Development and Psychopathology (2024), 1–12
doi:10.1017/S0954579424000725

Regular Article

Childhood maltreatment and resting-state network connectivity: The risk-buffering role of positive parenting

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Abstract

Unraveling the neurobiological foundations of childhood maltreatment is important due to the persistent associations with adverse mental health outcomes. However, the mechanisms through which abuse and neglect disturb resting-state network connectivity remain elusive. Moreover, it remains unclear if positive parenting can mitigate the negative impact of childhood maltreatment on network connectivity. We analyzed a cohort of 194 adolescents and young adults (aged 14–25, 47.42% female) from the Neuroscience in Psychiatry Network (NSPN) to investigate the impact of childhood abuse and neglect on resting-state network connectivity. Specifically, we examined the SAN, DMN, FPN, DAN, and VAN over time. We also explored the moderating role of positive parenting. The results showed that childhood abuse was linked to stronger connectivity within the SAN and VAN, as well as between the DMN-DAN, DMN-VAN, DMN-SAN, SAN-DAN, FPN-DAN, SAN-VAN, and VAN-DAN networks about 18 months later. Positive parenting during childhood buffered the negative impact of childhood abuse on network connectivity. To our knowledge, this is the first study to demonstrate the protective effect of positive parenting on network connectivity following childhood abuse. These findings not only highlight the importance of positive parenting but also lead to a better understanding of the neurobiology and resilience mechanisms of childhood maltreatment.

Keywords: childhood abuse; resting-state network connectivity; positive parenting; indirect effects; risk-buffering effect

(Received 23 July 2023; revised 6 March 2024; accepted 7 March 2024)

Introduction

Childhood maltreatment, encompassing abuse (physical, sexual, and emotional) and neglect, represents a significant public health crisis with far-reaching consequences (Agorastos et al., 2018; Lieberman et al., 2011; Oral et al., 2016). The prevalence of this issue is alarming, as studies across various regions reveal that over 60% of children endure at least one form of maltreatment (Devries et al., 2018, 2019; Meinck et al., 2016). This widespread problem not only devastates the mental health of individuals but also imposes considerable societal burdens.

The detrimental impact of maltreatment extends to the brain's development, notably affecting regions critical for threat detection, emotional regulation, and reward anticipation (McLaughlin et al., 2019; Teicher et al., 2016). Despite this understanding, the precise neural mechanisms by which various forms of maltreatment, such as abuse and neglect, disrupt the connectivity within large-scale resting-state networks (RSNs) and heighten the risk of poor mental health outcomes throughout life remain inadequately understood. This gap in knowledge highlights the urgent need for continued research in this area.

The Dimensional Model of Adversity and Psychopathology (DMAP) categorizes maltreatment into two distinct types: threat and deprivation. Threat encompasses experiences such as physical, sexual, or emotional abuse, which involve injury or the imminent risk of harm. Deprivation, on the other hand, pertains to the absence of essential emotional, cognitive, and social stimuli, manifesting in conditions like poverty, neglect, and caregiver absence. According to McLaughlin, these dimensions exert divergent influences on mental health through unique neuro-developmental pathways (McLaughlin et al., 2019, 2020). They further elaborated that these dimensions can distinctly affect neurodevelopmental processes, thereby shaping cognitive and emotional functions in different ways (McLaughlin & Sheridan, 2016). In light of this framework, it becomes essential to separately examine the impacts of childhood abuse, representing threat-related adversity, and childhood neglect, indicative of deprivation-related adversity, on resting-state networks (RSNs).

Childhood maltreatment is associated with changes in the functional connectivity of multiple brain regions, and changes in large-scale RSNs connectivity underlie many psychological symptoms (Blithikioti et al., 2022; Smith & Pollak, 2020; Yu et al., 2019). The study of large-scale RSNs is a reliable way to investigate the prominent neural features of psychiatric disorders. According to the triple network model of psychopathology (Menon, 2011), the disrupted organization and functioning of the salience network (SAN), which is involved in the engagement of saliency detection and attentional capture (Seeley et al., 2007); frontoparietal network (FPN), which has an important role in cognitive control and working memory (Seeley et al., 2007); and the default mode network (DMN), which has an important role in

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Cite this article: Cao, X., Wang, Z., Chen, Y., Consortium the NSPN, and Zhu, J. (2024). Childhood maltreatment and resting-state network connectivity: The risk-buffering role of positive parenting. *Development and Psychopathology*, 1–12, https://doi.org/10.1017/S0954579424000725

response to stimulus-independent, self-referential, and emotional thoughts (Raichle et al., 2001) are core features of multiple symptoms of adult psychopathology. A systematic review of 109 studies using MRI-based methods suggested that childhood maltreatment may lead to impaired connectivity between brain regions within the salience network (SAN) and frontoparietal network (FPN) (McLaughlin et al., 2019). In line with this review, a growing literature on adolescents and adults has demonstrated that the severity of childhood maltreatment is positively associated with the within-network connectivity of SAN (Mao et al., 2020; Rakesh et al., 2021, 2023; Sheynin et al., 2020) and FPN (Chahal et al., 2022; Luo et al., 2022). Moreover, adolescents who experienced childhood maltreatment exhibited reduced functional connectivity between the posterior cingulate cortex and the hippocampus, both of which are regions within the default mode network (DMN) (Sheynin et al., 2020).

In addition to the three networks in the triple network model (Menon, 2011), two other stress-susceptible regions are the dorsal attention network (DAN) and ventral attention network (VAN), and these have been found to be central to depressive symptoms (Mao et al., 2020; Sylvester et al., 2013; Yu et al., 2019). The DAN is involved in goal-directed and top-down attention processes, and the VAN is involved in salience processing and the mediation of stimulus-driven, bottom-up attention processes (Fox et al., 2006; Kim, 2010). Aberrant functional connectivity within both VAN and DAN in adolescents and young adults has been linked to greater exposure to childhood maltreatment (Hart et al., 2017; Mao et al., 2020). However, existing studies have the limitation of using cross-sectional designs. As such, it is important to examine the longitudinal effect of childhood maltreatment on resting-state network connectivity.

Significant alterations in connectivity between several resting-state networks involving SAN, DMM, FPN, DAN, and VAN could also underly multiple psychopathologies. For instance, increased DAN-VAN, DMN-FPN, DMN-SAN, and DAN-FPN connectivity have been found to be higher in patients with major depressive disorder (Yu et al., 2019). To date, the effect of childhood maltreatment on between-network connectivity has received little attention. Using a seed-to-voxel approach, the study found that youth who were exposed to childhood trauma exhibited increased functional connectivity between the amygdala (a region within the SAN) and the superior parietal lobule (a region within the DAN) (Sripada et al., 2014). Many studies have utilized self-report questionnaires for measuring childhood maltreatment, although some used interview-based assessments. Recently, a longitudinal study that used interviews to measure traumatic experiences reported a positive association between childhood abuse and the stability in DMN-SAL connectivity from ages 9 to 19 years (Chahal et al., 2022). However, this effect did not survive correction for multiple comparisons. The existing knowledge does not provide clarity on the associations between various dimensions of adversity and the connectivity patterns within and between the SAN, DMN, DAN, VAN, and FPN.

