volumes in the bilateral thalamic-limbic cluster, left dACC and dLPFC (all p s < 0.05 after Bonferroni correction, Fig. 1). Examination of correlation coefficients between the groups additionally revealed significant different associations between CTQ and volumes in these regions between TT and TG carriers ($p_{corrected} < 0.01$) (details online Supplementary Table S3, effect sizes online Supplementary Table S4). Findings remained stable after excluding the demographic covariates (online Supplementary Table S5). No significant main and genotype interaction effects of current stress (PSS) were observed for brain structure.

Interactive effects of *TPH2* × ELS on intrinsic network communication

ELS and *TPH2* rs4570625 interactively impacted functional connectivity strengths between the left dACC and left DLPFC ($MNI_{xyz} = (-6, 42, 27)$, $k = 24$, $p_{FWE-TFCE} < 0.05$), with subsequent post-hoc tests demonstrating that the interaction was driven by pronounced effects of ELS in the TT homozygotes, whereas both TG and GG groups did not show significant associations (TT: $r = -0.43$, $p_{corrected} = 0.0021$, $d = 0.95$; TG: $r = 0.11$, $p = 0.27$, $d = 0.22$; GG: $r = 0.20$, $p = 0.18$, $d = 0.41$; Fisher's Z : $z_{TTvsTG} = 3.61$, $p < 0.001$, $q = 0.57$; $z_{TTvsGG} = 3.47$, $p = 0.001$, $q = 0.66$; $z_{GTvsGG} = 0$, $q = 0.09$) (Fig. 2). Given previously reported genotype-dependent effects of ELS on amygdala activity (White et al., 2012) an amygdala-focused analysis (small-volume correction, SVC) was employed which revealed interactive effects on left dACC-left amygdala functional connectivity ($MNI_{xyz} = (-21, 0, -12)$, $k = 2$, $p_{FWE} < 0.05$) (Fig. 2). The interaction was driven by

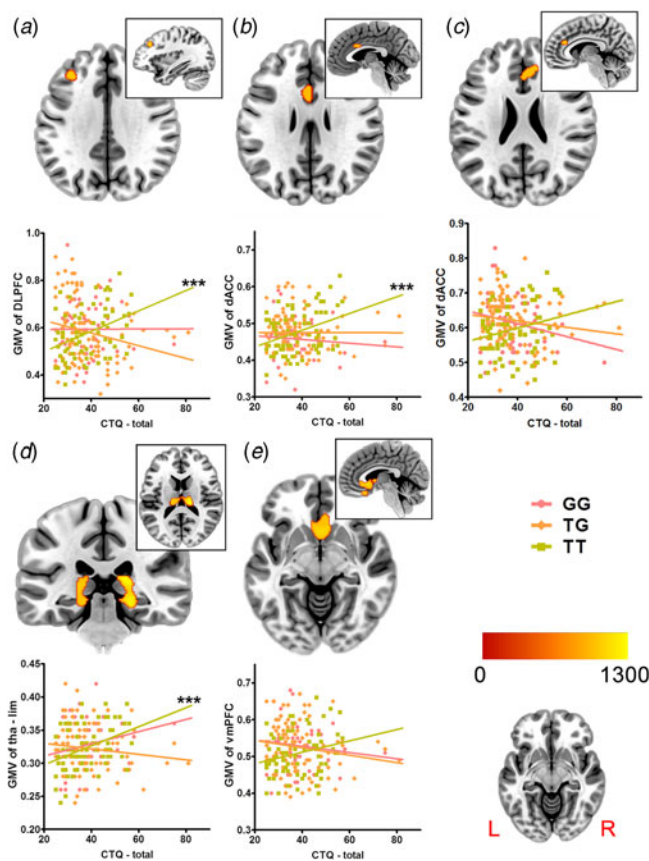


Fig. 1. Interaction of *TPH2* rs4570625 and early life stress (ELS) on gray matter volume and relationship between gray matter volume and Childhood-Trauma-Questionnaire (CTQ) scores. Regions showing significant interaction effects between genotype and ELS (color bar = TFCE value, p_{FWE} with TFCE < 0.05) (a–e). CTQ, Childhood-Trauma-Questionnaire; dACC, dorsal anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex; ELS, early life stress; tha-lim, parahippocampus/hippocampus/amygdala/thalamus; vmPFC, ventromedial frontal cortex; *** $p < 0.001$, Bonferroni-corrected.

a pronounced effect of ELS on left dACC-left amygdala connectivity in TT homozygotes, whereas TG and GG groups did not show significant associations (TT: $r = -0.34$, $p_{corrected} = 0.032$, $d = 0.072$; TG: $r = 0.28$, $p_{corrected} = 0.055$, $d = 0.58$; GG: $r = -0.14$, $p = 0.35$, $d = 0.28$; Fisher's Z : $z_{TTvsTG} = 3.93$, $p < 0.001$, $q = 0.64$; $z_{TTvsGG} = 1.136$, $p = 0.26$, $q = 0.21$; $z_{GTvsGG} = 2.31$, $p = 0.021$, $q = 0.43$) (Fig. 2). No significant interactive effects were observed for

Fig. 2. Interaction of *TPH2* rs4570625 and early life stress (ELS) on the functional connectivity strength of the left dorsal anterior cingulate cortex (dACC) (a). Associations between extracted parameter estimates and Childhood-Trauma-Questionnaire (CTQ) total scores for dACC – left dorsolateral prefrontal cortex (DLPFC) (b) and left amygdala (c), respectively. amy, amygdala; CTQ, Childhood-Trauma-Questionnaire; dACC, dorsal anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex; ELS, early life stress; * $p < 0.05$; ** $p < 0.01$, Bonferroni-corrected.

