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ARTICLE

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Examining the association between posttraumatic stress disorder and disruptions in cortical networks identified using data-driven methods

Jin Yang[1], Ashley A. Huggins[2,3], Delin Sun[2,3,4], C. Lexi Baird[2,3], Courtney C. Haswell[2,3], Jessie L. Frijling[5], Miranda Olff[5,6], Mirjam van Zuiden[5], Saskia B. J. Koch[5,7], Laura Nawijn[5], Dick J. Veltman[5], Benjamin Suarez-Jimenez[8], Xi Zhu[9,10], Yuval Neria[9,10], Anna R. Hudson[11], Sven C. Mueller[11], Justin T. Baker[12,13], Lauren A. M. Lebois[12,14], Milissa L. Kaufman[12,15], Rongfeng Qi[16], Guang Ming Lu[16], Pavel Říha[17,18], Ivan Rektor[18], Emily L. Dennis[19,20], Christopher R. K. Ching[21], Sophia I. Thomopoulos[21], Lauren E. Salminen[21], Neda Jahanshad[21], Paul M. Thompson[21], Dan J. Stein[22], Sheri M. Koopowitz[22], Jonathan C. Ipser[22], Soraya Seedat[23], Stefan du Plessis[23], Leigh L. van den Heuvel[23], Li Wang[24,25], Ye Zhu[24,25], Gen Li[24,25], Anika Sierk[26], Antje Manthey[26], Henrik Walter[26], Judith K. Daniels[27], Christian Schmahl[28], Julia I. Herzog[28], Israel Liberzon[29], Anthony King[30], Mike Angstadt[30], Nicholas D. Davenport[31,32], Scott R. Sponheim[31,32], Seth G. Disner[31,32], Thomas Straube[33], David Hofmann[33], Daniel W. Grupe[34], Jack B. Nitschke[35], Richard J. Davidson[34,35,36], Christine L. Larson[37], Terri A. deRoon-Cassini[38,39], Jennifer U. Blackford[40,41], Bunmi O. Olatunji[42], Evan M. Gordon[1], Geoffrey May[43,44,45,46], Steven M. Nelson[43,44,45,46], Chadi G. Abdallah[47,48], Ifat Levy[49,50,51,52,53], Ilan Harpaz-Rotem[47,51,53], John H. Krystal[47,53], Rajendra A. Morey[2,3]✉ and Aristeidis Sotiras[1,54]

Posttraumatic stress disorder (PTSD) is associated with lower cortical thickness (CT) in prefrontal, cingulate, and insular cortices in diverse trauma-affected samples. However, some studies have failed to detect differences between PTSD patients and healthy controls or reported that PTSD is associated with greater CT. Using data-driven dimensionality reduction, we sought to conduct a well-powered study to identify vulnerable networks without regard to neuroanatomic boundaries. Moreover, this approach enabled us to avoid the excessive burden of multiple comparison correction that plagues vertex-wise methods. We derived structural covariance networks (SCNs) by applying non-negative matrix factorization (NMF) to CT data from 961 PTSD patients and 1124 trauma-exposed controls without PTSD. We used regression analyses to investigate associations between CT within SCNs and PTSD diagnosis (with and without accounting for the potential confounding effect of trauma type) and symptom severity in the full sample. We performed additional regression analyses in subsets of the data to examine associations between SCNs and comorbid depression, childhood trauma severity, and alcohol abuse. NMF identified 20 unbiased SCNs, which aligned closely with functionally defined brain networks. PTSD diagnosis was most strongly associated with diminished CT in SCNs that encompassed the bilateral superior frontal cortex, motor cortex, insular cortex, orbitofrontal cortex, medial occipital cortex, anterior cingulate cortex, and posterior cingulate cortex. CT in these networks was significantly negatively correlated with PTSD symptom severity. Collectively, these findings suggest that PTSD diagnosis is associated with widespread reductions in CT, particularly within prefrontal regulatory regions and broader emotion and sensory processing cortical regions.

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INTRODUCTION

Posttraumatic stress disorder (PTSD) is a debilitating psychiatric illness with a lifetime prevalence of nearly 10% [1]. PTSD is characterized by a constellation of symptoms including intrusive memories, avoidance, negative alterations in cognition and mood, and hyperarousal [2]. Consistent with this phenotype, a wealth of research has demonstrated that PTSD is associated with several structural and functional differences in brain regions involved in affect, cognition, and memory [3–5].

As a metric of grey matter integrity, cortical thickness studies have been particularly illuminating for understanding the pathophysiology of PTSD. In general, PTSD has been associated with lower cortical thickness in regions including the prefrontal [6–11], cingulate [6, 12–14], and insular [15] cortices in diverse trauma-affected samples, including veterans [6, 7, 9–11, 15–17], and individuals with a history of childhood trauma [6, 8, 14]. Notably, some studies have also shown that greater cortical thickness may be an important marker of resilience and recovery in trauma-exposed samples [18–21].

However, some studies have failed to detect differences between PTSD patients and healthy controls [22–29], or have suggested that PTSD is associated with greater cortical thickness

A full list of author affiliations appears at the end of the paper.

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in specific regions, including the precuneus [30], calcarine cortex [31], and superior and frontal gyri [21, 32]. PTSD is highly heterogeneous—both in symptom profiles [33] and trauma type—researchers have proposed that differences in cortical thickness may be related to specific populations and/or symptom clusters [13, 26]. However, most efforts to characterize cortical thickness differences implicated in PTSD have also relied upon small samples and region of interest (ROI) approaches [25, 28, 29] or trauma naive [24, 26, 27] individuals. Indeed, results from recent meta-analytic work suggest different cortical thickness correlates emerge depending on whether the control group was trauma-exposed or not [32]. Although focusing on specific regions of the brain involved with neurobiological systems implicated in PTSD symptoms has proven to be an effective strategy, regional differences in cortical thickness may not necessarily adhere to strict neuroanatomical boundaries or may be associated with brain regions not previously implicated in PTSD.

To this end, novel, data-driven methods, such as non-negative matrix factorization (NMF), may provide powerful insights about the localized effects of PTSD on cortical thickness. NMF is an unsupervised machine learning method for multivariate analysis of high-dimensional neuroimaging data. NMF factorizes data under non-negativity constraints leading to a parts-based representation, which enhances interpretability and statistical power [34, 35]. Applied to anatomical data, NMF can elucidate patterns in cortical thickness variation that are shared within a sample, which may not adhere to neuroanatomical boundaries [35]. NMF-derived structural covariance networks map onto functionally-derived brain networks [35, 36], and can aid in the interpretability of cortical thickness findings related to disease states and behavioral phenotypes [37]. Although no published studies have used NMF to examine structural measures in PTSD, the technique has been successfully implemented in various samples to identify cortical thickness differences related to neurodevelopment [35, 38, 39], impulsivity [40], and other psychopathology [41–44].

