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Functional brain changes related to adverse childhood experiences and the presence of psychopathology

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Received: 27 August 2024 / Accepted: 28 April 2025
Published online: 08 May 2025

Abstract
Research suggests that associated changes in brain function may underlie the vulnerabilities for psychopathology following adverse childhood experiences (ACEs). In addition to the ACEs themselves, the development of trauma symptoms following ACEs may also contribute to psychopathology. The present study investigates how exposure to certain ACEs, specifically child maltreatment, and trauma symptoms both individually and combined, influence the presence of psychopathology in a sample of adolescents. Participants were 52 adolescents between the ages of 12–14 years recruited from New Hanover County Health and Human Services (NHC-HHS). Further, this study seeks to identify functional brain changes with electroencephalography (EEG) that may impact psychopathology in youth. While child maltreatment and trauma symptoms were not associated, results indicated that frontal and central EEG alpha power, but not alpha asymmetry, were associated with an increased likelihood of experiencing psychopathology in adolescents, with higher alpha power reflecting lower cortical activation. The results of this study suggest that certain changes in patterns of neural activity may be candidates for psychopathology prevention in adolescents.

Keywords Adverse childhood experiences (ACEs) · Child maltreatment · EEG · Brain function · Trauma · Psychopathology

1 Introduction

Adverse childhood experiences (ACEs), often called early life stressors or childhood adversity, refer to a wide range of negative events or circumstances that may occur during childhood [1]. The term includes experiences from physical, sexual, and emotional abuse and family violence to institutional (orphanage) rearing and economic adversity [1–3]. Research in the past decade points to an association between childhood adversity and the onset of psychopathology across developmental stages [1, 4]. Specifically, exposure to adverse experiences in childhood increases the risk of developing a broad range of psychiatric disorders, such as mood, anxiety, and behavior disorders, substance use disorders, and other chronic diseases [1, 2, 4, 5]. While there is a connection between ACEs and psychopathology, the ACEs themselves may not directly lead to an increased risk of psychopathology. Instead, evidence suggests it may be the associated brain and behavioral outcomes following exposure to ACEs which connote the heightened risk of developing psychopathological symptoms. For example, early adversity can contribute to detriments to neural development. These include functional changes in fronto-limbic regions of the brain which regulate higher-order emotion, learning, and memory processes, such as the prefrontal cortex (PFC), hippocampus, and anterior cingulate cortex (ACC) [6–8]. Among these alterations in brain function following ACEs are changes that include dissociative behaviors, a common response to many types

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of traumatic experiences [9]. Given the links between ACEs and changes in neural function, examining functional brain changes related to child maltreatment may be important to informing prevention and treatment of psychopathology.

Childhood maltreatment, a subset of ACEs, is unfortunately, not uncommon; in a sample of youth admitted to a psychiatric hospital, almost half had experienced maltreatment, with 59% of children experiencing two or more types of maltreatment [10]. One mechanism identified by prior research that helps explain the relationship between ACEs and increased risk for psychological and behavioral difficulties is through changes in neural function. The neurophysiological impact of childhood maltreatment is supported by altered activation of brain regions involved in fear circuitry [11]. Connectivity between the amygdala and vmPFC is important for the processing and regulation of fear responses, especially for the extinction of conditioned fear responses [11]. Reduced resting-state amygdala-vmPFC connectivity has been observed in adolescents with a maltreatment history [12]. This reduced coupling is proposed to result in the reduced ability to regulate fear responses in the absence of a threat [12]. Altered fronto-hippocampal connectivity is proposed to lead to an increased risk for internalizing disorders, such as anxiety and depression, by late adolescence [12].

It is important to differentiate between ACEs, trauma symptoms, and posttraumatic stress disorder (PTSD) when trying to understand how these related but distinct factors impact functioning. As previously stated, an ACE is the traumatic event itself, such as an event that poses a significant threat to one's life or safety. Trauma symptoms refer to the sequelae of emotional and psychological responses experienced by an individual after a traumatic event, such as being fearful of falling asleep following a traumatic event [13]. Other common trauma symptoms include sadness, grief, anger, shame, and physical symptoms, such as insomnia, changes in appetite, dizziness, and rapid breathing or heart rate [13]. In many individuals who have experienced a traumatic event, these symptoms improve over time without intervention [14]. However, if these symptoms cause significant distress and impairments in functioning or last for longer than 1 month, an individual may be at risk of developing PTSD [14].

Literature to date suggests that ACEs and trauma symptoms have distinct impacts on functioning. For instance, exposure to ACEs is associated with increased risk for alcoholism in adulthood as well as earlier initiation of alcohol use and use of other substances, such as marijuana, in adolescence [15–17]. In addition, ACEs such as child maltreatment can cause functional impairments in developmental areas, including difficulties in peer relationships, emotion dysregulation and cognitive and language deficits [18–20]. Adolescents with trauma symptoms after ACEs are more likely to develop comorbid psychopathology such as major depression, conduct disorder and suicidal ideation [21]. Trauma symptoms, particularly those related to child maltreatment, are also related to negative impacts on cognitive function like poorer visual memory, attention, and executive function abilities [22, 23].