Not all children exposed to childhood maltreatment develop adverse consequences and neurodevelopmental patterns. Researchers have suggested that positive family factors may protect against the development of aberrant social information processing, emotional processing, and biological aging as well as psychopathology following childhood trauma (McLaughlin et al., 2020; McLaughlin & Lambert, 2017). Positive parenting may be one of the protective factors of children, and it refers to the active involvement of parents in their children's lives and the existence of a supportive relationship between parents and their children (Elgar et al., 2007; Li et al., 2023). Neuroimaging research has preliminarily explored the protective effect of positive parenting on resting-state network connectivity in adults who grew up in conditions of poverty or neighborhood disadvantage (Brody et al., 2019; Rakesh et al., 2021). For instance, the association between the cumulative number of years lived in poverty in childhood and aberrant connectivity within the central-executive and emotion-regulation neural networks in adulthood was only significant in the group with low levels of supportive parenting (Brody et al., 2019). Positive parenting promotes the development of processes related to the SN, DMN, FPN, VAN and DAN, such as threat detection, emotional regulation and cognitive control (Davis et al., 2022; Holmes et al., 2018; Pozzi et al., 2021; Teicher et al., 2016). The role of positive parenting in mitigating the effects of childhood maltreatment has not been extensively explored. Given the large number of children affected by maltreatment (Dube et al., 2003; Nelson et al., 2017), such investigations are pivotal for identifying modifiable targets for intervention.

The primary aim of this study was to investigate the longitudinal effect of childhood maltreatment on within- and between-network connectivity of critical networks that are stress-susceptible (i.e., SAN, DMN, FPN, VAN, and DAN). We used the Dimensional Model of Adversity and Psychopathology framework to investigate the impact of childhood maltreatment on RSNs. This framework suggests that threat and deprivation have different impacts on mental health through differential (McLaughlin et al., 2019, 2020). Hence, we examined the effect of childhood maltreatment on RSNs by evaluating the differential effects of childhood abuse (threat-related adversity) and childhood neglect (deprivation-related adversity). Furthermore, a recent study found that positive parenting served as a buffer against the association between childhood stress and decreased hippocampal volumes (Kahhalé et al., 2023). Positive parenting may play a protective role in how abuse affects the structure of the brain. Therefore, an exploratory analysis of the present study was to examine the moderating role of positive parenting in the relationship between childhood maltreatment and within- and between-network connectivity.

Our study approached the investigation of the effects of childhood maltreatment on resting-state networks (RSNs) without any preconceived hypotheses. This stance was adopted due to the limited research and varying findings reported in this field. However, to our knowledge, the longitudinal association between childhood maltreatment and within- and between-network connectivity has not been explored. Additionally, considering existing research on the influence of positive parenting in childhood on adult RSNs (Brody et al., 2019; Rakesh et al., 2021), our study also aims to explore the potential protective role of positive parenting against the adverse effects of childhood maltreatment on connectivity within and between networks.

Methods and materials

Participants

Participants were from a large longitudinal study, the NSPN (Neuroscience in Psychiatry Network), which was established in July 2012. The NSPN is a multi-center accelerated longitudinal study to measure developmental change in a demographically representative sample of 2,406 young people aged 14–24 years from north London and Cambridgeshire, UK (Kiddle et al., 2017). Participants received a Home Questionnaire Pack (HQP) and a Sociodemographic Questionnaire to assess their mood, behavior,

Table 1. Sample characteristics

Characteristic	Time points	*n* or Mean ± SD
No. of Subjects (Female)		194 (92)
Age	IUA1(T1)	18.78 ± 2.85
IQ	IUA2(T2)	112.1 ± 10.9
FD	IUA1(T1)	0.13 ± 0.051
Total brain volume	IUA1(T1)	1190747 ± 125506.2
CTQ	IUA1(T1)	32.33 ± 7.50
Childhood abuse	IUA1(T1)	12.93 ± 3.29
Childhood neglect	IUA1(T1)	14.21 ± 4.56
Positive Parenting	HPQ2	11.16 ± 2.81

well-being, and demographic characteristics at three time points (HQP1, HQP2, HQP3). They completed repeated symptom questionnaires at home and returned them to the study team by post. The median interval for return of subsequent questionnaires (inter-quartile range) between HQP and first follow-up was 12 months (11–14 months), and between second and third assessments was 13 months (12–16 months). Two in-unit assessments (IUA1, and IUA2) comprised questionnaires, cognitive assessments, and MRI scanning. For ease of understanding, we used T1 and T2 instead of IUA1 and IUA2 (T1 = IUA1, T2 = IUA2). Detailed descriptions of the recruitment methods and sample are available in recent publications (Dorfschmidt et al., 2022; Vaghi et al., 2020; Váša et al., 2020).

A subsample of 318 healthy youth participated in an MRI study, with approximately 60 participants in each of five age bins (14 to 15 years, 16 to 17 years, 18 to 19 years, 20 to 21 years, and 22 to 24 years). Participants were excluded if they reported a history of psychiatric treatment or neurological disorder, head injury, or intellectual disability. After rigorous visual quality control and excluding 10% of scans with highest during-scan motion, the final evaluable dataset included 298 participants. Of these, 281 subjects were scanned at baseline (IUA1) and 211 were scanned approximately 18 months later at follow-up (IUA2). For the present study, the final sample included 194 participants (age range 14–25 years; mean [SD] age, 18.78 [2.85] years; 47.42% female) who were scanned at both time points. Further demographic information can be found in Table 1. Participants aged 16–25 gave written informed consent for each aspect of the study; a legal guardian's written informed consent was obtained for those aged 14–15 years, and those youth gave assent to participate. The NSPN study was approved by the Cambridge Central Research Ethics Committee (12/EE/0250). This study was approved as a secondary data analysis protocol by the Institutional Review Board of our university.