Leveraging a large, multisite dataset from the PGC-ENIGMA PTSD Working Group, we employed NMF to identify structural covariance networks (SCNs) and examine differences in cortical thickness within these networks associated with PTSD. In a series of linear regression models, we tested whether PTSD diagnosis and severity were associated with abnormalities within NMF-derived networks. Additionally, we examined the potential confounding effect of trauma type on PTSD-associated group differences by including it as a binary categorical covariate. Lastly, to examine the specificity of effects, we also ran models that examined associations between SCNs and major depressive disorder (MDD), alcohol abuse and childhood trauma severity, respectively. These disorders are known to have a high co-occurrence with PTSD and have also been linked to cortical thickness alterations [8, 37, 45–49]. We conducted these additional analyses on subsets of the data where necessary information was available. While we hypothesized that PTSD would be associated with lower cortical thickness in specific structural networks in prefrontal [6–11] and cingulate [6, 12–14] cortices, the data-driven capability of NMF enabled us to identify heretofore undocumented areal features on the cortical surface associated with PTSD.

METHODS

Overview

Data analysis consisted of 8 major steps (Fig. 1). (1) We assembled imaging, clinical, and demographic data from 22 sites participating in ENIGMA-PTSD and harmonized clinical variables, including PTSD and symptom severity scores. (2) We created vertex-wise cortical surface maps for each participant using the FreeSurfer software suite [50] (Fig. 1A). (3) We performed harmonization of cortical thickness data to account for site and scanner effects using *ComBat* [51] (Fig. 1B). (4) We applied a multivariate, hypothesis-free method, non-negative matrix factorization (NMF), to identify SCNs (Fig. 1C). (5) Split-half reproducibility analysis and reconstruction error evaluation were used to select the optimal number of components (Fig. 1D). (6) We then conducted regression analyses to investigate respective associations between cortical thickness and PTSD diagnosis and symptom severity. The mean cortical thickness of 20 covariance networks from step #4 were used as the dependent variables in regression analyses. Regressors were added to the model to test for potential confounding effects of demographic variables, including sex, age, and the quadratic effect of age (Fig. 1E). (7) We conducted a confirmatory analysis with more homologous case-control samples without age or sex differences. (8) We conducted regression analyses to investigate the respective associations between comorbid depression, childhood trauma severity, and comorbid alcohol abuse and cortical thickness within SCNs.

Participants

Population information and T1-weighted magnetic resonance imaging (MRI) data were collected from 2085 individuals who were assigned to the PTSD group ($n = 961$) or trauma-exposed non-PTSD control group ($n = 1124$). Participant data was shared by 22 sites from seven countries on four continents. Descriptive information on the samples is provided in Table S1. Inclusion and exclusion criteria for each site are summarized in Table S2. For all sites (and sub-sites) where imaging data and demographic data were collected, current PTSD was diagnosed according to Diagnostic and Statistical Manual of Mental Disorders (DSM) IV or 5 criteria, using the following standard instruments: Clinician-Administered PTSD Scale-IV (CAPS-4; 10 sites, 14 sub-sites; DSM-IV), CAPS-5 (5 sites, 8 subsites; DSM-5), Structured Clinical Interview (SCID-4; 4 sites; DSM-IV), Mini International Neuropsychiatric Interview 6.0.0 (2 sites; DSM-IV), PTSD Checklist-5 (PCL-5; 2 sites; DSM-5), and PTSD Checklist-Civilian Version (PCL-C; 1 site; DSM-IV). All study sites obtained approval from local institutional review boards or ethics committees. All participants provided written informed consent.

Imaging acquisition and processing

High-resolution 3D T1-weighted brain structural MRI (sMRI) scans were collected at contributing laboratories. Anatomical brain images were preprocessed at Duke University through a standardized neuroimaging and quality control pipeline developed by the ENIGMA Consortium (http://enigma.ini.usc.edu/protocols/imaging-protocols/) [52]. The raw T1 sMRI data were pre-processed using the *FreeSurfer* software suite [50] (version 5.3.0, 6.0.0 or 7.1.0; see Table S1) to create cortical thickness maps for each individual subject, which were mapped to the fsaverage5 template space. Following our previous works [35, 37, 44], cortical thickness maps were smoothed using an isotropic Gaussian filter kernel with full width at half maximum (FWHM) size of 20 mm (Fig. 1A; Sec. S1.1).

Harmonization

An important challenge when analyzing consortium data is variation introduced by site-specific acquisition protocols and MRI scanners, which may interact with site-specific demographic and clinical profiles. To address this challenge, we employed harmonization using ComBat [51, 53, 54] (Fig. 1B). ComBat removes undesired site-associated differences while preserving inherent biological variance in the data [51]. In the present study, three variables (i.e., age, sex, and PTSD diagnosis) were included as covariates to preserve associated biological variability. Batches were created to remove unwanted variability associated with sites and scanners. The ComBat approach was implemented using scripts (https://github.com/Jfortin1/ComBatHarmonization) running on MATLAB, version R2018b.9.5.0.1033004.

Non-negative matrix factorization analysis

We used non-negative matrix factorization (NMF) to identify structural networks where cortical thickness covaries consistently across participants (Fig. 1C). NMF is an unsupervised, data-driven technique that factors the data by positively weighting cortical elements that covary. NMF yields a parts-based representation, which is more interpretable and reproducible than representations obtained by other decomposition techniques (e.g., Principal Component Analysis and Independent Component Analysis) [34, 35] and has greater statistical power than standard mass univariate analyses [40, 41]. Details regarding the formalization of NMF have been provided elsewhere [34, 35] and in the Supplementary Material (see Sec. S1.2).

The NMF algorithm may approximate the input data at different resolutions depending on the user-specified parameter K that denotes the