While ACEs are positively associated with trauma symptomatology [23–26] and poorer mental health functioning [3], exposure to ACEs does not lead to trauma symptoms or poorer mental health for the majority of individuals [27, 28]. Additionally, the mechanisms that link specific aspects of child maltreatment to the development of trauma symptoms and mental health problems, including PTSD, are not entirely known. The effects of child maltreatment on brain development and changes in functioning of biological stress systems are thought to be at least partly responsible and are the focus of the present study [25, 29].

2 Electroencephalography (EEG)

One way to measure functional brain changes is using electroencephalography (EEG). EEG is a noninvasive neuroimaging tool that measures electrical activity in the brain using small electrodes. Alpha waves (813 Hz) are commonly studied in research on EEG because they are comparatively large waves that are easy to detect when people are awake, relaxed, and not actively engaged in any task. Measures of alpha EEG activity, including alpha power and asymmetry, have been implicated as markers of neurodevelopment, making it important to consider developmental stages in interpretations of EEG measures [30].

Alpha asymmetry is a measure of the resting-state lateralization of electrical activity in the brain [31]. Research on EEG asymmetry, particularly alpha asymmetry, has focused on identifying the emotional and behavioral responses associated with left- versus right-brain activity [31]. Alpha asymmetry refers to the activity differences in alpha waves across the left and right sides of the brain. While greater left-brain activation is associated with positive emotions and bias towards more approach-related behaviors, negative emotions and withdrawal-related behaviors are reflected in greater right-brain activation [32, 33].

The connection between child maltreatment and alpha asymmetry has been the subject of many research efforts. Specifically, right EEG asymmetry has shown clear trends in its relationship to child maltreatment. For instance, increased right

parietal and frontal activity have been demonstrated in maltreated children, with non-maltreated children showing an opposite pattern of heightened left activity in parietal and frontal regions [34]. Further, one study found greater right cortical activity in the frontal cortex during resting-state in children exposed to maltreatment, which the authors interpreted as a tendency towards avoidance-based motivation that may confer later risk for trauma symptoms [35]. In addition to maltreatment exposure, trauma-related symptoms resulting from maltreatment show similar patterns of right EEG asymmetry. Children exposed to maltreatment but who have greater left alpha asymmetry and less severity of maltreatment are less likely to display trauma symptoms [36]. Other maltreatment-related psychopathology that has been linked to patterns of heightened right EEG asymmetry including PTSD symptoms, depression, anxiety, and negative emotions [33, 37]. However, the specific role that alpha asymmetry plays in the association between child maltreatment and the presence of psychopathology in adolescents is still largely unclear.

As such, other measures of alpha, including alpha power, have also been investigated as a potential contributor to poor mental health outcomes. In adults, alpha peak activity during resting-state EEG is associated with higher reported depressive symptoms [38]. While considerably less research exists on the relation between alpha power and psychopathology, a recent review investigating the role of alpha oscillations in neuropsychiatric disorders provided support for alterations in alpha rhythms as contributing to symptoms of some disorders [39]. In one study, adults with depressive disorders showed a pattern of heightened alpha power in parietal regions of the brain [40]. Additionally, increased alpha power in frontal and central brain regions has been demonstrated in adolescents with bipolar depression [41]. Reductions in cortical activity in frontocentral regions of the brain may be especially impactful, given the role of the frontal lobe in higher-order executive functions. For instance, lower frontal activation may lead to increased impulsivity and risk-taking behavior, as evidenced by heightened frontal alpha power in childhood predicting later aggression and antisocial behavior in male adolescents [42].

The present study seeks to evaluate whether the likelihood of having psychopathology is influenced by experiences of exposure to certain ACEs, specifically child maltreatment, trauma symptoms, and alpha asymmetry and power. Specifically, this study hypothesized that child maltreatment and trauma symptoms would increase the likelihood of having psychopathology, reflected by the presence of at least one psychiatric diagnosis, in adolescents. Additionally, we hypothesized that accounting for child maltreatment, the presence of trauma symptoms would increase the likelihood of having at least one psychiatric diagnosis. To assess the influence of brain function on psychopathology, the present study hypothesized that parietal alpha asymmetry would be associated with an increased likelihood of having psychopathology. Finally, we hypothesized that alpha power in the brain's frontal, central, and parietal regions would influence the likelihood of psychopathology in adolescents.

3 Method

3.1 Participants

Participants in this study included 52 adolescents between the ages of 12–14 years recruited from New Hanover County Health and Human Services (NHC-HHS). Over 80% of the adolescents had child maltreatment reports, while the rest of the sample was involved with NHC-HHS for services that were not maltreatment related, such as housing, food, and medical assistance. Exclusion criteria include serious medical conditions, such as the history of seizures or other contraindications to EEG, loss of consciousness or history of significant head trauma, current pregnancy, intellectual disability, and neurological disorders. All procedures in this study were approved by the University of North Carolina Wilmington Institutional Review Board. This study was funded by the National Institutes of Health–National Institute of Alcohol Abuse and Alcoholism (NIH-NIAAA–R15 AA028911).