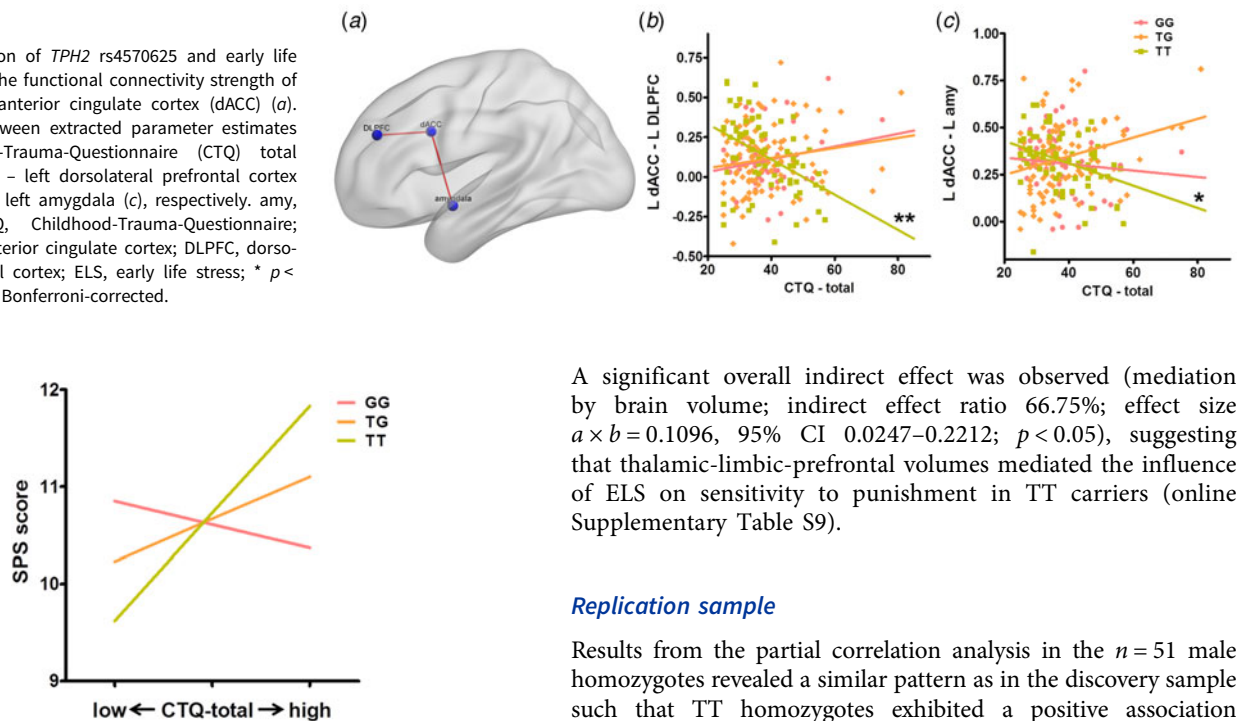


Fig. 3. Moderation effect of genotype on the association between the sensitivity to punishment scale (SPS) and Childhood Trauma Questionnaire (CTQ) scores. CTQ, Childhood Trauma Questionnaire; SPS, sensitivity to punishment scale.

other seed regions. Findings remained stable after excluding the demographic covariates (online Supplementary Table S6). No significant main and genotype interaction effects of current stress (PSS) were observed.

Associations with anxious avoidant behavior

The moderation analysis revealed a significant moderation effect ($R^2 = 0.05$, $F_{(4,224)} = 3.12$, $p = 0.016$) reflecting that the interaction between CTQ and *TPH2* rs4570625 significantly predicts punishment sensitivity ($B = 0.094$, $S.E. = 0.044$, $t_{(224)} = 2.15$, $p = 0.03$). Genotype thus significantly moderated the association between ELS and punishment sensitivity, with post hoc tests indicating that higher ELS selectively associated with higher punishment sensitivity in TT carriers ($t_{(224)} = 2.59$, $p = 0.01$, Fig. 3, visualization via Johnson-Neyman approach splitting CTQ scores into low, medium, high).

Non-parametric correlation analysis revealed that specifically in TT homozygotes sensitivity to punishment was significantly positively associated with volumes of the thalamic-limbic region, right vmPFC and left DLPFC (vmPFC: $r = 0.359$, $p_{\text{corrected}} = 0.006$, $d = 0.77$; DLPFC: $r = 0.387$, $p_{\text{corrected}} = 0.008$, $d = 0.84$; thalamic-limbic: $r = 0.370$, $p_{\text{corrected}} = 0.026$, $d = 0.80$) (Fig. 4, online Supplementary Table S8). Associations between sensitivity to punishment and left dACC connectivity failed to reach significance and were not further examined.

The mediation model reached significance in the TT group only, implying individual variations in sensitivity to punishment may be explained by the level of ELS exposure in the TT group.

A significant overall indirect effect was observed (mediation by brain volume; indirect effect ratio 66.75%; effect size $a \times b = 0.1096$, 95% CI 0.0247–0.2212; $p < 0.05$), suggesting that thalamic-limbic-prefrontal volumes mediated the influence of ELS on sensitivity to punishment in TT carriers (online Supplementary Table S9).