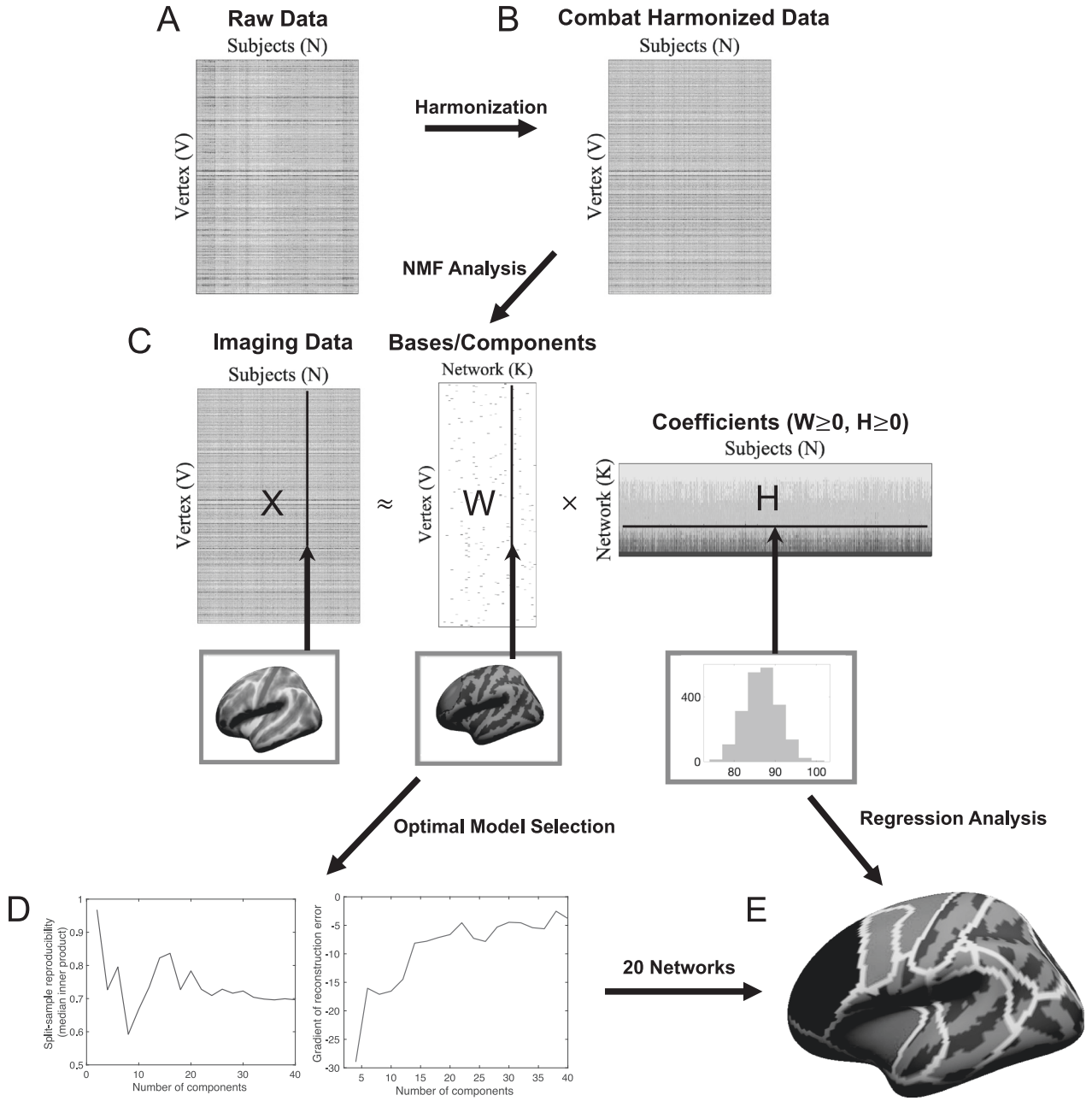

Fig. 1 Workflow. A We created cortical thickness maps for each subject from T1 sMRI data preprocessed using the FreeSurfer software. Cortical thickness measurements for all subjects were arrayed column-wise to form a cortical thickness matrix. **B** Cortical thickness data was harmonized using Combat to remove variation introduced by site-specific acquisition protocols and MRI scanners. **C** We applied non-negative matrix factorization (NMF) on the ComBat-harmonized cortical thickness matrix *X* to identify structural covariance networks. NMF decomposed this input matrix *X* into a component matrix *W* and a coefficient matrix *H*. The component matrix *W* represents estimated networks (columns) and their loadings on each vertex (rows); the example map shows loadings from one network and corresponds to a column in the *W* matrix. The weight matrix *H* provides the subject-specific weights (columns) for each network (rows); the histogram shows CT scores in a single network and corresponds to a row in the *H* matrix. **D** Split-half reproducibility analysis and reconstruction quality evaluation were performed to select the optimal model. **E** Once the optimal solution was selected, regression analyses were performed to examine associations between each network and PTSD diagnosis, PTSD severity scores and depression symptom severity, respectively. Additional regression analyses were performed to examine associations between each network and alcohol abuse and childhood trauma severity. This figure is best viewed in color.

number of networks. Accordingly, we systematically examined multiple NMF resolutions ranging from 2 to 40 networks (in steps of 2). To determine the optimal number of components, we performed a split-half reproducibility analysis and evaluated the reconstruction quality (see Fig. 1D and Sec. S1.2). The goal was to select a model that was reproducible and fit the data well.

Statistical analyses

First, we examined associations between categorical PTSD diagnosis and brain structure (Fig. 1E). We used quadratic regression analysis to evaluate cortical thickness differences in each network between PTSD and control groups, after controlling for sex, age, and quadratic effects of age. Specifically, the following group-comparison model was employed, with

Table 1. Demographic and symptom characteristics of PTSD ($N = 961$) and control ($N = 1124$) groups.

Variable	Control	PTSD	Difference	*p* value
N (%)	1124 (53.9%)	961 (46.1%)		
Female *N* (%)	487 (43.3%)	519 (54.0%)	$\chi^2 = 23.67$ (df = 1)	<0.0001*
Male *N* (%)	637 (56.7%)	442 (46.0%)		
Ages (yrs: mean ± sd)	41.00 ± 14.41	39.40 ± 13.08	t = −2.65 (df = 2076)	0.0081*
Age range (yrs)	15–87	16–95		
PTSD Severity	8.64 ± 9.76	49.71 ± 17.03	$t = 64.93$ (df = 1146.7)	<0.0001*
N of depression High/Low	33/985	283/580	$\chi^2 = 289.69$ (df = 1)	<0.0001*

Data are reported as mean ± 1 standard deviation.
df degrees of freedom.
*significant at $p < 0.05$ level.

CT_{SCN} representing the average cortical thickness in an NMF-derived SCN:

$$CT_{SCN} \sim age + age^2 + sex + PTSD \quad (1)$$

The trauma type was also added to the statistical model as a binary categorical covariate (military vs. civilian) for all sites and cohorts (Table S1) to examine its potential confounding effect on PTSD-associated group differences. Interactions of age by diagnosis and sex by diagnosis terms were then added to the statistical model to examine potential interactive effects of these factors on group differences.

Second, associations between cortical thickness and dimensional posttraumatic stress symptom (PTSS) severity were examined. Instruments for assessing PTSS severity varied by site. Score homogenization was accomplished by calculating the percentage of the severity score relative to the maximum score possible for each instrument (Table S3). Most (20 out of 22, Table S3) sites assessed PTSS severities in trauma-exposed control subjects, resulting in a sub-sample of 1995 subjects (from both PTSD and control groups) with normalized PTSS severity scores. We used quadratic regression analysis to examine associations between cortical thickness in each network and PTSS severity, with adjustments for sex, age, and quadratic effects of age:

$$CT_{SCN} \sim age + age^2 + sex + PTSS\ severity \quad (2)$$

Lastly, we examined the respective associations of comorbid depression, childhood trauma severity, and comorbid alcohol abuse (referred to as 'confounder' in Eq. 3) with cortical thickness alternations. Specifically, we used regression analyses to examine whether cortical thickness within each network was associated with each of these confounders, after accounting for sex, age, and quadratic effects of age:

$$CT_{SCN} \sim age + age^2 + sex + confounder \quad (3)$$

This analysis was performed only for the subsets of the data that included the necessary information. In these subsets of the data, we performed two additional regression analyses. First, we included categorical PTSD diagnosis in the regression model to examine potential confounding effects of comorbid depression, childhood trauma severity, and comorbid alcohol abuse (referred to as 'confounder' in Eq. 4) on PTSD-associated group differences:

$$CT_{SCN} \sim age + age^2 + sex + PTSD + confounder \quad (4)$$

Second, we examined associations between categorical PTSD diagnosis and brain structure when not controlling for the confounder (Eq. 1).