4 Measures

4.1 Child maltreatment

4.1.1 Childhood Trauma Questionnaire (CTQ)-Short Form

The Childhood Trauma Questionnaire-Short Form (CTQ-SF) is a 28-item self-report questionnaire that assesses experiences of abuse and neglect. The items are split into five subscales: emotional physical, and sexual abuse, physical neglect, and emotional neglect. All items are rated on a Likert scale from one to five to indicate the extent to which the statement

relates to the participant's own childhood experiences, with one being "never true" and five being "very often true" [43]. Total scores were computed by summing the scores for each of the five categories and ranged from 20 to 100, with 20 indicating no abuse or neglect and 100 indicating the maximum number of experiences of abuse or neglect. The CTQ-SF showed excellent internal consistency for the overall measure (Cronbach's α = 0.94), as well as for all subscales (Cronbach's α = 0.79–0.94) [43]. CTQ summary scores were used as the primary child maltreatment variable in this study's models, which combines all types of abuse into one score. Use of a summary score to measure maltreatment is justified since all types of abuse have been found to contribute to poor mental health and behavioral outcomes.

4.2 Trauma symptoms

4.2.1 Trauma Symptom Checklist for Children (TSCC)

The Trauma Symptom Checklist for Children (TSCC) is a 54-item scale developed by Briere (1996) and measures the severity of posttraumatic symptoms and related effects of trauma in children 8–16 years old. All items are measured on a 4-point Likert scale ranging from 0 (*never*) to 3 (*almost all the time*). Total scores reflected the sum of all the items. Clinical significance was indicated by a score on any subscale at or above a T score of 65 [44]. The TSCC showed good validity as compared to other measures of child outcomes and reliability was excellent for all subscales (Cronbach's α = 0.81–0.88). Trauma symptoms were assessed in analyses using the TSCC total score, which combines scores across five subscales to provide a total score of post-traumatic symptomatology in youth.

4.3 Psychopathology

4.3.1 Kiddie Schedule for Affective Disorders and Schizophrenia (K-SADS)

The Kiddie Schedule for Affective Disorder for Children-Present and Lifetime Version (K-SADS-PL) is a questionnaire that assesses diagnoses according to the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) [45]. The K-SADS-PL has been shown to generate reliable and valid child psychiatric diagnoses [46]. The online version has an audio component for which the children and caregivers are given the option of putting in headphones or completing this in a private, quiet space due to the sensitive nature of the questions. The KSADS showed good to excellent test–retest reliability for present (κ = 0.63–1.00) and lifetime diagnoses (κ = 0.55–1.00) and good validity compared to other diagnostics instruments [46]. While the K-SADS-PL can provide individual diagnoses, the present study only had access to data from the K-SADS-PL that stated presence of psychopathology as an overall domain (present versus absent) and treated it as a dichotomous outcome variable in all analyses. Additionally, the variable was dummy coded so that scores indicated whether the participant met criteria for any DSM-5 diagnosis (1 = one or more diagnoses) or did not meet criteria for at least one DSM-5 diagnosis (0 = no diagnosis). The KSADS was administered by a trained doctoral student in clinical psychology.

4.4 EEG

All EEG data was collected and processed in a separate study [31]. Statistical analyses for EEG measures were performed using alpha power and alpha asymmetry values from this study's existing dataset. Participants completed a six-minute resting-state condition of 3 min with eyes closed and 3 min with eyes open. Only parietal alpha asymmetry was analyzed in the present study, as these were the only asymmetry values available in the prior dataset. Procedures for EEG data analysis are described below.

4.5 Procedures

The present study was conducted on an existing data set, the first phase of an NIH-NIAAA funded, IRB approved study. Participants aged 12–14 were recruited from New Hanover County HHS.

4.5.1 Surveys

The parent/guardian was emailed a private link to the online survey in Qualtrics. Research assistants then reviewed the parent/guardian consent forms (embedded as downloadable PDFs in the survey) and youth assent with the parent/guardian and youth to obtain consent/assent. While the parent/guardian and adolescent took the survey, their progress was monitored and any selection of critical items indicating immediate harm to self or others were flagged for review. If abuse/neglect or suicidal ideation was indicated, the principal investigator (PI), who is a licensed psychologist, was notified and acted according to mandated reporting laws.

4.5.2 EEG procedures

Upon arrival at the participant's home, adolescents were fitted for an EEG cap and completed two resting-state conditions (eyes open and eyes closed) and a task condition. For this study's purposes, only data from the resting-state conditions were analyzed. Upon completion of the study, participants and their parent/guardian will receive monetary compensation at an IRB-approved rate as described above.

4.6 Analytic strategy

Potential covariates, including sex, age, race, ethnicity, and socioeconomic status (SES), were accounted for in all regression analyses. These covariates were selected due to their potential impacts on the main study variables [47, 48, 70]. Covariates that were statistically significant remained in models; those not significant were removed from the final models. All hypotheses were tested using binomial logistic regression with continuous predictors and psychopathology as the outcome variable (0 = no, 1 = yes). This study had planned hypotheses/comparisons and was an exploratory study, therefore correction for multiple comparisons was not warranted [49].

4.7 EEG data recording and analysis

Resting-state EEG activity was measured from eight channels based on the international 10–20 system using the g.Nautilus g.Ladybird Electroencephalogram (EEG) system, along with MATLAB Simulink library and g.Nautilus software (g.tec® medical engineering GmbH, Austria). The reference electrode was placed on the right ear lobe. Data were sampled at 250 Hz, and electrode impedances were kept below 100 kΩ. Data were filtered using 0.5 Hz high-pass and 50 Hz low-pass filters. Data from the resting-state conditions were processed in a previous study [31] and available for use in the present study. This processing included segmenting data into 2-s epochs with 1-s (50%) overlap and all epochs containing artifacts were removed from analyses using a voltage threshold (± 150 μV) rejection. Epoched data were then re-referenced to an average of all channels and any participant with less than 30 artifact-free epochs were excluded from further analysis.