Replication sample

Results from the partial correlation analysis in the $n = 51$ male homozygotes revealed a similar pattern as in the discovery sample such that TT homozygotes exhibited a positive association between ELS and GMV (online Supplementary Table S7). Specifically, in TT homozygotes, higher stress exposure during childhood associated with higher GMV in bilateral dACC and vmPFC. However, associations between higher ELS and increased volume in thalamic-limbic regions failed to reach significance in TT carriers but exhibited a positive association in GG homozygotes. Thus, the positive associations between ELS and vmPFC and dACC volume in TT homozygotes appear to be robust, while associations in thalamic-limbic regions were less robust.

Discussion

Previous animal models and initial findings in humans suggest that variations in serotonergic signaling-associated individual differences in the *TPH2* polymorphism mediate the effects of early adverse experiences on emotional dysregulations (Forsman *et al.*, 2014; Mandelli *et al.*, 2012; Sachs *et al.*, 2013). The current discovery sample found that *TPH2* rs4570625 genotype and ELS interact to shape the structural and functional architecture of thalamic-limbic-prefrontal circuits. Specifically, we observed that in TT homozygotes higher ELS exposure was associated with increased volumes of hippocampal-amygdala, thalamic and frontal regions and decreased functional connectivity between left dACC and left DLPFC, left amygdala, respectively. No associations were observed in the G-carrier groups. The replication dataset confirmed the robustness of the association between higher ELS and increased dACC and vmPFC volumes – at least for male subjects – whereas the observed associations in thalamic-limbic regions appeared to be less robust. Moreover, in the discovery sample *TPH2* genotype significantly moderated the impact of ELS on punishment sensitivity. In TT homozygotes higher levels of sensitivity to punishment were associated with both higher exposure to ELS and limbic and frontal brain volumes. An additional mediation analysis furthermore suggests that increased brain volumes in this circuitry critically mediate the impact of adverse childhood experiences on sensitivity to punishment solely in TT carriers.

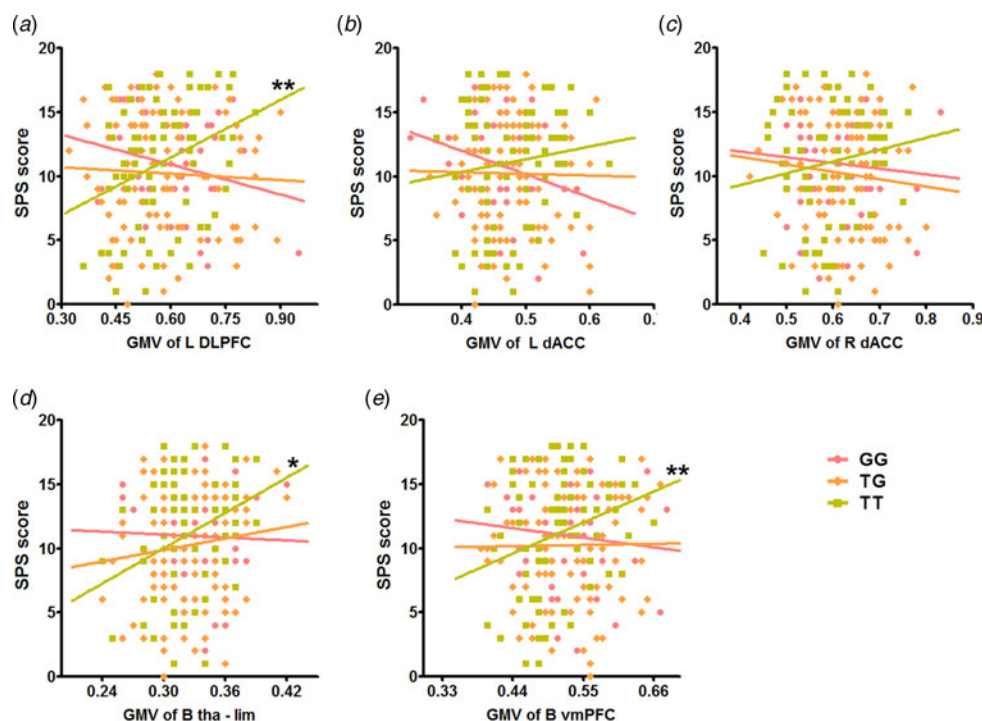


Fig. 4. Relationship between gray matter volume and sensitivity to punishment scale (SPS) scores for TT homozygotes, TG heterozygotes and GG homozygotes in the regions showing significant genotype \times early life stress effects (a–e). dACC, dorsal anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex; GMV, gray matter volume; SPS, sensitivity to punishment scale; vmPFC, ventromedial frontal cortex; tha-lim, parahippocampus gyrus/ hippocampus/thalamus; L, left; R, right; B, bilateral; * $p < 0.05$; ** $p < 0.01$, Bonferroni-corrected.

In contrast to the present findings several previous studies that did not account for genetic differences, reported that higher ELS associated with decreased brain volumes in limbic and prefrontal regions (Maier et al., 2020; Teicher et al., 2016). An additional analysis that pooled the G-carriers of the present sample, revealed a negative association between ELS and brain volumes in the pooled G-carrier group partly replicating the previous findings (online Supplementary Table S10). According to Cohen's (1988) convention of effect sizes, the observed significant correlations in the pooled G-carrier group are small (between 0.1 and 0.3), while the associations in the TT group were in the medium range (between 0.3 and 0.5). Animal models suggest that prolonged stress during sensitive developmental periods detrimentally impacts dendritic growth in limbic and prefrontal regions (Yang et al., 2015) which could partially explain lower volumes observed on the macro-anatomic level (Ivy et al., 2010). The few previous studies that examined whether genetic polymorphisms modulate the impact of ELS on brain structure in humans observed that carriers of specific allelic variants coding brain-derived neurotrophic growth factor and oxytocin pathway genes exhibit pronounced volumetric decreases following ELS (Dannowski et al., 2016; van Velzen et al., 2016).