Measures

Childhood maltreatment

Childhood maltreatment at T1 and T2 was assessed by the Childhood Trauma Questionnaire (CTQ). It is important to note that only 55 participants reported their scores on childhood maltreatment at T2 (see Fig S1 in supplementary file). Therefore, for the formal analysis, only childhood maltreatment scores at T1 were utilized. The CTQ is a 28-item retrospective self-report questionnaire that assesses five sub-dimensions of abuse and neglect history: emotional abuse, physical abuse, sexual abuse, emotional neglect, and physical neglect. Each item of the CTQ is scored on a five-point Likert-type scale (1 = "never true" to 5 = "very often true"). We used the emotional abuse, physical abuse, emotional neglect, and physical neglect subscales. In the present study, items on the emotional abuse and physical abuse subscales (10 items) were summed to acquire a total score for childhood abuse, and items on the emotional neglect and physical neglect subscales (10 items) were summed to acquire a total score for childhood neglect. A higher score indicates a higher level of exposure to abuse or neglect during childhood. Confirmatory factor analysis supported the measure's construct validity, and the internal consistency and two-week test-retest reliability were excellent, in a sample of young adults (Bernstein et al., 2003). For the 10 items measuring physical and emotional abuse at T1, the Cronbach's alpha was 0.73, while for the 10 items measuring physical and emotional neglect, it was 0.84. These results suggest that the measures exhibited good internal consistency in this sample.

We excluded the sexual abuse subscale from our study for two reasons. First, only 5% of participants reported one or more items in the child sexual abuse subscale, which would not have provided us with a large enough sample size to conduct meaningful statistical analyses. It was more appropriate to focus on the other subscales which were more prevalent in our sample. Secondly, sexual abuse can have unique and complex effects on brain structure (Heim et al., 2013) and networks (Crum et al., 2021) compared to other forms of abuse or trauma. Including this subscale may have confounded our results and made it difficult to interpret the findings.

Positive parenting

Positive parenting at HQP2 was assessed by the three-item positive parenting subscale of the Alabama Parenting Questionnaire (Elgar et al., 2007). Participants were asked to rate the typical degree to which each example of positive parenting occurs or has occurred in their household over all the time in the past (i.e. "Your parent(s) tell you that you are doing a good job"; "Your parent(s) compliment you when you have done something well"; "Your parent(s) praise you for behaving well"). All items are scored on a 4-point Likert-type scale (0 = "never" to 3 = "very often"). Ratings on the three items were summed to get a composite score, with a higher score indicating more frequent positive parenting. For positive parenting at HPQ2, the Cronbach's alpha in this sample was 0.87, suggesting good internal consistency of the measure.

Magnetic resonance imaging acquisition and preprocessing

Functional MRI Scanning was performed at three sites, all operating identical 3T MRI systems (Magnetom TIM Trio; Siemens Healthcare; VB17 software). The resting-state scanning sequence for each participant lasted approximately 10 minutes. Resting-state fMRI data were acquired using a multi-echo echoplanar imaging sequence: 263 volumes; repetition time = 2.42 s; GeneRalized Autocalibrating Partial Parallel Acquisition with acceleration = 2; matrix size = 64 × 64 × 34; field of view = 240 × 240 mm; in-plane resolution = 3.75 × 3.75 mm; slice thickness = 3.75 mm with 10% gap, 34 oblique slices; bandwidth = 2,368 Hz per pixel; echo time = 13, 30.55, 48.1 ms. Data preprocessing strategies are presented in eMethods in the Supplement.

Functional-connectivity analyses

Construction of functional connectivity was performed using the CONN Toolbox (Whitfield-Gabrieli & Nieto-Castanon, 2012).

https://doi.org/10.1017/S0954579424000725 Published online by Cambridge University Press

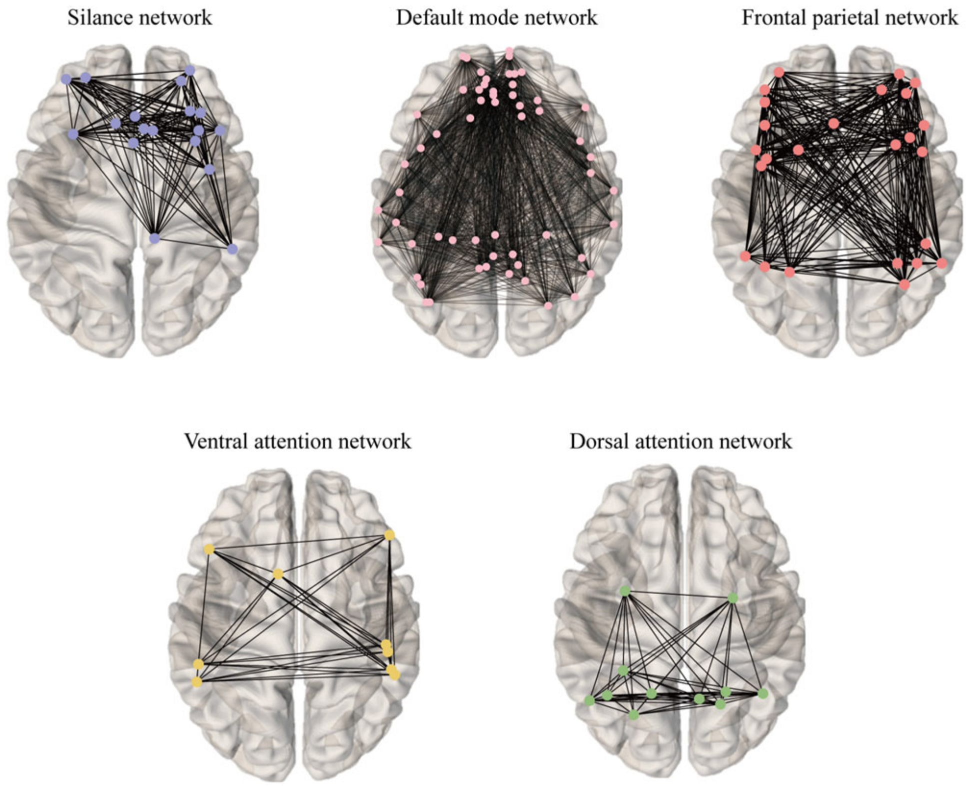

Figure 1. Axial views of regions of interest for the resting-state functional connectivity networks.

SAN, VAN, DAN, FPN, and DMN were based on seeds from the Power 264 atlas (Power et al., 2011). Figure 1 presents axial view of the Region-of-interest seeds for these networks. The BOLD time course of each region of interest (ROI) was defined as the average of its voxels' time courses. Within-network functional connectivity was measured using the average of Pearson's correlations computed for every pair of Fisher's z-transformed ROIs within the network. Between-network connectivity was measured using the average of the correlations computed for every pair of Fisher's z-transformed ROI across networks. Finally, as previously described, confounding effects of head movement on network connectivity at T2 after ME-ICA preprocessing were corrected by regressing with- and between-network connectivity on mean FD (Gu et al., 2015; Satterthwaite et al., 2019). Multi-Echo Independent Component Analysis (ME-ICA), a sophisticated technique in functional magnetic resonance imaging (fMRI) analysis, was employed in this study. This approach is particularly effective in differentiating neurobiological signals from non-neurobiological signals, such as those arising from motion or other physiological artifacts, within fMRI data. By utilizing ME-ICA, the precision and reliability of the analysis were significantly enhanced, ensuring a more accurate interpretation of the fMRI results.