After preprocessing, EEG asymmetry values were calculated by Meiers et al. (2020). Relative alpha power was computed by dividing the mean absolute alpha power (8–13 Hz) by the mean absolute total power (1–40 Hz). Relative alpha power values were then computed for the P3 and P4 electrodes corresponding to the left (P3) and right (P4) parietal sites on the headcap. Absolute alpha power values were computed for the three main midline electrodes including, frontal (Fz), central (Cz), and parietal (Pz). These analyses were done separately for the eyes-closed and eyes-open conditions. To calculate the final parietal alpha EEG asymmetry value, the relative alpha power of P3 was subtracted from that of P4. Only alpha asymmetry from the parietal cortex was analyzed as these were the only asymmetry values available in the existing data set. Additionally, alpha asymmetry in parietal regions of the brain has been previously associated with psychopathology in adults and adolescents [31, 36, 37]. Positive asymmetry values represent relatively greater left hemispheric activity and negative values represent greater relative right hemispheric activity.

5 Results

Descriptive statistics for the variables of interest and the current sample's ($N = 45$) demographics are outlined in Table 1. The mean age for the sample was 13 years old (range = 12–14, $SD = 0.85$) and was 57.8% male ($N = 26$). Approximately 84.4% of the adolescents in the current sample had CPS-reported incidents of maltreatment. Eighteen percent of

participants reported childhood trauma symptoms that were higher than normed averages, and two participants (0.4%) had scores that fell in the clinical cutoff range [46]. Overall, approximately 62% of the sample met the criteria for having at least one DSM-5 diagnosis [47]. The covariates sex, ethnicity, and SES were not found to contribute significantly (p's > 0.4) to any of the models and were therefore excluded from further discussion of the results.

5.1 Child maltreatment and trauma symptoms

Binomial logistic regressions were conducted to predict the likelihood of having any psychiatric diagnosis (0 = none, 1 = one or more) from childhood maltreatment and trauma symptoms. Results indicated there were no significant associations between childhood maltreatment, $\chi 2$ (1, $n = 46$) = 3.08, $p = 0.124$, or trauma symptoms, $\chi 2$ (1, $n = 46$) = 1.35, $p = 0.184$, and the likelihood of experiencing psychopathology. Next, a binomial logistic regression was used to examine if trauma symptoms changed the likelihood of experiencing psychopathology (0 = no, 1 = yes), accounting for childhood maltreatment. Child maltreatment was entered into the model and then the likelihood of psychopathology was assessed based on trauma symptoms. Results indicated that the model was nonsignificant, $\chi 2$ (0, $n = 46$) = – 1.38, $p = 0.259$, indicating that adding trauma symptoms into the model did not account for significantly more variance than childhood maltreatment alone.

5.2 Alpha asymmetry and power

Complete resting-state EEG data was available for 25 participants. Descriptive statistics and demographics for the EEG subset of participants are detailed in Table 2. After the removal of one outlier, the final sample for alpha asymmetry included 24 adolescents. The same pattern of results was found for analyses conducted with and without removing the

Table 1 Descriptive statistics for sample demographics and variables of interest

Variable	N	%	Range	M	SD
Age	45		12–14	13	0.85
Sex	45				
Female	19	42.2			
Male	26	57.8			
Race	45				
Black/African American	26	57.8			
White/Caucasian	17	37.8			
More than one	2	4.4			
American Indian	0	0			
Asian	0	0			
Ethnicity	45				
Hispanic	10	22.2			
Non-Hispanic	35	77.8			
Parents' Annual Income	43				
< $10,000	15	34.9			
$10,000–14,999	7	16.3			
$15,000–24,999	3	7			
$25,000–34,999	5	11.6			
$35,000–49,999	7	16.3			
$50,000–74,999	4	9.3			
$75,000–99,999	1	2.3			
> $100,000	1	2.3			
CTQ Total Score	46		28	26.96	7.58
TSCC Total Score	46		76	26.26	18.23
Presence of Psychopathology	46		1.00	0.63	0.49
Yes	29	63			
No	17	37			

outlier. There were no differences in sex, age, race, ethnicity, or SES (p's > 0.4) or in the means of the model variables (i.e., CTQ scores, TSCC scores, and presence of psychopathology) for those who did or did not complete the EEG.

A binomial logistic regression was performed to predict the likelihood of experiencing any psychopathology (0 = no, 1 = yes) from alpha asymmetry. None of the covariates were found to contribute significantly to the model and were therefore removed from all further analyses. The model was not significant, $\chi 2$ (1, $n = 24$) = 4.69, $p = 0.059$, and, additionally, the coefficients for this model were positive.