The observed opposite association between higher ELS and increased brain volumes observed in the *TPH2* rs4570625 TT homozygotes contrasts with these previous reports on a genetic susceptibility for pronounced ELS-associated brain structural deficits. Furthermore, some studies that combined the low-frequency *TPH2* rs4570625T-carrier groups (TT and TG) initially revealed increased psychopathological risk (Gao et al., 2012), anxiety-associated traits (Gutknecht et al., 2007) and detrimental effects of ELS (Forssman et al., 2014; Mandelli et al., 2012). However, accumulating evidence indicates that TT homozygotes

differ from both, TG and GG variants in terms of lower anxiety-related behavior and psychopathological risk (Ottenhof et al., 2018). While reduced gray matter volumes in limbic-prefrontal regions have been consistently reported in psychiatric disorders characterized by exaggerated anxiety and deficient emotion regulation (Bora, Fornito, Pantelis, & Yucel, 2012), associations between emotional functioning and limbic-prefrontal volumes in healthy subjects remain less clear, with elevated anxiety being associated with both volumetric increases and decreases in this circuitry (e.g. Günther et al., 2018). On the other hand, a growing number of studies consistently reported positive associations between aversive learning and volumetric indices in this circuit (e.g. Hartley, Fischl, and Phelps, 2011). Trauma exposure in adulthood has been associated with volumetric increases of the amygdala and concomitantly facilitated aversive learning (Cacciaglia et al., 2017). In the present study, both, aversive childhood experience and thalamic-limbic-prefrontal volumes were positively associated with higher punishment sensitivity in the TT homozygotes. According to the reinforcement sensitivity theory, individual differences in punishment sensitivity are neurally underpinned by the BIS, a brain-behavioral system that facilitates the formation of aversive motivation by orchestrating behavior in response to conditioned aversive events (Gray, 1987; Gray & McNaughton, 2000) and interacts with associative learning to facilitate aversive learning and future avoidance of threats (Reynolds, Askew, & Field, 2018). Increased punishment sensitivity on the phenotype level is considered to reflect an underlying hyperactive BIS system and has been consistently associated with better threat detection and facilitated aversive and avoidance learning (Avila & Parcet, 2000). The identified network exhibiting genotype \times ELS exposure interaction effects highly overlaps with the neural circuits engaged in these functional domains,

specifically the acquisition and extinction of conditioned threat responses (Milad & Quirk, 2012). Within this circuitry, the amygdala, hippocampus and dACC detect and encode threat probability of stimuli in the environment (e.g. Rodrigues, LeDoux, and Sapolsky, 2009) and are regulated by prefrontal-limbic circuits that subservise implicit and explicit regulation of the innate or acquired threat response (Kalisch, 2009; Ramanathan, Jin, Giustino, Payne, & Maren, 2018). Serotonin plays an important role in these aversive learning mechanisms and underpins neuroplasticity in limbic-prefrontal circuits (Lesch & Waider, 2012). Mice with a knockin mutilated *TPH2* polymorphism (rs4570625) resulting in serotonin deficiency exhibit a phenotype characterized by facilitated threat reactivity and threat acquisition that are mediated by neural morphology in limbic regions, particularly the hippocampal-amygdalar complex (Waider *et al.*, 2019).

Although the neurobiological implications of the *TPH2* rs4570625 polymorphism are not fully understood, the T-variant has been associated with increased as well as decreased central serotonergic transmission in limbic-prefrontal circuits (Lin *et al.*, 2007; Zhang *et al.*, 2004). The present findings may thus reflect that the *TPH2* polymorphism, perhaps underlying individual differences in 5-HT neurotransmission, may mediate the impact of ELS via experience-dependent neuroplastic changes in limbic-prefrontal circuits engaged in aversive learning. This suggests that this polymorphism interacts with aversive environmental factors to shape a neural and behavior phenotype with an enhanced capability to detect and avoid threat and thus facilitating survival in a malevolent environment (Teicher *et al.*, 2016).

On the network level, ELS-associated volumetric increases observed in TT carriers were accompanied by decreased functional communication of the dACC with both, the DLPFC and the amygdala. Deficient intrinsic functional interaction within this circuit has been increasingly reported following ELS and has been associated with increased emotional dysregulations and threat reactivity on the behavioral level (Kaiser *et al.*, 2018). Deficient recruitment of the dACC and functional communication within the dACC-DLPFC-amygdala circuitry have been associated with impaired voluntary emotion regulation (Zilverstand, Parvaz, & Goldstein, 2017; Zimmermann *et al.*, 2017). In this context, the present findings could suggest that the increased regional-specific volumes of the aversive learning circuit in TT carriers come at the expense of less regulatory control within this circuitry, shifting the systems towards higher sensitivity for reacting to threatening stimuli in the environment rather than focusing on internal emotion regulation. These alterations may reflect experience-dependent adaptations that promote avoidance of further harm in a malevolent childhood environment however may render individuals at an increased (latent) psychopathological vulnerability in adulthood. Although individuals with a psychiatric diagnosis were not enrolled in the present study, TT carriers reported slightly elevated levels of perceived current stress possibly reflecting elevated threat reactivity or deficient emotion regulation respectively. Alterations in these domains have been associated with aberrant amygdala-frontal functional connectivity that normalize with symptom-reduction in stress-related disorders (Spengler *et al.*, 2017). Behavioral interventions and neuromodulatory strategies have been shown to facilitate emotion regulation via modulating amygdala-prefrontal connectivity (Zhao *et al.*, 2019) and similar mechanisms could be harnessed to alleviate increased psychopathological vulnerability following ELS.