Comorbid depression was modeled as a binary index distinguishing high ($N = 316$) vs. low ($N = 1565$) depression symptom severity based on either questionnaire-specific depression cut-off scores or SCID diagnosis (Table S3). We use the shorthand designation of *depression* throughout to refer to severity of depressive symptoms as reflected by the derived binary label. Thus, in the present context, *depression* does not necessarily meet strict diagnostic criteria for major depressive disorder per the DSM. The derived binary categorical variable was included as covariate in the regression analysis (Eq. 3) to investigate the association between the cortical thickness within each SCN and depression. This analysis was performed separately for PTSD patients only ($N = 863$) and the full sub-sample ($N = 1881$). Lastly, two separate regression analyses (Eqs. 1 and 4) were performed in the full sub-sample ($N = 1881$) to examine group differences associated with PTSD and to assess the potential confounding effect of depression.

Childhood trauma severity was evaluated by the total Childhood Trauma Questionnaire (CTQ) [55] for each subject and was recorded as the total CTQ value for each site (Table S3; Fig. S1). The total CTQ value was transformed to remove skewness (see Sec. S1.3) and was then included as covariate in the regression model (Eq. 3) to examine the associations between the cortical thickness within each SCN and childhood trauma severity. This analysis was conducted on the full sub-sample ($N = 589$), as well as separately on PTSD patients ($N = 355$) and control subjects ($N = 234$). Lastly, two separate regression analyses (Eqs. 1 and 4) were performed in the full sub-sample ($N = 589$). These analyses examined group differences associated with PTSD and assessed the potential confounding effect of childhood trauma severity.

Comorbid alcohol abuse was assessed through the diagnosis of alcohol abuse disorder (AUD) by different AUD tools (Table S3). Based on exclusion criteria and diagnostic information, we defined a binary index to distinguish potential alcohol abuse disorder ($N = 110$) vs. non-comorbid alcohol ($N = 963$) (Table S4). The binary label was then included as covariate in the regression model (Eq. 3) to examine the associations between the cortical thickness within each SCN and alcohol abuse. Separate analyses were performed for PTSD patients ($N = 469$) and the full sub-sample ($N = 1073$). Lastly, two separate regression analyses (Eqs. 1 and 4) were performed in the full sub-sample ($N = 1073$). These analyses examined group differences associated with PTSD and assessed the potential confounding effect of alcohol abuse.

To account for multiple comparisons across all estimations, we controlled the false discovery rate (FDR) [56] as implemented in R [57]. An FDR corrected $p < 0.05$ was considered significant. All statistical analyses were performed using R, version 3.5.1.

RESULTS

Sample characteristics

Male and female subjects between 15 and 95 years old were studied. Compared to controls, participants with PTSD were more likely to be female ($p < 0.0001$) and were younger in age ($p = 0.0081$) (Table 1). The PTSD group had significantly greater PTSD severity scores ($p < 0.0001$) and higher comorbid depression than controls ($p < 0.0001$) (Table 1).

NMF identifies reproducible structural covariance networks

All measures before and after harmonization were reported as mean and standard deviation values for both left and right hemispheres (Table S5). Site-associated differences were removed by ComBat to generate harmonized cortical thickness measurements (Fig. S2, Fig. S3; see also Table S6). NMF analyses delineated SCNs at multiple resolutions ranging from 2 to 40 (in steps of 2). The 20-SCN solution was selected based on reconstruction error evaluation and split-half reproducibility analysis (Fig. S4). Reconstruction error decreased consistently with increasing resolution and stabilized at 20 networks. Although