Binomial logistic regression models were conducted to predict the likelihood of having any psychopathology from frontal (Fz), central (Cz), and parietal (Pz) absolute alpha power values, controlling for sex, age, race, ethnicity, and SES. Three participants had incomplete data for demographics and were therefore excluded from all further analyses accounting for covariates. Two binomial logistic regression models were separately conducted to predict the likelihood of experiencing psychopathology from frontal, central, and parietal alpha power during an eyes-closed and an eyes-open condition. None of the EEG power measures from the eyes-closed conditions were found to significantly predict the likelihood of having any psychopathology. Frontal alpha power ($\chi 2$ [1, $n = 27$] = 5.05, $p = 0.07$), central alpha power ($\chi 2$ [1, $n = 27$] = 5.31, $p = 0.07$), and parietal alpha power ($\chi 2$ [1, $n = 27$] = 4.66, $p = 0.08$ were all not significantly related to likelihood of experiencing one or more DSM-5 diagnoses.

Of the covariates, sex, race, ethnicity, and SES were not found to contribute significantly to the models and are therefore excluded from further discussion. Age was found to contribute significantly to the regression model for the frontal alpha power and was therefore included in further analyses. The eyes-open condition model predicting psychopathology from frontal alpha power was significant, $\chi 2$ (2, $n = 24$) = 10.86, $p = 0.037$, $R^2_L = 0.48$. Higher frontal alpha power was significantly associated with the greater likelihood of experiencing psychopathology (see Fig. 1).

Table 2 Descriptive statistics for demographics and variables of interest for EEG subset of participants

Variable	N	%	Range	M	SD
Age	24		12–14	13.29	0.75
Sex	24				
Female	8	33.3			
Male	16	66.7			
Race	24				
Black/African American	12	50			
White/Caucasian	11	45.8			
More than one	1	0.4			
American Indian	0	0			
Asian	0	0			
Ethnicity	24				
Hispanic	5	20.8			
Non-Hispanic	19	79.2			
Parents' Annual Income	23				
< $10,000	7	30.4			
$10,000–14,999	5	21.7			
$15,000–24,999	0	0			
$25,000–34,999	4	17.4			
$35,000–49,999	2	8.8			
$50,000–74,999	5	21.7			
$75,000–99,999	0	0			
> $100,000	0	0			
CTQ Total Score	22		28	27.91	8.35
TSCC Total Score	22		62	27.95	17.06
Presence of Psychopathology	24		1.00	0.58	0.50
Yes	14	58.3			
No	10	41.7			

Additionally, the eyes-open condition model predicting likelihood of experiencing psychopathology from central alpha power was found to be significant, $\chi 2$ (1, $n = 24$) = 7.87, $p = 0.027$, $R^2_L = 0.31$. Higher central alpha power was significantly associated with greater likelihood of having psychopathology (see Fig. 2).

Parietal alpha power during the eyes-open condition was found not to be significantly associated with likelihood of experiencing psychopathology, $\chi 2$ (1, $n = 24$) = 8.92, $p = 0.069$.

6 Discussion

This study examined the likelihood of having any psychopathology relating to ACEs, specifically child maltreatment, trauma symptoms, and EEG alpha asymmetry and power. Findings indicated that neither child maltreatment nor trauma symptoms nor severity significantly predicted the odds of experiencing psychopathology. While alpha asymmetry was not significantly associated with psychopathology, higher resting-state frontal and central alpha power were significantly associated with the presence of psychopathology in adolescents. These findings suggest that alpha asymmetry may not be a reliable biomarker of psychopathology in adolescents. However, this finding does not rule out its potential relevance, and other indicators, such as alpha power, warrant further investigation as possible biomarkers of psychopathology in adolescents.

6.1 Alpha power

The present study links higher alpha power to less cortical activation, a possible indicator of psychiatric vulnerability [40]. Specifically, in this sample of 12–14-year-old adolescents, youth with higher alpha power tended to have more psychopathology. Higher alpha power is linked to lower cortical activation, which is associated with symptoms of inattention in adolescents [41] and could be a global indicator of vulnerability to psychopathology as has been indicated in adults [40].