Data analysis

Regression analysis

Statistical analyses were performed in R version 4.2.0 statistical software. The association between childhood maltreatment at T1 and network connectivity at T2 was tested using linear regression, controlling for gender, age, total brain volume, IQ, FD, and network connectivity at T1. Due to the significant association between whole-brain volume and childhood maltreatment (Geerlings & Gerritsen, 2017), it was incorporated as a covariate in our analyses. Likewise, considering that the connectivity within networks and between networks can differ based on participants' IQ levels, we integrated IQ as a covariate in our analysis (DeSerisy et al., 2021). Additionally, in order to accurately isolate and understand the specific impact of childhood maltreatment on the changes in network connectivity from T1 to T2, we also controlled for network connectivity in T1. This approach is crucial as it allows us to account for the initial levels of network connectivity, providing a baseline against which changes at the second time point (T2) can be measured. By including T1 connectivity as a covariate, we can more accurately isolate and understand the specific impact of childhood abuse on the changes in network connectivity from T1 to T2. This method is essential in longitudinal studies to distinguish between preexisting conditions and the effects that emerge over the course of the study.

We applied the FDR correction method proposed by Benjamini and Hochberg (1995) to account for multiple comparisons in our study. It involves ordering the p-values from smallest to largest, calculating critical values based on the desired FDR level, and then comparing each p-value to its corresponding critical value. If a p-value was less than or equal to its critical value, the null hypothesis was rejected (Benjamini & Hochberg, 1995). Specifically, we controlled the FDR at a threshold of 0.05 for all the within- and between-networks included in the regression analysis.

Moderation analysis

The moderation effect of the positive parenting score at HPQ2 on the association between abuse/neglect scores at T1 and network connectivity at T2 was explored in R (The model assumptions are

https://doi.org/10.1017/S0954579424000725 Published online by Cambridge University Press

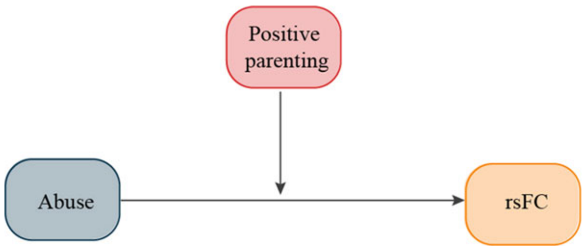

Figure 2. Schematic diagram of moderation analysis.

shown in Figure 2). We included both childhood abuse and positive parenting as covariates in addition to the interactive term, to effectively control for the confounding effect of these variables. Simple slope tests were performed to probe the nature of significant interaction effects. Simple slope test determines whether the association between childhood maltreatment and network connectivity is significantly different from zero at 1SD above and 1SD below the mean positive parenting score. Given the exploratory nature of the moderation analyses, p values were not adjusted for multiple comparisons.

Results

Longitudinal associations between childhood abuse/neglect and within-network connectivity

Linear regression analyses were performed to examine whether childhood abuse or childhood neglect at T1 was associated with within-network connectivity at T2 when age, gender, IQ, total brain volume, FD, and the network connectivity at T1 were included as covariates (Table 2). Childhood abuse was significantly associated with the within-VAN connectivity ($\beta = 0.191$, $p_{\text{fdr}} = 0.030$) and the within-SAN connectivity ($\beta = 0.169$, $p_{\text{fdr}} = 0.044$) (Figure 3). There were no significant associations between childhood abuse and the within-FPN connectivity ($\beta = 0.049$, $p_{\text{fdr}} = 0.489$), within-DMN connectivity ($\beta = 0.075$, $p_{\text{fdr}} = 0.293$), or within-DAN connectivity ($\beta = 0.108$, $p_{\text{fdr}} = 0.213$). We did not find significant associations between childhood neglect and within-network connectivity.

Longitudinal associations between childhood abuse/neglect and between-network connectivity

In similar analyses, linear regression was performed to examine whether childhood abuse or childhood neglect at T1 was associated with between-network connectivity at T2 (Table 2). Abuse was associated with the between-network connectivity of following network pairs: DMN-DAN ($\beta = 0.173$, $p_{\text{fdr}} = 0.025$), DMN-SAN ($\beta = 0.154$, $p_{\text{fdr}} = 0.033$), DMN-VAN ($\beta = 0.159$, $p_{\text{fdr}} = 0.025$), FPN-DAN ($\beta = 0.152$, $p_{\text{fdr}} = 0.045$ SAN-DAN ($\beta = 0.218$, $p_{\text{fdr}} = 0.021$), SAN-VAN ($\beta = 0.190$, $p_{\text{fdr}} = 0.022$) and VAN-DAN ($\beta = 0.191$, $p_{\text{fdr}} = 0.022$) (Figure 3). There was no significant association between neglect and between-network connectivity.

Positive parenting as a moderator of the association between childhood abuse/neglect and within-network connectivity

Our moderation analyses were exploratory in nature, and thus the results were interpreted and discussed based on uncorrected p values at $p < 0.05$. We first tested positive parenting as a moderator of the association between childhood maltreatment and within-network connectivity. The results are shown in Table 3. Positive parenting significantly moderated the relationship between childhood abuse and within-DAN connectivity ($\beta = -0.199$, 95% CI = –0.341 to –0.056, $\eta^2 = 0.043$). The follow-up simple slopes test indicated that when positive parenting was low, there was a significant positive association between childhood abuse and the increases in within-DAN connectivity over time. However, under conditions of high positive parenting, this significant association was not observed (see Figure 4). Moreover, the moderating effect of within-DAN connectivity remained significant after FDR correction ($\beta = -0.199$, $p = 0.006$, $p_{\text{fdr}} = 0.033$).

Meanwhile, childhood neglect interacted with positive parenting to be associated with within-DAN connectivity ($\beta = -0.129$, 95% CI = (–0.253 to –0.006, $\eta^2 = 0.025$). However, the simple slope tests indicated that childhood neglect was not associated with within-DAN connectivity at both high and low positive parenting (see Figure 4).