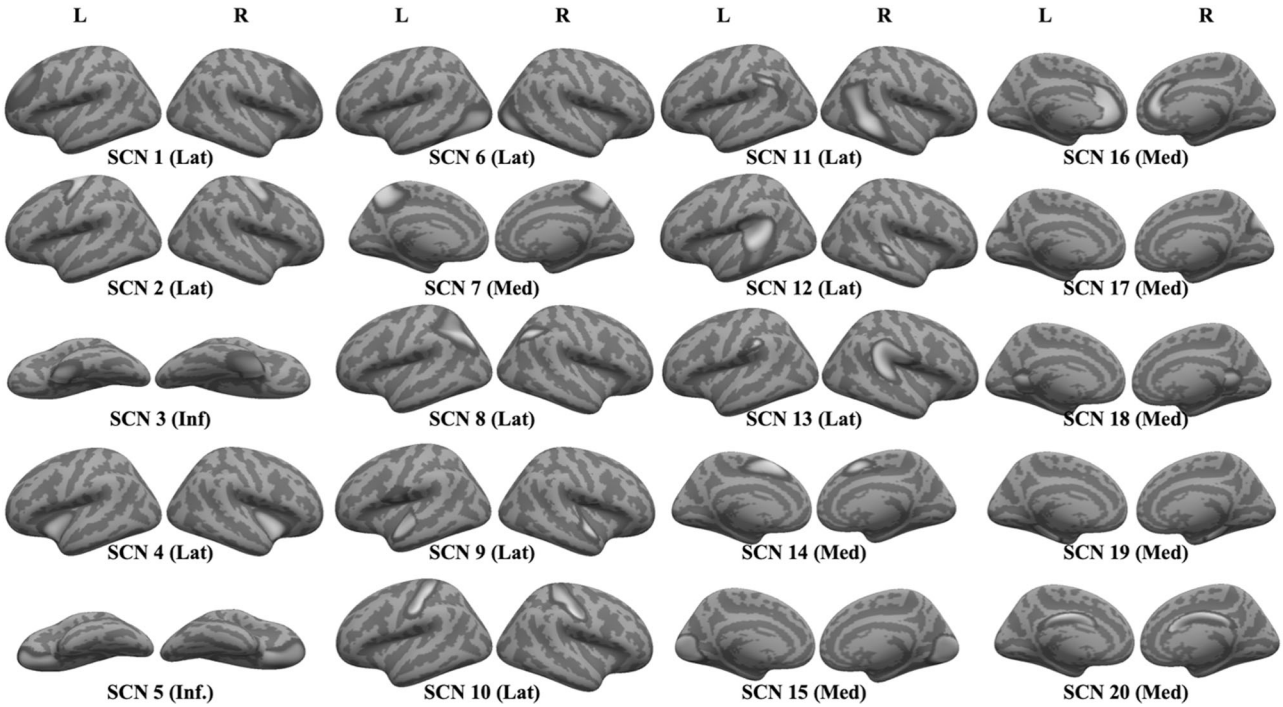

Fig. 2 Structural covariance networks delineated by NMF are shown for the 20-network solution. The spatial distribution of each network is indicated by loadings at each vertex in arbitrary units (warmer colors represent higher loadings). High symmetry can be found between left (L) and right (R) hemisphere. The anatomic coverage of each structural covariance network was as follows: 1) superior frontal cortex (Lateral); 2) motor cortex (Lateral); 3) temporal pole (Inferior); 4) insular cortex (Lateral); 5) orbitofrontal cortex (Inferior); 6) lateral occipital cortex (Lateral); 7) precuneus (Medial); 8) left superior parietal cortex (Lateral); 9) anterior superior temporal gyrus (Lateral); 10) primary somatosensory cortex (Lateral); 11) right middle temporal gyrus (Lateral); 12) posterior middle temporal gyrus (Lateral); 13) temporoparietal junction (Lateral); 14) medial superior frontal cortex (Medial); 15) medial occipital cortex (Medial); 16) anterior cingulate cortex (Medial); 17) cuneus (Medial); 18) posterior cingulate cortex (Medial); 19) fusiform gyrus (Medial); and 20) middle cingulate gyrus (Medial). Since the networks were defined using a data-driven process, the anatomic naming is intended to be a rough approximation for the location, not a precise description. This figure is best viewed in color.

reproducibility was not uniformly stable, a local peak was clearly present for the 20-SCN. Accordingly, the 20-network solution was used for all subsequent analyses. As in previous work using NMF [35], nearly all structural components were highly symmetric bilaterally (Fig. 2).

PTSD is significantly associated with structural differences in multiple networks

Having identified 20 interpretable SCNs using NMF, we next examined associations between mean cortical thickness in each SCN with PTSD diagnosis while controlling for sex, as well as linear and nonlinear age effects (Eq. 1). Univariate analyses revealed that there was a significant association between PTSD diagnosis and cortical thickness measurements in 8 SCNs after FDR correction (Fig. 3; see also Table S7), though characterized by small effect sizes. Regions associated with PTSD included the bilateral superior and medial superior frontal cortex (SCN 1 and 14), the motor cortex (SCN 2), the insular cortex (SCN 4), the orbitofrontal cortex (SCN 5), the medial occipital cortex (SCN 15), the anterior and the posterior cingulate cortex (SCN 16 and 18). PTSD diagnosis was associated with lower cortical thickness in each of these networks (Tables S7 and S8). Inclusion of the trauma type as covariate in the regression models consistently produced similar results. The significant associations between the SCNs and PTSD diagnosis remained unchanged (Table S7).

Association between PTSD diagnosis and SCNs is independent of age and sex

Having established that diminished cortical thickness was associated with PTSD, we next examined whether this effect was moderated by age or sex. Notably, there were no significant interactions of sex and age by PTSD diagnosis in any network (Table S9). Considering age and sex were significantly different between PTSD and control subjects (Table 1), we repeated the NMF analysis in age- and sex-matched subsamples obtained by excluding 4 subsites, including 2 cohorts of young female PTSD patients (Groningen, Mannheim) and 2 cohorts with old male control subjects (Duke-TBIPTSD, Nanjing-Yixing). The rebalanced groups did not show significant age or sex differences (39.66 ± 13.26 years in PTSD vs. 40.10 ± 14.35 years in control, $T = 0.69$, df $= 1886$, $p = 0.49$; 917 female subjects vs. 986 male subjects, $\chi^2 = 0.74$, df $= 1$, $p = 0.39$). Despite the reduced power of the rebalanced groups, 6 of the 8 significant SCNs were still found to be associated with PTSD diagnosis (Table S10) and characterized by small effect sizes. Although the motor cortex (SCN 2) and the posterior cingulate cortex (SCN 18) were not significant in this subsample, they trended toward significance ($p_{fdr} = 0.0621$ and $p_{fdr} = 0.0710$, respectively). Again, within all these networks, PTSD diagnosis was associated with lower cortical thickness.

Regression analysis with PTSS severity yields similar results

We next examined associations between dimensional PTSS severity and cortical thickness across SCNs (Eq. 2). Results revealed that increased PTSS severity was associated with reduced cortical thickness in 8 networks (FDR-corrected; Table S11), though characterized by small effect sizes. Notably, 7 of these 8 networks overlapped with those found to be related to PTSD diagnosis (Fig. 4). The posterior cingulate cortex (SCN 18) and the anterior superior temporal gyrus (SCN 9) were the only differences

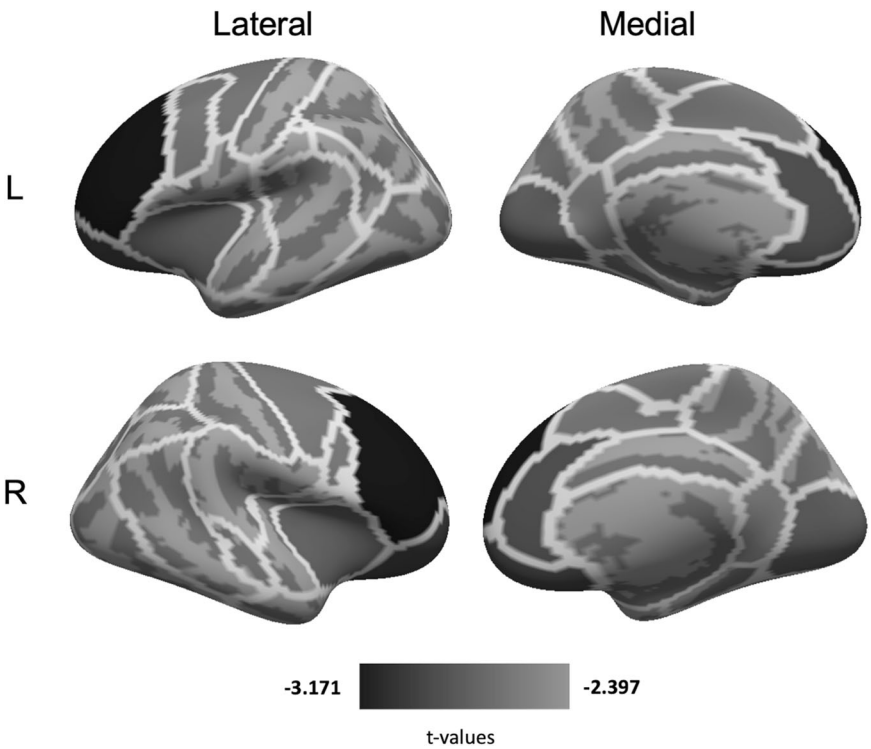

Fig. 3 Regression analysis results revealed that PTSD diagnosis was associated with thinner cortex in multiple SCNs. The composite network visualization was obtained by assigning each vertex to the network that has the highest loading for that vertex (from the *W* matrix), across all 20 networks. This association was maximal in SCNs 1 and 5, which included superior frontal cortex (SCN 1) and orbitofrontal cortex (SCN 5). Significant associations were also present in SCNs that included the motor cortex (SCN 2), insular cortex (SCN 4), medial superior frontal cortex (SCN 14), medial occipital cortex (SCN 15), anterior cingulate cortex (SCN 16), and posterior cingulate cortex (SCN 18). Both significant and non-significant SCNs are annotated with boundaries. Lateral and medial views of these significant SCNs are shown for left and right hemisphere, respectively. This figure is best viewed in color.