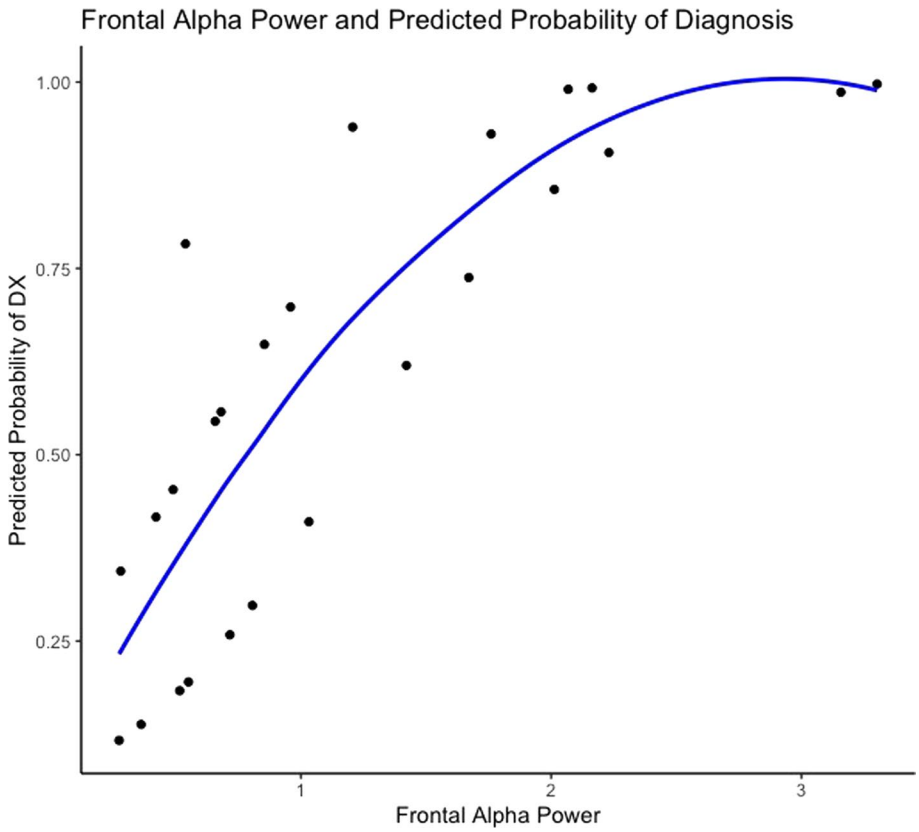

Fig. 1 Predicted probabilities of psychopathology based on frontal alpha power. $N = 24$. Presence of psychopathology (0 = no, 1 = yes). Scatterplot showing the predicted probabilities for presence of psychopathology based on frontal alpha power values

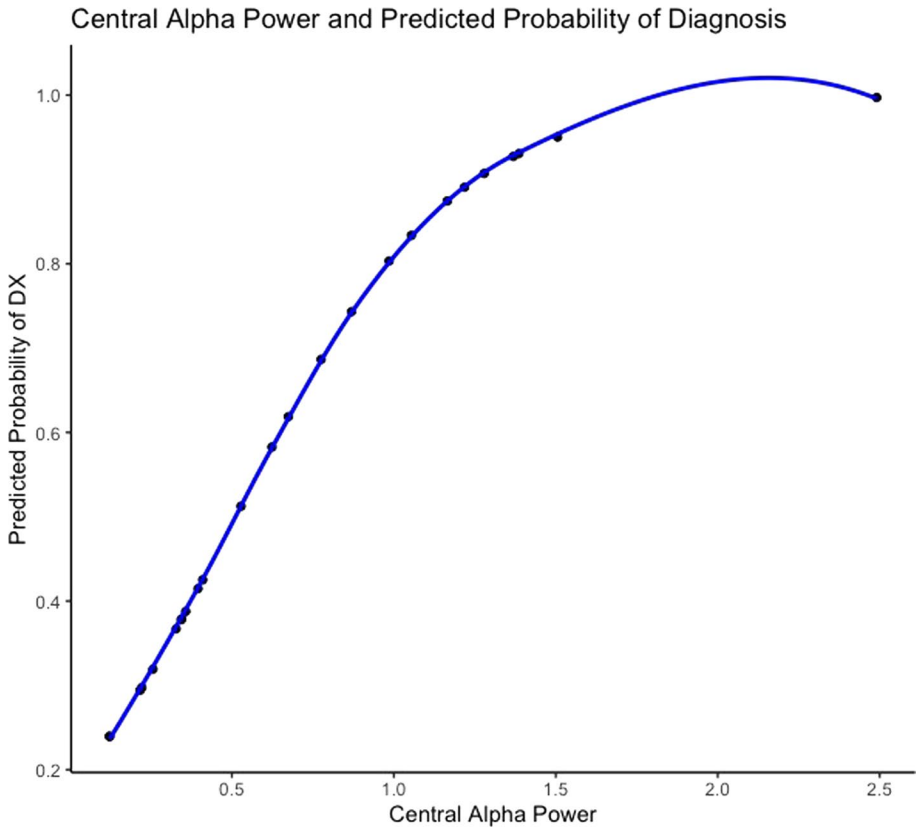

Fig. 2 Predicted probabilities of psychopathology based on central alpha power. *N* = 24. Presence of psychopathology (0 = no, 1 = yes). Scatterplot showing the predicted probabilities for presence of psychopathology based on central alpha power values

Higher alpha power in frontal and central regions mirrors prior findings with adolescents with a range of psychopathology. For example, adolescents diagnosed with bipolar disorder had heightened alpha power across several brain regions, including frontocentral areas, which was associated with increased inattention and cortical inhibition [41]. In adults with depressive disorders a similar pattern emerges, with increases in overall alpha power in parietal regions of the brain, reflecting decreased cortical activation [40]. In non-maltreated adolescents, less left-sided alpha activity, reflecting greater alpha power, is associated with the presence of depressive symptoms [50]. These findings support early research on the role of alpha activity in overall cortical activation and provide evidence that an inverse relationship may be present between alpha power and attention. While the present study did not specifically measure attention, prior research suggests that changes in alpha wave activity may be associated with deficits in attention, which can be present in certain psychopathologies, such as ADHD and bipolar disorder [39, 41].

Furthermore, it is worth noting that alpha power was only a significant predictor of psychopathology for the eyes-open conditions, not the eyes-closed conditions. This finding is likely due to power in the alpha band being increased when participants' eyes are closed, compared to eyes-open conditions. The increased alpha band power observed in the eyes-closed condition is expected, as alpha activity naturally rises when the eyes are closed compared to when they are open. This increase likely occurred across all participants, regardless of psychopathology status. As a result, the widespread elevation in alpha power may have reduced the sensitivity to detect significant differences, potentially obscuring any underlying relationships between alpha power and psychopathology.