Positive parenting as a moderator of the association between childhood abuse/neglect and between-network connectivity

Positive parenting was then tested as a moderator of the association between child maltreatment and between-network connectivity. Positive parenting significantly moderated the association of abuse with between-network connectivity in the following pairs: FPN-VAN ($\beta = -0.134$, 95% CI = –0.263 to –0.004, $\eta^2 = 0.024$), DMN-DAN ($\beta = -0.145$, 95% CI = –0.279 to –0.011, $\eta^2 = 0.026$), FPN-DAN ($\beta = -0.180$, 95% CI = –0.320 to –0.04, $\eta^2 = 0.036$), and DMN-VAN ($\beta = -0.126$, 95% CI = –0.252 to –0.001, $\eta^2 = 0.023$). As seen in Figure 4, simple slope tests indicated that childhood abuse was significantly associated with increased between-network connectivity at low, but not high, positive parenting. This implies that abuse leads to increased functional connectivity at lower levels of positive parenting, whereas the relationship between abuse and positive parenting is not significant at higher levels.

Meanwhile, positive parenting moderated the association between childhood neglect and FPN-DAN ($\beta = 0.141$, 95% CI = –0.264 to –0.019, $\eta^2 = 0.030$) connectivity. However, the simple slope tests indicated that childhood neglect was not associated with FPN-DAN connectivity at both high and low positive parenting (see Figure 4). The other results involving childhood neglect were nonsignificant. Overall, these results suggest that positive parenting plays a risk-buffering role by weakening the effect of childhood abuse on network connectivity in neurodevelopment.

Supplemental analyses

Our previous results found significant interactions between abuse and positive parenting on network connectivity. We divided the subjects into two groups based on the 1 SD above and below the mean. Our findings indicated that the relationship between childhood abuse and positive parenting was not statistically significant in both the high positive parenting group ($r = -0.13$, $p = 0.39$) and the low positive parenting group ($r = -0.31$, $p = 0.07$). The association between positive parenting and childhood abuse was significant for all participants and remained significant after controlling for neglect ($r = -0.18$, $p = 0.01$). These results suggest that the relationship between maltreatment and positive parenting is complex and not necessarily inversely correlated. Further longitudinal studies are needed to explore

https://doi.org/10.1017/S0954579424000725 Published online by Cambridge University Press

Table 2. Longitudinal effects of childhood abuse on network connectivity

Network connectivity at T2	β (95% CI)	p	p_{FDR}	$\eta2$ (95% CI)
Within-VAN	0.191(0.056 to 0.327)	0.006	**0.030**	0.042(0.007 to 1)
Within-DAN	0.108(−0.031 to 0.248)	0.128	0.213	0.010(0.000 to 1)
Within-SAN	0.169(0.030 to 0.308)	0.018	**0.044**	0.034(0.004 to 1)
Within-FPN	0.049(−0.09 to 0.188)	0.489	0.489	0.023(0.000 to 1)
Within-DMN	0.075(−0.049 to 0.198)	0.235	0.293	0.065(0.019 to 1)
DMN-VAN	0.159(0.035 to 0.283)	0.012	**0.025**	0.069(0.021 to 1)
DMN-FPN	0.099(−0.031 to 0.228)	0.136	0.136	0.059(0.016 to 1)
DMN-SAN	0.154(0.025 to 0.284)	0.020	**0.033**	0.067(0.020 to 1)
DMN-DAN	0.173(0.041 to 0.305)	0.011	**0.025**	0.043(0.008 to 1)
FPN-SAN	0.140(0.003 to 0.277)	0.045	0.050	0.057(0.014 to 1)
FPN-VAN	0.133(0.003 to 0.262)	0.045	0.050	0.092(0.035 to 1)
FPN-DAN	0.152(0.013 to 0.291)	0.032	**0.045**	0.014(0.000 to 1)
SAN-VAN	0.190(0.058 to 0.321)	0.005	**0.022**	0.085(0.031 to 1)
SAN-DAN	0.218(0.080 to 0.356)	0.002	**0.021**	0.031(0.003 to 1)
VAN-DAN	0.191(0.054 to 0.328)	0.006	**0.022**	0.035(0.004 to 1)

Note. [a] Gender, Age, Total brain volume, IQ, FD, and Network connectivity at T1 were included as variates across the analyses. Significant p values after FDR correction are bolded.

Table 3. Moderating effects of positive parenting on the association between maltreatment subtype and network connectivity

	Childhood abuse × Positive parenting[a]		Childhood neglect × Positive parenting[a]	
Network connectivity at T2	β (95% CI)	$\eta2$ (95% CI)	β (95% CI)	$\eta2$ (95% CI)
Within-VAN	−0.132(−0.270 to 0.006)	0.020(0 to 1)	−0.073(−0.194 to 0.049)	0.008(0 to 1)
Within-DAN	**−0.199(−0.341 to −0.056)**	0.043(0.007 to 1)	**−0.129(−0.253 to −0.006)**	0.025(0.001 to 1)
Within-SAN	−0.062(−0.207 to 0.083)	0.004(0 to 1)	−0.028(−0.153 to 0.097)	0.001(0 to 1)
Within-FPN	−0.113(−0.254 to 0.027)	0.015(0 to 1)	−0.036(−0.158 to 0.086)	0.002(0 to 1)
Within-DMN	−0.090(−0.217 to 0.037)	0.011(0 to 1)	−0.012(−0.122 to 0.098)	0.000(0 to 1)
DMN-VAN	**−0.126(−0.252 to −0.001)**	0.023(0 to 1)	−0.042(−0.153 to 0.069)	0.003(0 to 1)
DMN-FPN	−0.122(−0.253 to 0.009)	0.019(0 to 1)	−0.041(−0.156 to 0.073)	0.003(0 to 1)
DMN-SAN	−0.067(−0.201 to 0.067)	0.006(0 to 1)	−0.01(−0.126 to 0.107)	0.000(0 to 1)
DMN-DAN	**−0.145(−0.279 to −0.011)**	0.026(0.001 to 1)	−0.098(−0.216 to 0.019)	0.016(0 to 1)
FPN-SAN	−0.121(−0.262 to 0.020)	0.017(0 to 1)	−0.055(−0.177 to 0.068)	0.005(0 to 1)
FPN-VAN	**−0.134(−0.263 to −0.004)**	0.024(0 to 1)	−0.069(−0.183 to 0.045)	0.008(0 to 1)
FPN-DAN	**−0.180(−0.320 to −0.040)**	0.036(0.004 to 1)	**−0.141(−0.264 to −0.019)**	0.030(0.002 to 1)
SAN-VAN	−0.123(−0.258 to 0.011)	0.019(0 to 1)	−0.101(−0.218 to 0.017)	0.017(0 to 1)
SAN-DAN	−0.117(−0.259 to 0.025)	0.015(0 to 1)	−0.09(−0.216 to 0.036)	0.012(0 to 1)
VAN-DAN	−0.137(−0.278 to 0.003)	0.021(0 to 1)	−0.059(−0.183 to 0.064)	0.005(0 to 1)

Note. [a] Gender, Age, Total brain volume, IQ, and Network connectivity at T1 were included as variates across the analyses. Significant 95% confidence intervals are highlighted in bold to emphasize their statistical significance.

the dynamic and complex relationship between positive parenting and abuse.