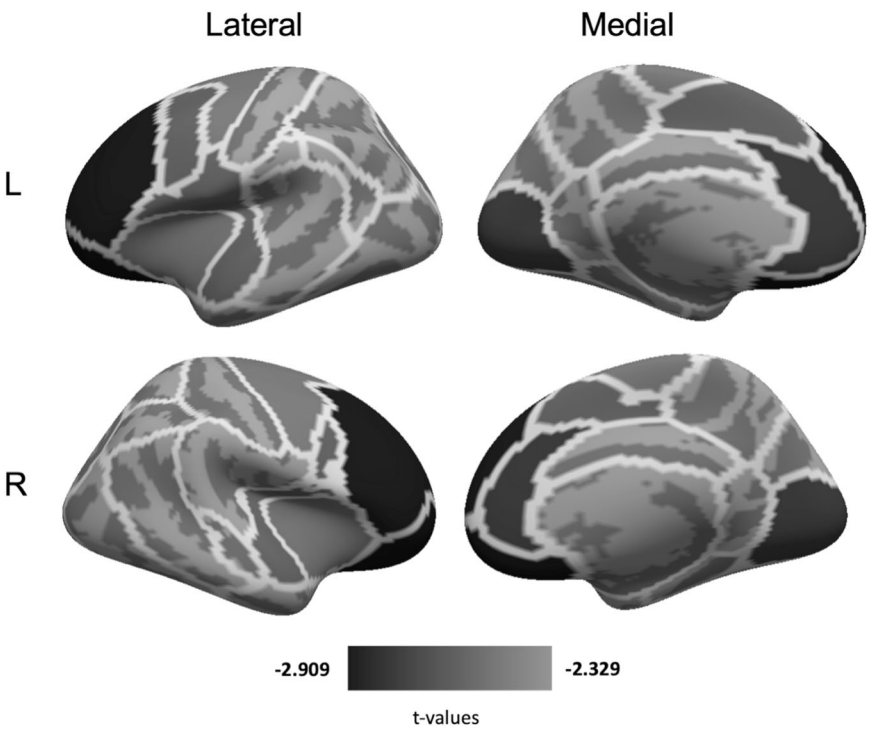

Fig. 4 Regression analysis results revealed that PTSS severity score was associated with thinner cortex in multiple SCNs. This association was maximal in SCNs 1 and 5, which included superior frontal cortex (SCN 1) and orbitofrontal cortex (SCN 5). Significant associations were also present in SCNs that included the motor cortex (SCN 2), insular cortex (SCN 4), anterior superior temporal gyrus (SCN 9), medial superior frontal cortex (SCN 14), medial occipital cortex (SCN 15), and anterior cingulate cortex (SCN 16). Both significant and non-significant SCNs are annotated with boundaries. Lateral and medial views of these significant SCNs are shown for left and right hemisphere, respectively. This figure is best viewed in color.

between the categorical and dimensional analyses. The former was FDR-significant in the categorical group analysis, while the latter was FDR-significant in the dimensional analysis. However, the posterior cingulate cortex (SCN 18) trended toward significance in dimensional analysis ($p_{fdr} = 0.0621$), and the anterior superior temporal gyrus (SCN 9) trended toward significance in the categorical group analysis ($p_{fdr} = 0.0547$).

Significant association with depression level is found in medial occipital cortex

Next, we examined the associations between depression and cortical thickness separately for PTSD participants and all subjects with depression information (Eq. 3). When examining only PTSD participants, no significant effects of depression severity were found in any network (Table S12), suggestive of PTSD-specific cortical thickness associations. When examining the entire sample, cortical thickness in the medial occipital cortex (SCN 15) was found to be significantly associated with depression severity (Fig. S5; see also Table S12), albeit with a small effect size. In this case, subjects with high depression symptoms demonstrated lower cortical thickness in this network compared to those with low depression symptoms. When including categorical PTSD diagnosis and depression in the same regression model (Eq. 4), no significant associations with SCNs were detected for either depression severity or PTSD diagnosis. This is potentially because of the moderate to strong positive correlation between depression severity and PTSD diagnosis (Pearson correlation coefficient (r) was $r = 0.39$ ($p < 0.001$)), and between depression and PTSS ($r = 0.47$ ($p < 0.001$)). The observed multicollinearity may have effectively lowered the statistical power to detect individual effects of either PTSD or depression. When repeating the primary regression analysis (Eq. 1) in this sub-sample, a statistically significant association between PTSD diagnosis and cortical thickness measurements was detected in the same 8 SCNs as in the full sample (Table S13). The results were characterized by small effect sizes. In summary, the separate analyses for depression and PTSD revealed non-overlapping associations with cortical thickness in distinct SCNs. These findings suggest that the effects observed for PTSD are likely specific to this condition and are not influenced by depression.

Assessing the association between cortical thickness with childhood trauma severity or alcohol abuse

Lastly, we conducted separate examinations to assess the associations between childhood trauma severity or alcohol use disorder and cortical thickness for all subjects with available corresponding information (Eq. 3). Our analysis, including the full sub-sample, PTSD patients only, and control subjects only, revealed no significant associations between CTQ and SCNs (Table S14). Similarly, we did not identify any significant associations between AUD and SCNs in both the subset of PTSD participants and the full sub-sample (Table S15). Additionally, when we separately assessed the potential confounding effect of childhood trauma or alcohol abuse on PTSD-associated group differences (Eq. 4) in the sub-sample for which CTQ or AUD data was available, no significant associations were detected for CTQ or AUD. Additionally, in these much smaller samples, it was not possible to identify statistically significant effects of PTSD, irrespective of whether we included the confounder in the regression analyses (Eq. 4) or not (Eq. 1).

DISCUSSION

In 2085 participants from 22 international sites, we investigated associations between PTSD and cortical thickness in networks with strong cortical thickness covariance patterns ascertained by NMF. PTSD was associated with decreased cortical thickness in 8 of the 20 distinct SCNs characterized by vertices within the following anatomic structures: bilateral superior and medial superior frontal cortex, motor cortex, insular cortex, orbitofrontal cortex, medial occipital cortex, anterior and posterior cingulate cortex. Including trauma type as covariate in the regression analysis did not change the results. Associations with PTSD symptom severity (rather than diagnosis) were consistent: cortical thickness differences were related to PTSD severity in all networks associated with PTSD diagnosis except for the posterior cingulate cortex. One additional network in the anterior superior temporal gyrus was associated with PTSD symptom severity. The group with moderate/severe comorbid depression symptoms differed from the group with mild comorbid depression symptoms in cortical thickness within the medial occipital cortex. In the sub-samples where CTQ or AUD information was available, we did not identify any significant associations with PTSD, CTQ or AUD, irrespective of whether we ran the regression analysis by separately including only PTSD, only the confounder, or both.