In the current study, genotype groups did not differ in the anxiety-related trait (sensitivity to punishment) which is not consistent with previous studies (Gutknecht *et al.*, 2007; Laas *et al.*, 2017; Reuter *et al.*, 2007). For instance, Gutknecht *et al.*, found that the T allele was a risk allele for cluster B and cluster C personality disorders and an anxiety-related phenotype (harm avoidance) in patients with personality disorders. On the other hand, Reuter *et al.* (2007) found lower harm avoidance in healthy TT homozygotes. The inconsistent findings may be related to population, ethnic, and cultural diversity. In addition, the current results found that in TT carriers, there was a positive correlation between ELS and sensitivity to punishment, suggesting that the difference in early life experience may contribute to the diverse findings observed in previous studies.

By capitalizing on genotyping of an apparently functional and common *TPH2* SNP for central serotonergic neurotransmission in combination with MRI and trait assessments in a representative sample of healthy subjects, the present study allowed us to determine the role of polymorphic gene differences that modulate serotonergic signaling and mediate adaptation to early life stress on the neural and phenotype level. Owing to the low prevalence of the T-allele in Caucasian populations, previous studies combined T-carriers (Markett *et al.*, 2017), whereas the higher frequency of the T-variant in Asian populations uniquely enabled us to additionally examine characteristics of the TT-homozygote variant. Nevertheless, the current findings need to be tempered by the following limitations: (1) Early life stress was retrospectively assessed; however, the reported level of ELS did not differ between the genotype groups. (2) Different effects of ELS during different developmental periods have been reported, however, the retrospective assessment does not allow further determination of genotype-dependent differences in the onset of stress exposure. (3) Finally, the replication sample did not include resting-state data, female subjects or TG carriers and hence, the current findings require further replication.

Conclusions

The present findings suggest that ELS shapes the neural organization of the thalamic-limbic-prefrontal circuits in interaction with individual genetic variations in a *TPH2* polymorphism. The identified network strongly overlaps with the circuitry engaged in aversive learning and avoidant behavior. Previous studies suggest that serotonin facilitates aversive learning via promoting neuroplasticity in thalamic-limbic-prefrontal circuits. Within this context, the present findings suggest that genetic differences in serotonergic signaling associated with a specific *TPH2* polymorphism partially determine the impact of adverse early life experiences on the structural and functional architecture of the brain and shape a phenotype adapted to avoid threat in a malevolent environment.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/S0033291720002809>

Acknowledgements. This work was supported by the National Key Research and Development Program of China (2018YFA0701400); National Natural Science Foundation of China (91632117, 31530032, 31700998); Open Research Fund of the State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University; Science, Innovation and Technology Department of the Sichuan Province (2018JY0001). The authors report no conflict of interest.