Discussion

This study employed a longitudinal dataset from an NSPN cohort and provided new evidence of the links among childhood maltreatment, connectivity of selected large-scale networks (SAN, VAN, DAN, DMN, and FPN). We found that retrospective reports of childhood abuse were associated with stronger within- and between- network connectivity of higher order systems. Furthermore, positive parenting moderated the effect of childhood abuse on within- and between-network connectivity, suggesting a risk-buffering process.

The present study showed a positive association between childhood abuse with within-network connectivity of the SAN and VAN, which are stress-susceptible functional systems (Mao et al., 2020; Sylvester et al., 2013; Yu et al., 2019). This result is consistent with the broader literature indicating the effects of childhood maltreatment on brain functional connectivity (Teicher et al., 2016),

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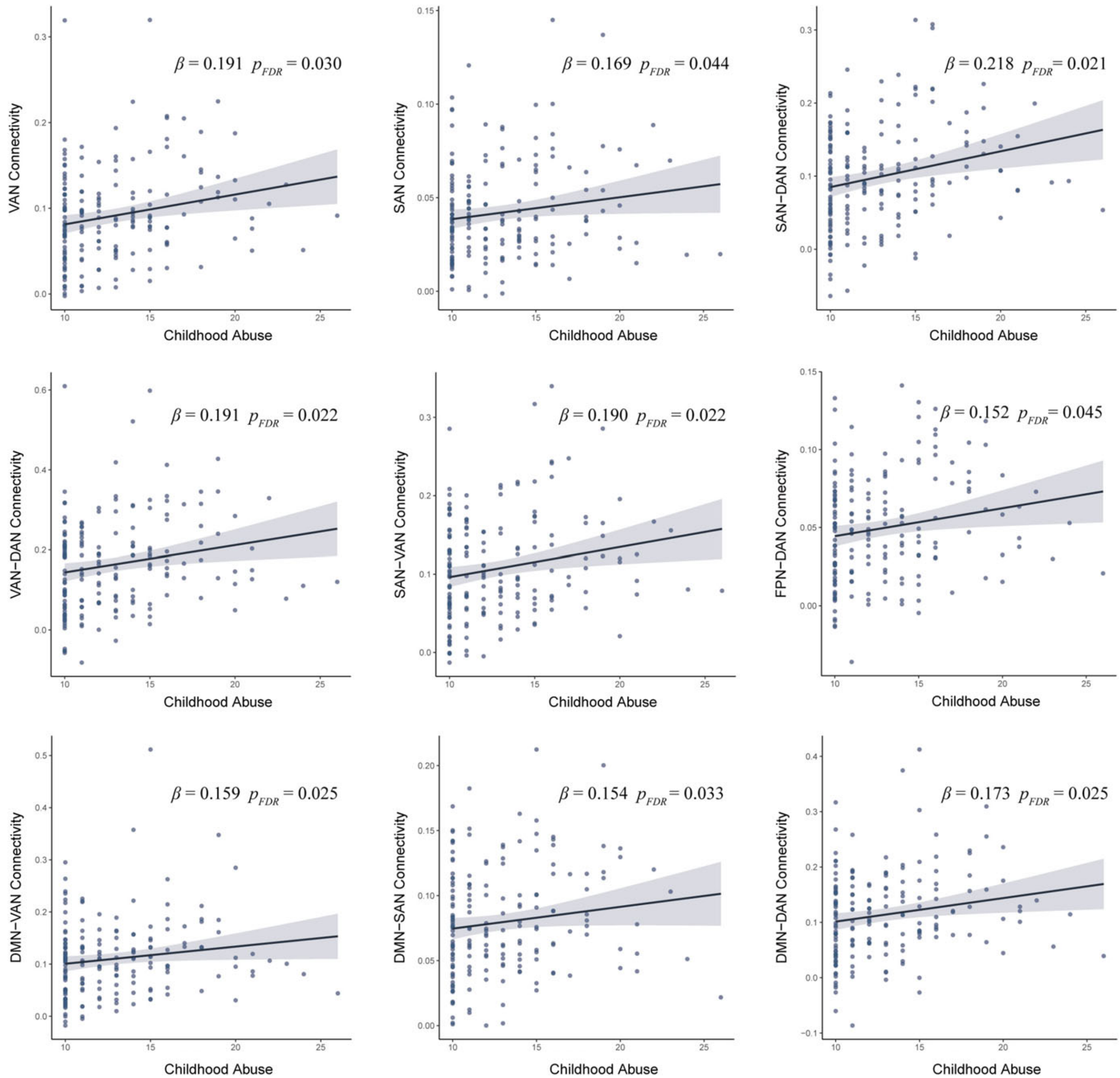

Figure 3. Relationship between within- and between-network connectivity at T2 and childhood abuse at T1. *Note*. Age, gender, IQ, total brain volume, FD and the network connectivity at T1 were added into the analyses as covariates. Abbreviations: SAN = salience network, DMN = default mode network, FPN = frontoparietal network, VAN = ventral attention network, DAN = dorsal attention network.

and further suggests that childhood abuse could promote a more synchronous SAN and VAN at rest. Most seed regions of SAN and VAN undergo protracted maturation throughout adolescence and into young adulthood through the formation of optimally sculpted neural representations, such as greater functional segregation, significant reorganization, and strengthening of connections in network components (Fair et al., 2009; Uddin et al., 2011). In line with the stress-acceleration hypothesis, childhood abuse may cause accelerated development of SAN and VAN, resulting in premature manifestation of emotional and attention processing. If this holds true, then individuals exposed to early abuse would have stronger saliency detection, attentional capture, and bottom-up attention processes, whereas long-term survival of psychopathology is uncertain (Callaghan & Tottenham, 2016; Teicher et al., 2016).