6.2 Alpha asymmetry

The findings of the present study suggest that no clear relationship was detected between patterns of alpha asymmetry and the likelihood of having psychopathology. However, this does not eliminate the possibility of an effect. Further research is needed to explore alternative explanations and contributing factors. Meta-analyses on the relation between alpha asymmetry and psychopathology, such as depression and anxiety, have identified inconsistencies in the literature for alpha asymmetry [51, 52]. For example, among adolescents with CPS-reported maltreatment, those

at moderate to high levels of child maltreatment showed patterns of right frontal alpha asymmetry, indicative of increased odds of PTSD symptoms [36]. However, the same study also found that in maltreated adolescents, frontal alpha asymmetry was not associated with the diagnosis of major depressive disorder (MDD) [36]. In looking more broadly, a recent meta-analysis of EEG asymmetry in relation to suicidal ideation found that there was not a consistent relationship between these constructs and that EEG asymmetry did not seem to be a candidate as a biomarker for suicide [53]. Taken together, alpha asymmetry may not be a biomarker of psychopathology or related constructs or may be differentially related to specific diagnoses.

Likely contributing to inconsistencies in results, the presence of methodological confounds are problematic in the literature. Most notably, the location of alpha asymmetry in the brain, sex/gender differences, and methods for measuring symptom severity cloud the relation between alpha asymmetry and disorders such as depression [52]. Heterogeneity and comorbidity of psychiatric disorders also pose issues for the interpretability of asymmetry results and a focus on relating left versus right alpha activity to symptom clusters instead of specific diagnoses has been suggested [54, 55]. In addition, some evidence suggests that intelligence may be related to different patterns of asymmetry [56]. While measures of intelligence, such as intelligence quotients (IQ), were not assessed in the present study, future work should investigate IQ/cognitive performance as potential confounds. Taken together, the potential of alpha asymmetry as an informative neural marker may be limited by the presence of many confounding variables. Therefore, alpha power rather than alpha asymmetry may be more useful as a biomarker of psychopathology for adolescents following further study.

6.3 ACEs and trauma symptoms

This study found no significant association between self-reported instances of ACEs, specifically child maltreatment, or trauma symptoms and the likelihood of psychopathology. In addition, when self-reported child maltreatment was considered, trauma symptoms also did not predict the odds of psychopathology. However, in the present study, only two adolescents (0.4%) met the threshold for having clinically significant trauma symptoms. Given that very few participants reported trauma symptoms in the clinical range, with the vast majority (> 80%) reporting in the low range, it is not surprising that a relationship between trauma symptoms and psychopathology was not apparent. The low report of trauma symptoms is somewhat surprising, considering the high number of participants who had reports of child maltreatment (84.4%). This rate of prevalence in the present study is more than double what has been reported by the National Child Abuse and Neglect Data System (NCANDS), which estimates that 37.4% of children will have a reported incident of maltreatment by age 18 [57]. Taken together, it may be that additional measures or longitudinal assessments may be needed to understand how these variables interrelate during this adolescence developmental period.

In addition, self-reported child maltreatment was less common than documented reports ($M = 26.96$), though this may be due to adolescents' reluctance to disclose abuse victimization [58], especially since preliminary analyses found that adolescent self-reported maltreatment scores did not differ between those who had documented reports of child maltreatment and those who did not have documented maltreatment reports. Therefore, it is possible that documented reports may not fully capture all aspects of child maltreatment. Indeed, the national prevalence and incidence of child abuse and neglect are estimated to be far greater than the actual number of cases that get reported and documented [59].

Although the current study did not measure resilience, future studies might explore whether low reports of trauma symptoms in maltreated adolescents could be due to some degree of resilience to the development of post-traumatic symptomatology. Resiliency refers to adaptive functioning in the face of trauma or other severe stressors and has been conceptualized as existing along a continuum where it can present differently in various domains of one's life [60, 61]. While not observed in the current study, prior studies have shown that adolescents who experienced ACEs, particularly child maltreatment, were more at risk for developing psychopathology when they showed lower levels of resilience and that factors such as social support and peer relationships contributed to increased resilience to the psychological effects of maltreatment [62, 63].

As stated, the presence of psychiatric diagnoses in the present study was quite high at 62%, which was more than three times the national normed average of 20% for adolescents 13–18 years old [64]. Rather than showing resilience, the present sample seemed to show the opposite in terms of psychopathology. The low association between ACEs, trauma symptoms, and psychopathology in the present study is likely due to other factors that are worthy of future study, such

as an overall pattern of under-reporting. Further, it is possible that low power and a small sample size limited the ability to detect these nuances in the present study.

Further, research suggests that types of self-reported ACEs, including child maltreatment, may be differentially associated with psychopathology. Emotional abuse, for instance, has been shown to be more strongly associated with trauma symptomatology and internalizing problems than other maltreatment subtypes [65]. However, multiple types of child maltreatment often co-occur and are highly interrelated, with multi-type maltreatment exposure considered to be the norm [65, 66]. Due to the small sample size in the current study, it was not possible to separately assess risk for psychopathology based on the type of ACE in the current study. Further research should examine how types of maltreatment and exposure to multiple types of ACEs differentially influence psychological, cognitive, and behavioral functioning.