References

- Avila, C., & Parcet, M. A. (2000). The role of Gray's impulsivity in anxiety-mediated differences in resistance to extinction. *European Journal of Personality*, *14*, 185–198. doi: 10.1002/1099-0984(200005/06)14:3<185::AID-PER370>3.0.CO;2-U.
- Avinun, R., Nevo, A., Knodt, A. R., Elliott, M. L., & Hariri, A. R. (2018). Replication in imaging genetics: The case of threat-related amygdala reactivity. *Biological Psychiatry*, *84*, 148–159. doi: 10.1016/j.biopsych.2017.11.010.
- Bernstein, D. P., Stein, J. A., Newcomb, M. D., Walker, E., Pogge, D., Ahluvalia, T., ... Desmond, D. (2003). Development and validation of a brief screening version of the Childhood Trauma Questionnaire. *Child abuse & neglect*, *27*, 169–190. doi: 10.1016/S0145-2134(02)00541-0.
- Birn, R. M., Roeber, B. J., & Pollak, S. D. (2017). Early childhood stress exposure, reward pathways, and adult decision making. *Proceedings of the National Academy of Sciences*, *114*, 13549–13554. doi: 10.1073/pnas.1708791114.
- Booij, L., Turecki, G., Leyton, M., Gravel, P., Lopez De Lara, C., Diksic, M., & Benkelfat, C. (2012). Tryptophan hydroxylase(2) gene polymorphisms predict brain serotonin synthesis in the orbitofrontal cortex in humans. *Molecular Psychiatry*, *17*, 809–817. doi: 10.1038/mp.2011.79.
- Bora, E., Fornito, A., Pantelis, C., & Yucel, M. (2012). Gray matter abnormalities in Major Depressive Disorder: A meta-analysis of voxel based morphometry studies. *Journal of Affective Disorders*, *138*, 9–18. doi: 10.1016/j.jad.2011.03.049.
- Border, R., Johnson, E. C., Evans, L. M., Smolen, A., Berley, N., Sullivan, P. F., & Keller, M. C. (2019). No support for historical candidate gene or candidate gene-by-interaction hypotheses for major depression across multiple large samples. *American Journal of Psychiatry*, *176*, 376–387. doi: 10.1176/appi.ajp.2018.18070881.
- Cacciaglia, R., Nees, F., Grimm, O., Ridder, S., Pohlack, S. T., Diener, S. J., ... Flor, H. (2017). Trauma exposure relates to heightened stress, altered amygdala morphology and deficient extinction learning: Implications for psychopathology. *Psychoneuroendocrinology*, *76*, 19–28. doi: 10.1016/j.psneuen.2016.11.012.
- Canli, T., Congdon, E., Gutknecht, L., Constable, R. T., & Lesch, K. P. (2005). Amygdala responsiveness is modulated by tryptophan hydroxylase-2 gene variation. *Journal of Neural Transmission*, *112*, 1479–1485. doi: 10.1007/s00702-005-0391-4.
- Canli, T., Congdon, E., Todd Constable, R., & Lesch, K. P. (2008). Additive effects of serotonin transporter and tryptophan hydroxylase-2 gene variation on neural correlates of affective processing. *Biological Psychology*, *79*, 118–125. doi: 10.1016/j.biopsycho.2008.01.004.
- Carter, C. S., Bearden, C. E., Bullmore, E. T., Geschwind, D. H., Glahn, D. C., Gur, R. E., ... Weinberger, D. R. (2017). Enhancing the informativeness and replicability of imaging genomics studies. *Biological Psychiatry*, *82*, 157–164. doi: 10.1016/j.biopsych.2016.08.019.
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (pp. 20–26). Hillsdale, NJ: Lawrence Earlbaum Associates.
- Cohen, S., Kamarck, T., & Mermelstein, R. (1983). A global measure of perceived stress. *Journal of Health and Social Behavior*, *24*, 385–396. doi: 10.2307/2136404.
- Culverhouse, R. C., Saccone, N. L., & Bierut, L. J. (2018). The state of knowledge about the relationship between 5-HTTLPR, stress, and depression. *Journal of Affective Disorders*, *228*, 205–206. doi: 10.1016/j.jad.2017.12.002.
- Dannlowski, U., Kugel, H., Grotegerd, D., Redlich, R., Opel, N., Dohm, K., ... Baune, B. T. (2016). Disadvantage of social sensitivity: Interaction of oxytocin receptor genotype and child maltreatment on brain structure. *Biological Psychiatry*, *80*, 398–405. doi: 10.1016/j.biopsych.2015.12.010.
- Dannlowski, U., Kugel, H., Huber, F., Stuhmann, A., Redlich, R., Grotegerd, D., ... Suslow, T. (2013). Childhood maltreatment is associated with an automatic negative emotion processing bias in the amygdala. *Human Brain Mapping*, *34*, 2899–2909. doi: 10.1002/hbm.22112.
- Forssman, L., Peltola, M. J., Yrttiaho, S., Puura, K., Mononen, N., Lehtimäki, T., & Leppänen, J. M. (2014). Regulatory variant of the TPH 2 gene and early life stress are associated with heightened attention to social signals of fear in infants. *Journal of Child Psychology And Psychiatry*, *55*, 793–801. doi: 10.1111/jcpp.12181.