Moreover, we found longitudinal associations between childhood abuse and greater DMN-DAN, DMN-VAN, DMN-SAN, FPN-DAN, SAN-DAN, SAN-VAN, and VAN-DAN connectivity. Abuse-induced increases in between-network connectivity may represent a neurobiological basis for sensitive perception of stress. This possibility is consistent with the role of the VAN and DAN in regulating salience processing and attention control (Kim, 2010; Yu et al., 2019). Among those individuals exposed to early abuse, increases in SAN and DMN may drive more bottom-up signaling of VAN, and then top-down signaling from DAN would gradually

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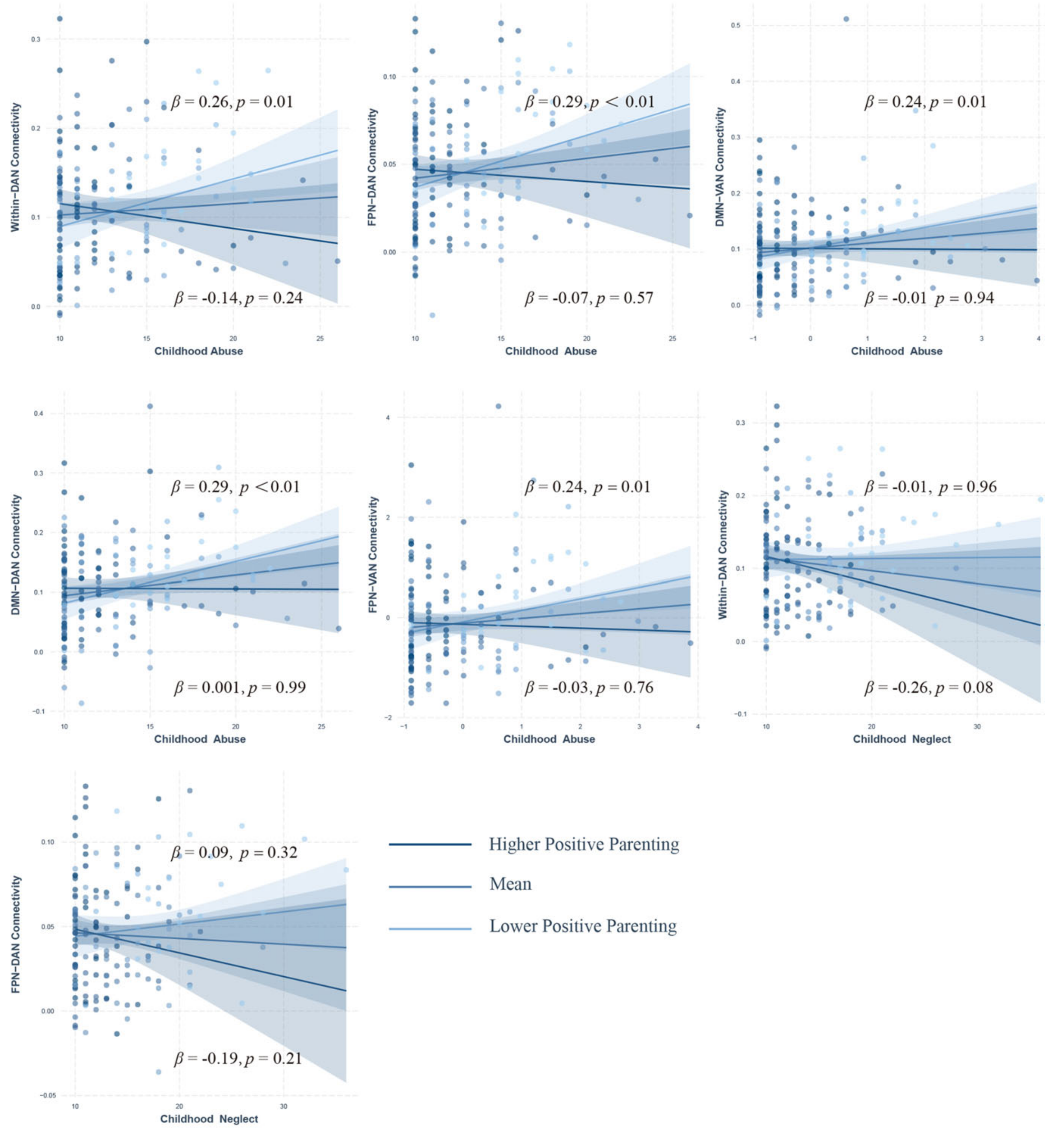

Figure 4. Within- and between-network connectivity as a function of childhood maltreatment and levels of positive parenting. *Note.* Light blue and Dark blue regression lines are shown for low (1 *SD* below the mean) and high (1 *SD* above the mean) levels of positive parenting, respectively. Age, gender, IQ, total brain volume, and the network connectivity at T1 were added into the moderation analyses as covariates. Abbreviations: SAN = salience network, DMN = default mode network, FPN = frontoparietal network, VAN = ventral attention network, DAN = dorsal attention network.

begin to emerge simultaneously, repeatedly reorienting attention toward threatening stimuli. Greater between-network connectivity across SAN, DMN, and attention networks could cause disruptions in disengagement and orienting of attention, which could be associated with unrestrained internally directed cognitions including emotionally charged self-focused rumination (Sheline et al., 2009) and overestimation of threat (Yu et al., 2019). Our results support this possibility. Childhood abuse was associated with increased SAN-DMN connectivity, which is consistent with the results of Chahal's study (Chahal et al., 2022). Heightened SAN-DMN connectivity was associated with the enhanced allocation of saliency to internal mental state for survival and less accurate self-appraisal (Hogeveen et al., 2018). These results support the triple network model, which assumes that aberrant

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connectivity within one network may alter other networks and that childhood abuse impedes the functional segregation of these networks (Stevens, 2016). The exploratory nature of our analyses allowed us to identify potentially important associations between maltreatment and specific connectivity networks. These findings underscore the need for further research in this area to more fully understand the mechanisms underlying the effects of maltreatment on brain development and functioning.

Our results found that only abuse leads to subsequent functional connectivity changes, but neglect does not. The results are consistent with the DMAP in which abuse is associated with threat detection, and salience processing (Sheridan & McLaughlin, 2014). There are several possible reasons for our findings. Firstly, it is possible that network connectivity is more sensitive to the effects of abuse compared to neglect. This could be due to the distinct neurobiological impacts of these different types of maltreatment, with abuse potentially exerting a more direct influence on the brain networks we studied. On the other hand, neglect might have more pronounced effects on other brain indicators that were not the focus of our current study. Secondly, we hypothesize that the level of childhood neglect experienced by the participants in our study may not have been severe enough to elicit detectable changes in network connectivity. This could explain the lack of significant findings related to neglect in our analyses.