A unique aspect of our study is the two-stage approach with an initial data reduction followed by a hypothesis generation stage. NMF is well suited to tackling inter-individual spatial heterogeneity because it identifies networks without regard to neuroanatomic boundaries. Instead, NMF identifies patterns of thickness covariation that transcend gyral-based ROI boundaries. Prior studies applying NMF to healthy subjects identified patterns of gray matter structural covariance that differed anatomically but aligned closely with functionally defined brain networks [35]. Additionally, SCNs defined by NMF provide a parsimonious summary of high-dimensional data, which may be more interpretable than data reduction with principal component analysis or independent component analysis [34]. Importantly, the concise summary of the data provided by NMF limits multiple comparisons, thus reducing the need for correction that can plague mass-univariate vertex-wise studies. Consequently, we were able to apply a rigorous FDR correction to all comparisons, instead of relying on cluster-based inference, which may lead to higher rates of type I errors [58].

Another unique aspect of our study is that it represents the largest published cortical thickness study in PTSD to date. The large sample size enhanced our statistical power and sensitivity to detect effects in multiple networks. Despite the small effect sizes observed, extensive prior research has documented that small underpowered studies often yield inflated effect sizes [59, 60]. Therefore, our results likely provide a more accurate representation of the true effect size compared to findings from smaller studies. This may explain discrepancies with previous studies reporting increased cortical thickness in smaller samples consisting of 67 patients with PTSD [30], 15 patients with recent onset PTSD [31] and 30 patients who successfully recovered from PTSD [21], respectively. Additional factors might have contributed to the reported differences, including methodological choices. For instance, the use of cluster-based inference employed in [21, 30] can lead to significant type I error rates [58].

The present study is comparable in scale and scope to the ENIGMA-PTSD study of regional cortical volume by Wang and colleagues [61] who assessed regional cortical volume (i.e., the product of cortical thickness and cortical surface area for any given region). Despite different analytic approaches, our cortical thickness findings similarly implicate cortical differences within the R-superior frontal gyrus, bilateral orbitofrontal gyrus, insular cortex, L-anterior cingulate gyrus, and L-posterior cingulate gyrus related to PTSD. In addition, we found PTSD to be associated with cortical thickness in the R-anterior cingulate gyrus, R-posterior cingulate gyrus, and the L-superior frontal gyrus, which were not linked to cortical volume. By contrast, Wang et al. (2021) reported cortical volume differences associated with PTSD for several regions, not identified by the present study, including the precuneus, middle temporal gyrus, superior parietal gyrus, and inferior parietal gyrus [61]. As cortical volume captures both cortical thickness and surface area, the latter set of regions may

possess stronger associations with regional surface area but may be weakly linked to cortical thickness.

The partially overlapping and partially divergent associations of PTSD to cortical thickness in comparison to cortical volume may relate to the stronger role of genetics in determining cortical surface area than cortical thickness, which is more influenced by environmental factors, effects of PTSD illness, or individual PTSD symptom features [62]. Specifically, cortical volume may better index combined genetic and environmental effects, whereas cortical thickness may capture the deleterious effects of trauma exposure and pathology and cortical surface area may be more influenced by genetic contributors.

In addition to links between cortical structural alterations and PTSD [6, 7, 13–16], prior evidence links altered cortical structure to brain function in PTSD [63]. Disruption in emotion processing circuits and top-down prefrontal dysregulation of these circuits are linked to PTSD [64]. In this context, the left orbitofrontal gyrus plays an important role in integrating sensory and limbic inputs and in top-down prefrontal inhibitory regulation of emotion and sensory regions [65, 66]. Patients with orbitofrontal gyrus lesions demonstrate attention deficits and impaired response inhibition to emotional stimuli [67]. Thus, low left orbitofrontal gyrus thickness/volume may impair inhibitory top-down regulation of emotion and sensory attention. Reduced gray-matter density in the anterior insula has been linked to greater intrusive memories following trauma [68, 69], which may explain anterior insula over-responsiveness to negative emotions in PTSD [70]. We found reduced bilateral cortical thickness in the insula, which is consistent with a heightened sensitivity to interoceptive sensations, internal body cues, and a predilection toward threat-biased interpretations, which are common features of PTSD.

Lower cortical thickness in motor cortex and primary visual cortex while unexpected, is nonetheless supported by recent discoveries. In sexual assault survivors with PTSD, reduced gray matter density and functional connectivity within the visual cortex are associated with re-experiencing symptoms and self-blame [71]. These primary sensory regions are activated by intrusive memories that are experienced in PTSD and MDD [72]. Functional MRI studies reveal hyperresponsiveness of the anterior cingulate in PTSD [73], including in monozygotic twins, which represents a familial risk marker for PTSD [74]. Similarly, pre-conscious actions to mitigate threat or danger in PTSD patients are associated with stronger functional connectivity between motor cortex and periaqueductal gray, which initiates defensive responding [75, 76]. The medial occipital cortex, which is well known for primary visual perception, is engaged in feedforward and feed backward signaling of threat or danger [77, 78]. A recent demonstration of neuromodulation of the visual cortex reduced the intensity of intrusive trauma memories [79], while treatment directed at modification of attentional bias reduced PTSD symptoms and modulated activity in visual processing pathways. Thus, converging evidence implicates the involvement of primary sensory and motor regions in PTSD [80, 81], which may explain reduced cortical thickness in these regions. However, the precise causal mechanisms connecting brain structure to function are unclear, as are the cellular mechanisms of learning-induced grey matter changes. Recent evidence suggests that the remodeling of neuronal processes, which involves presynaptic terminals forming synapses with dendritic spines, as a possible mechanism [82–85].

When we examined associations between cortical thickness and depression symptom severity in PTSD patients, no networks were significantly associated with depression severity. Additionally, when examining associations between cortical thickness and PTSD diagnosis while controlling for depression in the full sub-sample, no networks were significantly associated with PTSD diagnosis. These results have various potential interpretations. First, we found greater depression symptom severity in PTSD patients and greater PTSD symptom severity in depressed subjects, suggesting a positive association between PTSD and depression symptoms. This raises a possibility that variance shared across PTSD and depression effectively lowered the statistical power to detect true PTSD effects [86, 87]. Second, symptoms such as negative emotions, cognitive distortions, and avoidance are common to both disorders. Third, it is possible that depression symptoms and PTSD symptom severity are mediated, in part, by shared brain abnormalities. If any or all these explanations are valid, our findings would suggest that lower cortical thickness in some regions could be associated with PTSD. Alternatively, the current results cannot rule out the possibility that thinner cortex in these regions may be associated with depression, but not PTSD.