Other factors related to risk and resiliency, such as emotion regulation and peer acceptance, may influence the relationship between ACEs and psychopathology, which were not measured in the present study and could be considered in further investigations [18]. For example, it has been recently suggested that the relationship between ACEs and psychopathology may be confounded by other genetic and environmental risk factors for psychopathology [67]. Environmental risks, such as socioeconomic disadvantage, are associated with an increased risk for psychiatric disorders and are more likely to be experienced following ACEs [68]. Additionally, family histories of psychiatric disorders are more common among youth reporting ACEs [68]. Thus, future research into the association between ACEs and psychopathology should consider these risk factors. Identifying these factors is also relevant for informing interventions and prevention efforts.

7 Limitations and strengths

Though this study provides some preliminary support for alpha power as a potential biomarker for psychopathology in adolescents, it is not without limitations. First, the current sample was fairly homogenous in racial identity, age, and SES and may not generalize to other populations. Additionally, the presence of psychiatric diagnoses and experiences of ACEs were common, contributing to the homogeneity. All the participants were between 12–14 years old, and most came from lower-income families. However, the uniformity of these aspects of this sample could also be seen as a strength given that lower-SES youth are often underrepresented in the literature, despite evidence that youth from lower-SES families are at an increased risk of experiencing trauma [69]. In addition, despite being part of a larger study that investigated the behavioral, neural, and affective outcomes of maltreated adolescents across 3 years, the data analyzed in the present study were cross-sectional.

Furthermore, the sample size for the available EEG data was small ($N = 24$), and a post-hoc power analysis indicated that analyses for alpha asymmetry and alpha power were somewhat underpowered (64%). To achieve 80% power, approximately 36 participants would have been needed to detect a significant association between alpha asymmetry/power and the likelihood of experiencing psychopathology. However, the use of a mobile EEG system was a strength as it allowed research assistants to travel to participants' homes to collect data from those who may not have the resources or ability to come into the lab.

The results of the present study, while supportive of the frontal and central alpha power as potential biomarkers for psychopathology in adolescents and bolstered by current literature, should be interpreted with caution. Specific diagnoses could not be differentiated in the current sample due to the small number of participants in each group. Due to this limitation, it was not possible to determine which psychiatric diagnoses were associated with these increases in frontocentral alpha power. As various types of psychopathologies appear to be differentially linked to increases and decreases in alpha power, it will be important to distinguish between different disorders in future investigations. Further, rather than assessing psychopathology based on the presence or absence, future studies should explore the associations between neural markers, such as alpha power and asymmetry, and specific symptom domains. Understanding how certain clusters of symptoms, such as anhedonia and hyperarousal, relate to specific biomarkers would be more informative and provide richer insight into identifying neurodevelopmental vulnerabilities for the development of psychopathology.

Additionally, it is important to note that age was a significant predictor in the model predicting psychopathology from frontal power. Alpha oscillations show clear shifts across development and much of the current literature is conducted with adult samples. For example, changes in the EEG power spectrum across development have been observed, reflecting age-related neural maturation, and EEG measures have been shown to be highly accurate in predicting the age classification of children and adults [70, 71]. EEG brain rhythms show differences in temporal

and spatial organization as a function of age, with posterior regions maturing earlier than anterior regions [70]. For instance, compared to young adults, children demonstrate higher spectral power in all EEG frequency bands, including alpha [70]. Thus, more research focusing on altered alpha activity, specifically in adolescents, is necessary to clarify its role in psychiatric diagnoses for this developmental stage.

8 Conclusion

The current study found preliminary evidence of associations between frontal and central alpha power and the likelihood of developing psychopathology in an understudied adolescent sample. These findings suggest alpha power may serve as a biomarker of psychopathology in adolescents. Adolescence is a critical period for brain development and a time when vulnerability to traumatic experiences is increased. Children exposed to maltreatment are up to three times more likely to develop psychopathology than children with no history of maltreatment [72]. Despite their increased risk for negative mental, emotional, and behavioral outcomes, adolescents from underrepresented groups are less likely to have access to mental health care, especially if they are also socioeconomically disadvantaged [73]. Further research to clarify the role of alpha power as a potential biomarker of psychopathology is critical to have more tools for the prevention of negative outcomes for adolescents following child maltreatment exposure.

Acknowledgements We would like to thank New Hanover County Health and Human Services (NHC-HHS) and the National Institutes of Health–National Institute on Alcohol Abuse and Alcoholism (R15 AA028911, R15 AA023251) for their support of this research.

Author contributions All authors contributed equally to the study conception and design. Material preparation, data collection and analysis were performed by Sophia Laney and Kate Nooner. The first draft of the manuscript was written by Sophia Laney and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The data reported in this study was obtained with support from the U.S. National Institute on Alcohol Abuse and Alcoholism R15 AA028911, R15 AA023251 (Nooner).

Data availability The data are available from the authors upon reasonable request.

Declarations

Ethics approval and consent to participate All procedures in this study were approved by the University of North Carolina Wilmington Institutional Review Board and were carried out in accordance with the university's regulations. Parents provided informed consent to participate in the study and for their child to participate, and children provided their informed assent to participate in the study.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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