- Frodl, T., Skokauskas, N., Frey, E. M., Morris, D., Gill, M., & Carballedo, A. (2014). BDNF Val66Met genotype interacts with childhood adversity and influences the formation of hippocampal subfields. *Human Brain Mapping*, *35*, 5776–5783. doi: 10.1002/hbm.22584.
- Fung, B. J., Qi, S., Hassabis, D., Daw, N., & Mobbs, D. (2019). Slow escape decisions are swayed by trait anxiety. *Nature Human Behaviour*, *3*, 702–708. doi: 10.1038/s41562-019-0595-5.
- Furmark, T., Marteinsdottir, I., Frick, A., Heurling, K., Tillfors, M., Appel, L., ... Fredrikson, M. (2016). Serotonin synthesis rate and the tryptophan hydroxylase-2: G-703T polymorphism in social anxiety disorder. *Journal of Psychopharmacology*, *30*, 1028–1035. doi: 10.1177/0269881116648317.
- Gao, J., Pan, Z., Jiao, Z., Li, F., Zhao, G., Wei, Q., ... Evangelou, E. (2012). TPH2 Gene polymorphisms and major depression—a meta-analysis. *PLoS one*, *7*, e36721. doi: 10.1371/journal.pone.0036721.
- Gray, J. A. (1987). The neuropsychology of emotion and personality. In S. M. Stahl, S. D. Iversen, & E. C. Goodman (Eds.), *Cognitive neurochemistry* (pp. 171–190). New York, NY, USA: Oxford University Press.
- Gray, J., & McNaughton, N. (2000). Fundamentals of the septo-hippocampal system. In N. McNaughton (Ed.), *The neuropsychology of anxiety: An enquiry into the functions of septo-hippocampal system* (2nd ed., pp. 204–232). New York, NY, USA: Oxford University Press.
- Günther, V., Ihme, K., Kersting, A., Hoffmann, K.-T., Lobsien, D., & Suslow, T. (2018). Volumetric associations between amygdala, nucleus accumbens, and socially anxious tendencies in healthy women. *Neuroscience*, *374*, 25–32. doi: 10.1016/j.neuroscience.2018.01.034.
- Gutknecht, L., Jacob, C., Strobel, A., Kriegebaum, C., Muller, J., Zeng, Y., ... Lesch, K. P. (2007). Tryptophan hydroxylase-2 gene variation influences personality traits and disorders related to emotional dysregulation. *International Journal of Neuropsychopharmacology*, *10*, 309–320. doi: 10.1017/s1461145706007437.
- Hartley, C. A., Fischl, B., & Phelps, E. A. (2011). Brain structure correlates of individual differences in the acquisition and inhibition of conditioned fear. *Cerebral Cortex*, *21*, 1954–1962. doi: 10.1093/cercor/bhq253.
- Ivy, A. S., Rex, C. S., Chen, Y., Dube, C., Maras, P. M., Grigoriadis, D. E., ... Baram, T. Z. (2010). Hippocampal dysfunction and cognitive impairments provoked by chronic early-life stress involve excessive activation of CRH receptors. *Journal of Neuroscience*, *30*, 13005–13015. doi: 10.1523/jneurosci.1784-10.2010.
- Kaiser, R. H., Clegg, R., Goer, F., Pechtel, P., Beltzer, M., Vitaliano, G., ... Pizzagalli, D. A. (2018). Childhood stress, grown-up brain networks: Corticolimbic correlates of threat-related early life stress and adult stress response. *Psychological Medicine*, *48*, 1157–1166. doi: 10.1017/s0033291717002628.
- Kalisch, R. (2009). The functional neuroanatomy of reappraisal: Time matters. *Neuroscience and Biobehavioral Reviews*, *33*, 1215–1226. doi: 10.1016/j.neubiorev.2009.06.003.
- Kennedy, A. P., Binder, E. B., Bowman, D., Harenski, K., Ely, T., Cisler, J. M., ... Kils, C. D. (2012). A common TPH2 haplotype regulates the neural processing of a cognitive control demand. *American Journal of Medical Genetics Part B-Neuropsychiatric Genetics*, *159b*, 829–840. doi: 10.1002/ajmg.b.32090.
- Laas, K., Kiive, E., Maestu, J., Vaht, M., Veidebaum, T., & Harro, J. (2017). Nice guys: Homozygosity for the TPH2 –703G/T (rs4570625) minor allele promotes low aggressiveness and low anxiety. *Journal of Affective Disorders*, *215*, 230–236. doi: 10.1016/j.jad.2017.03.045.
- Lesch, K. P., & Waider, J. (2012). Serotonin in the modulation of neural plasticity and networks: Implications for neurodevelopmental disorders. *Neuron*, *76*, 175–191. doi: 10.1016/j.neuron.2012.09.013.
- Li, J., Xu, L., Zheng, X., Fu, M., Zhou, F., Xu, X., ... Becker, B. (2019). Common and dissociable contributions of alexithymia and autism to domain-specific interoceptive dysregulations: A dimensional neuroimaging approach. *Psychotherapy and Psychosomatics*, *88*, 187–189. doi: 10.1159/000495122.
- Lin, Y. M., Chao, S. C., Chen, T. M., Lai, T. J., Chen, J. S., & Sun, H. S. (2007). Association of functional polymorphisms of the human tryptophan hydroxylase 2 gene with risk for bipolar disorder in Han Chinese. *Archives of General Psychiatry*, *64*, 1015–1024. doi: 10.1001/archpsyc.64.9.1015.