Several limitations of our study should be considered when interpreting its results. First, while we primarily focused on the 20-network solution as the solution that is both reproducible and fits the data well, the optimal number of networks is likely a function of the input data. Second, data were derived from cohorts that varied in image acquisition, processing, and clinical assessment instruments. We adjusted for data source statistically and had acceptable heterogeneities of cortical regional volumes across cohorts. Third, additional factors could affect cortical thickness (e.g., cohort stratification, medications, duration of illness, trauma type, age at trauma exposure, trauma exposure of control subjects, and other comorbidities including anxiety disorders and substance abuse). However, we were unable to account for the potential effects of these factors on cortical thickness because we lacked reliable and consistent information across sites. To partially address this limitation, we performed additional analyses focusing on trauma type, child trauma severity and alcohol use disorder, which were the most commonly reported additional covariates across sites. When examining the effect of trauma type in the full sample, we did not observe any significant effects of trauma type on SCNs, while the associations between the SCNs and PTSD diagnosis remained unchanged. The effects of CTQ and AUD were separately analyzed in small subsets of the full dataset. We did not observe any significant effects of CTQ or AUD on SCNs. However, we also did not detect any significant effects of PTSD in these small subsets. Thus, the small subsets seem (1) inadequately powered to address the association of PTSD on SCNs, (2) perhaps inadequately powered to reveal associations between CTQ and AUD on the SCNs or possibly (3) there is shared variance between PTSD and CTQ or between PTSD and AUD that is producing a negative result when testing the association between PTSD and SCNs. Ultimately, the small sample size of participants with CTQ and AUD measures is a limitation and their associations with SCNs should be investigated in future analyses. Finally, the cross-sectional data also cannot distinguish the thickness differences that occurred before vs. after trauma exposure. Further studies are needed to examine confounding effects of comorbid disorders, and to identify age-specific PTSD abnormalities.

In summary, NMF identified unbiased patterns of cortical thickness covariation that are marked by low effect sizes and are associated with lower cortical thickness in PTSD. Our findings recapitulate prior reports using ROI and whole brain methods, but also align closely with functionally defined brain networks.

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AUTHOR CONTRIBUTIONS

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Correspondence and requests for materials should be addressed to Rajendra A. Morey.

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[1]Department of Radiology, Washington University in St. Louis, St. Louis, MO, USA. [2]Duke-UNC Brain Imaging and Analysis Center, Duke University, Durham, NC, USA. [3]Mid-Atlantic Mental Illness Research Education and Clinical Center, Durham VA Medical Center, Durham, NC, USA. [4]Department of Psychology, The Education University of Hong Kong, Hong Kong, China. [5]Department of Psychiatry, Amsterdam University Medical Center, Amsterdam, The Netherlands. [6]ARQ National Psychotrauma Centre, Diemen, The Netherlands. [7]Donders Institute for Brain, Cognition and Behavior, Centre for Cognitive Neuroimaging, Radboud University Nijmegen, Nijmegen, The Netherlands. [8]Del Monte Institute for Neuroscience, University of Rochester Medical Center, Rochester, NY, USA. [9]Department of Psychiatry, Columbia University Medical Center, New York, NY, USA. [10]New York State Psychiatric Institute, New York, NY, USA. [11]Department of Experimental Clinical and Health Psychology, Ghent University, Ghent, Belgium. [12]Department of Psychiatry, Harvard Medical School, Boston, MA, USA. [13]Institute for Technology in Psychiatry, McLean Hospital, Harvard University, Belmont, MA, USA. [14]Division of Depression and Anxiety Disorders, McLean Hospital, Belmont, MA, USA. [15]Division of Women's Mental Health, McLean Hospital, Belmont, MA, USA. [16]Department of Medical Imaging, Jinling Hospital, Medical School of Nanjing University, Jiangsu, China. [17]First Department of Neurology, St. Anne's University Hospital and Faculty of Medicine, Masaryk University, Brno, Czech Republic. [18]CEITEC-Central European Institute of Technology, Multimodal and Functional Neuroimaging Research Group, Masaryk University, Brno, Czech Republic. [19]Department of Neurology, University of Utah, Salt Lake City, UT, USA. [20]George E. Wahlen Veterans Affairs Medical Center, Salt Lake City, UT, USA. [21]Imaging Genetics Center, Mark & Mary Stevens Neuroimaging & Informatics Institute, Keck School of Medicine of USC, Marina del Rey, CA, USA. [22]Department of Psychiatry and Neuroscience Institute, University of Cape Town, Cape Town, South Africa. [23]Department of Psychiatry, Stellenbosch University, Cape Town, South Africa. [24]Laboratory for Traumatic Stress Studies, Chinese Academy of Sciences Key Laboratory of Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing, China. [25]Department of Psychology, University of Chinese Academy of Sciences, Beijing, China. [26]University Medical Centre Charité, Berlin, Germany. [27]Department of Clinical Psychology, University of Groningen, Groningen, The Netherlands. [28]Department of Psychosomatic Medicine and Psychotherapy, Central Institute of Mental Health, Medical Faculty Mannheim, Heidelberg University, Heidelberg, Germany. [29]Department of Psychiatry and Behavioral Science, Texas A&M University, College Station, TX, USA. [30]Department of Psychiatry, University of Michigan, Ann Arbor, MI, USA. [31]Minneapolis VA Health Care System, Minneapolis, MN, USA. [32]Department of Psychiatry, University of Minnesota, Minneapolis, MN, USA. [33]Institute of Medical Psychology and Systems Neuroscience, University of Münster, Münster, Germany. [34]Center for Healthy Minds, University of Wisconsin-Madison, Madison, WI, USA. [35]Department of Psychiatry, University of Wisconsin-Madison, Madison, WI, USA. [36]Department of Psychology, University of Wisconsin-Madison, Madison, WI, USA. [37]Department of Psychology, University of Wisconsin-Milwaukee, Milwaukee, WI, USA. [38]Division of Trauma and Acute Care Surgery, Department of Surgery, Medical College of Wisconsin, Milwaukee, WI, USA. [39]Comprehensive Injury Center, Medical College of Wisconsin, Milwaukee, WI, USA. [40]Munroe-Meyer Institute, University of Nebraska Medical Center, Omaha, NE, USA. [41]Department of Psychiatry and Behavioral Sciences, Vanderbilt University Medical Center, Nashville, TN, USA. [42]Department of Psychology, Vanderbilt University, Nashville, TN, USA. [43]Veterans Integrated Service Network-17 Center of Excellence for Research on Returning War Veterans, Waco, TX, USA. [44]Department of Psychology and Neuroscience, Baylor University, Waco, TX, USA. [45]Center for Vital Longevity, School of Behavioral and Brain Sciences, University of Texas at Dallas, Dallas, TX, USA. [46]Department of Psychiatry and Behavioral Science, Texas A&M University Health Science Center, Bryan, TX, USA. [47]Department of Psychiatry, Yale University School of Medicine, New Haven, CT, USA. [48]Department of Psychiatry of Behavioral Sciences, Baylor College of Medicine, Houston, TX, USA. [49]Department of Comparative Medicine, Yale University, New Haven, CT, USA. [50]Department of Neuroscience, Yale University, New Haven, CT, USA. [51]Department of Psychology, Yale University, New Haven, CT, USA. [52]Wu Tsai Institute, Yale University, New Haven, CT, USA. [53]Division of Clinical Neuroscience, National Center for PTSD, West Haven, CT, USA. [54]Institute for Informatics, Data Science & Biostatistics, Washington University in St. Louis, St. Louis, MO, USA. ✉email: rajendra.morey@duke.edu