Positive parenting provides some protective benefits for adolescents exposed to childhood abuse. In the present study, a significant interactive effect was found between childhood abuse and positive parenting in predicting within-network connectivity of DAN and between-network connectivity of DMN-DAN, DMN-VAN, FPN-VAN, and FPN-DAN. More precisely, the link between exposure to childhood abuse and higher connectivity in networks involved in attention control and emotion regulation was significant 18 months later among participants who had experienced lower positive parenting in childhood, but not among those who had experienced higher positive parenting. These findings appear to align with the transdiagnostic model of mechanisms linking childhood maltreatment to psychopathology (McLaughlin et al., 2020; McLaughlin & Lambert, 2017), and suggest a risk-buffering role of positive parenting in brain network development. When parents engage in more positive parenting behaviors, their children might have more opportunities to master cognitive control skills and problem-solving strategies; when parents engage in negative parenting, their children may instead learn negative coping and passive avoidance through observation and modeling (Brody et al., 2019; Morris et al., 2007). Much research supports the positive effect of positive parenting on brain regions within DMN, FPN, VAN, and DAN (Davis et al., 2022; Holmes et al., 2018; Pozzi et al., 2021; Teicher et al., 2016). This perhaps explains why positive parenting leads young adults exposed to childhood abuse to exhibit less aberrant patterns of neurodevelopment. To the best of our knowledge, this is the first study to present data on the benefit of positive parenting in buffering the associations between retrospective accounts of childhood abuse and large-scale RSNs in adolescents and young adults.

The primary caregivers, such as parents, are typically the central figures in the child's life and are more likely to have a significant impact on the child's well-being. Both the enforcer of positive parenting and the primary source of child maltreatment are parents. Parent-child relationships are complex and dynamic, and parenting styles can change over time and in contexts (Bridgett et al., 2015; Fang et al., 2021). In supplementary analyses, we found that abuse was not associated with abuse in either the high positive parenting or low positive parenting groups. These results suggest that the relationship between maltreatment and positive parenting is complex and not necessarily inversely correlated. Similar to our results, a recent study found that positive parenting served as a buffer against the association between childhood stress and decreased hippocampal volumes (Kahhalé et al., 2023). In this study, positive parenting was not associated with childhood stress measured by family-, community-, and school-based stressors. This evidence supports our assertion that the dynamics of positive parenting in the context of childhood maltreatment are multifaceted and warrant a nuanced understanding. Future research may need to consider more variables, such as family dynamics, parental emotional health, and the occurrence time of the behavior.

Our findings should be viewed in light of some limitations. First, exposure to childhood abuse and neglect were reported retrospectively. Recall biases associated with psychopathology may result in retrospective accounts of maltreatment that deviate from actual experiences, potentially reducing the reliability of the outcomes and increasing the risk of type-II error. However, retrospectively recalled maltreatment has been found to be a more powerful predictor of psychopathology than prospectively assessed exposure (Baldwin et al., 2019; Danese & Widom, 2020). Ideally, future researchers will incorporate prospective and objective measures of childhood maltreatment to validate the findings of the current study. Second, we were unable to identify the sensitive period of childhood maltreatment on resting-state network connectivity because the timing of maltreatment was not assessed. There have been calls for researchers to determine whether there are sensitive periods when exposure to particular types of maltreatment at specific ages exerts maximal effects on brain development (McLaughlin et al., 2019; Teicher et al., 2016; Zhu et al., 2019). Third, the NSPN cohort was recruited from a UK-based population of healthy young people aged 14–25, limiting the generalizability of our findings to other cultural backgrounds and across the entire age span. Therefore, future studies should aim to replicate our results in more diverse populations to better understand the cross-cultural validity of our findings. Moreover, including participants across the entire age span would enhance the validity of the results. Fourth, Parents are both the enforcers of positive parenting and the main perpetrators of childhood abuse. The relationship between parenting and abuse is complex and difficult to separate in the current study. Future research may consider using long-term follow-up and longitudinal study designs to investigate the dynamic interplay between parental behavior and child development. Fifth, the moderating effects of positive parenting were exploratory y and intended to identify patterns or associations preliminarily. Given the exploratory nature of these analyses, we used uncorrected p values. Future research should replicate these findings using more stringent statistical approaches, such as adjusting for multiple comparisons or employing stricter significance thresholds. Finally, in the adolescent developmental stage, the burgeoning influence of peer relationships becomes more pronounced. Peer relationships may also be a protective factor for children who have experienced abuse, and this could be studied in more depth in the future.

Conclusion

This study provides evidence that childhood abuse is longitudinally associated with stronger within-network connectivity of SAN and VAN, and with greater between-network connectivity of

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DMN-DAN, DMN-VAN, DMN-SAN, SAN-DAN, FPN-DAN, SAN-VAN, and VAN-DAN. Furthermore, the current study is the first to reveal the protective effect of positive parenting on within- and between-network connectivity following childhood abuse, supporting the potential value of prevention efforts designed to promote positive parenting.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0954579424000725

Acknowledgements. Data collection and sharing for this project was provided by the NeuroScience in Psychiatry Network funded through a strategic award from the Wellcome Trust to the University of Cambridge and University College London (095844/Z/11/Z). Additional support was provided by the National Institute for Health (NIHR) Applied Research Collaboration East of England and the NIHR Cambridge Biomedical Research Centre. We wish to thank all the members of the NSPN consortium for data collection, storage, and preprocessing.

NSPN Consortium member list: Principal investigators: Edward Bullmore (Chief Investigator from January 1, 2017), Raymond Dolan, Ian Goodyer (Chief Investigator until January 1, 2017), Peter Fonagy, Peter Jones; NSPN (funded) staff: Matilde Vaghi, Michael Moutoussis, Tobias Hauser, Sharon Neufeld, Rafael Romero-Garcia, Michelle St Clair, Kirstie Whitaker, Becky Inkster, Gita Prabhu, Cinly Ooi, Umar Toseeb, Barry Widmer, Junaid Bhatti, Laura Villis, Ayesha Alrumaithi, Sarah Birt, Aislinn Bowler, Kalia Cleridou, Hina Dadabhoy, Emma Davies, Ashlyn Firkins, Sian Granville, Elizabeth Harding, Alexandra Hopkins, Daniel Isaacs, Janchai King, Danae Kokorikou, Christina Maurice, Cleo McIntosh, Jessica Memarzia, Harriet Mills, Ciara O'Donnell, Sara Pantaleone, Jenny Scott; Affiliated scientists: Pasco Fearon, John Suckling, Anne-Laura van Harmelen, Rogier Kievit, Petra Vértes.

Jianjun Zhu and his colleagues' work was funded by the National Natural Science Foundation of China (32371117) and the Guangzhou Science and Technology Plan Project (2023A03J0048) to Jianjun Zhu. Additionally, Yuanyuan Chen's work was supported by the National Youth Project for National Social Sciences Fund of China (Education; CBA220314). The authors report no biomedical financial interests or potential conflicts of interest.

Competing interests. The authors report no biomedical financial interests or potential conflicts of interest.

Ethical standards. The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

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