- Maier, A., Gieling, C., Heinen-Ludwig, L., Stefan, V., Schultz, J., Güntürkün, O., ... Scheele, D. (2020). Association of childhood maltreatment with interpersonal distance and social touch preferences in adulthood. *American Journal of Psychiatry*, *177*, 37–46. doi: 10.1176/appi.ajp.2019.19020212.
- Mandelli, L., Antypa, N., Nearchou, F. A., Vaiopoulos, C., Stefanis, C. N., Serretti, A., & Stefanis, N. C. (2012). The role of serotonergic genes and environmental stress on the development of depressive symptoms and neuroticism. *Journal of Affective Disorders*, *142*, 82–89. doi: 10.1016/j.jad.2012.03.047.
- Markett, S., de Reus, M. A., Reuter, M., Montag, C., Weber, B., Schoene-Bake, J. C., & van den Heuvel, M. P. (2017). Serotonin and the brain's rich club-association between molecular genetic variation on the TPH2 gene and the structural connectome. *Cerebral Cortex (New York, N.Y.: 1991)*, *27*, 2166–2174. doi: 10.1093/cercor/bhw059.
- Milad, M. R., & Quirk, G. J. (2012). Fear extinction as a model for translational neuroscience: Ten years of progress. *Annual Review of Psychology*, *63*, 129–151. doi: 10.1146/annurev.psych.121208.131631.
- Montag, C., Sindermann, C., Melchers, M., Jung, S., Luo, R., Becker, B., ... Kendrick, K. M. (2017). A functional polymorphism of the OXTR gene is associated with autistic traits in Caucasian and Asian populations. *American Journal of Medical Genetics Part B-Neuropsychiatric Genetics*, *174*, 808–816. doi: 10.1002/ajmg.b.32596.
- Ottenhof, K. W., Sild, M., Levesque, M. L., Ruhe, H. G., & Booij, L. (2018). TPH2 Polymorphisms across the spectrum of psychiatric morbidity: A systematic review and meta-analysis. *Neuroscience and Biobehavioral Reviews*, *92*, 29–42. doi: 10.1016/j.neubiorev.2018.05.018.
- Preacher, K. J., & Hayes, A. F. (2004). SPSS And SAS procedures for estimating indirect effects in simple mediation models. *Behavior Research Methods, Instruments, & Computers volume*, *36*, 717–731. doi: 10.3758/BF03206553.
- Preacher, K. J., & Hayes, A. F. (2008). Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behavior Research Methods*, *40*, 879–891. doi: 10.3758/BRM.40.3.879.
- Ramanathan, K. R., Jin, J., Giustino, T. F., Payne, M. R., & Maren, S. (2018). Prefrontal projections to the thalamic nucleus reuniens mediate fear extinction. *Nature Communications*, *9*, 4527. doi: 10.1038/s41467-018-06970-z.
- Reuter, M., Esslinger, C., Montag, C., Lis, S., Gallhofer, B., & Kirsch, P. (2008). A functional variant of the tryptophan hydroxylase 2 gene impacts working memory: A genetic imaging study. *Biological Psychology*, *79*, 111–117. doi: 10.1016/j.biopsycho.2007.12.002.
- Reuter, M., Kuepper, Y., & Hennig, J. (2007). Association between a polymorphism in the promoter region of the TPH2 gene and the personality trait of harm avoidance. *International Journal of Neuropsychopharmacology*, *10*, 401–404. doi: 10.1017/s1461145706007073.
- Reynolds, G., Askew, C., & Field, A. P. (2018). Behavioral inhibition and the associative learning of fear. In K. Pérez-Edgar, & N. Fox (Eds.), *Behavioral inhibition* (pp. 263–282). Cham: Springer.
- Rodrigues, S. M., LeDoux, J. E., & Sapolsky, R. M. (2009). The influence of stress hormones on fear circuitry. *Annual Review of Neuroscience*, *32*, 289–313. doi: 10.1146/annurev.neuro.051508.135620.
- Sachs, B. D., Rodriguiz, R. M., Siesser, W. B., Kenan, A., Royer, E. L., Jacobsen, J. P., ... Caron, M. G. (2013). The effects of brain serotonin deficiency on behavioural disinhibition and anxiety-like behaviour following mild early life stress. *International Journal of Neuropsychopharmacology*, *16*, 2081–2094. doi: 10.1017/s1461145713000321.
- Sonuga-Barke, E. J. S., Kennedy, M., Kumsta, R., Knights, N., Golm, D., Rutter, M., ... Kreppner, J. (2017). Child-to-adult neurodevelopmental and mental health trajectories after early life deprivation: The young adult follow-up of the longitudinal English and Romanian Adoptees study. *Lancet (London, England)*, *389*, 1539–1548. doi: 10.1016/s0140-6736(17)30045-4.
- Spengler, F. B., Becker, B., Kendrick, K. M., Conrad, R., Hurlemann, R., & Schade, G. (2017). Emotional dysregulation in psychogenic voice loss. *Psychotherapy and Psychosomatics*, *86*, 121–123. doi: 10.1159/000452306.
- Teicher, M. H., Samson, J. A., Anderson, C. M., & Ohashi, K. (2016). The effects of childhood maltreatment on brain structure, function and connectivity. *Nature Reviews Neuroscience*, *17*, 652–666. doi: 10.1038/nrn.2016.111.
- Torrubia, R., Avila, C., Moltó, J., & Caseras, X. (2001). The Sensitivity to Punishment and Sensitivity to Reward Questionnaire (SPSRQ) as a measure of Gray's anxiety and impulsivity dimensions. *Personality and Individual Differences*, *31*, 837–862. doi: 10.1016/S0191-8869(00)00183-5.
- van Velzen, L. S., Schmaal, L., Jansen, R., Milaneschi, Y., Opmeer, E. M., Elzinga, B. M., ... Penninx, B. W. (2016). Effect of childhood maltreatment and brain-derived neurotrophic factor on brain morphology. *Social Cognitive and Affective Neuroscience*, *11*, 1841–1852. doi: 10.1093/scan/nsw086.
- Waider, J., Popp, S., Mlinar, B., Montalbano, A., Bonfiglio, F., Aboagye, B., ... Lesch, K. P. (2019). Serotonin deficiency increases context-dependent fear learning through modulation of hippocampal activity. *Frontiers in Neuroscience*, *13*, 245. doi: 10.3389/fnins.2019.00245.
- White, M. G., Bogdan, R., Fisher, P. M., Munoz, K. E., Williamson, D. E., & Hariri, A. R. (2012). FKBP5 And emotional neglect interact to predict individual differences in amygdala reactivity. *Genes Brain and Behavior*, *11*, 869–878. doi: 10.1111/j.1601-183X.2012.00837.x.
- Winkler, A. M., Ridgway, G. R., Webster, M. A., Smith, S. M., & Nichols, T. E. (2014). Permutation inference for the general linear model. *Neuroimage*, *92*, 381–397.
- Yang, X. D., Liao, X. M., Uribe-Marino, A., Liu, R., Xie, X. M., Jia, J., ... Si, T. M. (2015). Stress during a critical postnatal period induces region-specific structural abnormalities and dysfunction of the prefrontal cortex via CRF1. *Neuropsychopharmacology*, *40*, 1203–1215. doi: 10.1038/npp.2014.304.
- Zhang, X., Beaulieu, J.-M., Sotnikova, T. D., Gainetdinov, R. R., & Caron, M. G. (2004). Tryptophan hydroxylase-2 controls brain serotonin synthesis. *Science (New York, N.Y.)*, *305*, 217–217. doi: 10.1126/science.1097540.
- Zhao, Z., Yao, S., Li, K., Sindermann, C., Zhou, F., Zhao, W., ... Kendrick, K. M. (2019). Real-time functional connectivity-informed neurofeedback of amygdala-frontal pathways reduces anxiety. *Psychotherapy and Psychosomatics*, *88*, 5–15. doi: 10.1159/000496057.
- Zilverstand, A., Parvaz, M. A., & Goldstein, R. Z. (2017). Neuroimaging cognitive reappraisal in clinical populations to define neural targets for enhancing emotion regulation. A systematic review. *Neuroimage*, *151*, 105–116. doi: 10.1016/j.neuroimage.
- Zimmermann, K., Walz, C., Derckx, R. T., Kendrick, K. M., Weber, B., Dore, B., ... Becker, B. (2017). Emotion regulation deficits in regular marijuana users. *Human Brain Mapping*, *38*, 4270–4279. doi: 10.1002/hbm.23671.