Developmental Cognitive Neuroscience 71 (2025) 101479

Contents lists available at ScienceDirect

Developmental Cognitive Neuroscience

journal homepage: www.elsevier.com/locate/dcn

Interactive effects of social media use and puberty on resting-state cortical activity and mental health symptoms

Nathan M. Petro [a,b,1], Giorgia Picci [a,b,c,*,1], Lauren K. Webert [a,b], Mikki Schantell [a,b], Jake J. Son [a,b,d], Thomas W. Ward [a,c], Kellen M. McDonald [a,c], Cooper L. Livermore [a,b], Abraham D. Killanin [a,b,d], Danielle L. Rice [a,b], Grace C. Ende [a,b], Anna T. Coutant [a,b], Erica L. Steiner [a,b], Tony W. Wilson [a,b,c]

[a] Institute for Human Neuroscience, Boys Town National Research Hospital, Boys Town, NE, USA
[b] Center for Pediatric Brain Health, Boys Town National Research Hospital, Boys Town, NE, USA
[c] Department of Pharmacology & Neuroscience, Creighton University, Omaha, NE, USA
[d] College of Medicine, University of Nebraska Medical Center, Omaha, NE, USA

ARTICLE INFO

Keywords:
Resting state
MEG
Social media
Development
Puberty
Mental health

ABSTRACT

Adolescence is a period of profound biopsychosocial development, with pubertally-driven neural reorganization as social demands increase in peer contexts. The explosive increase in social media access has fundamentally changed peer interactions among youth, creating an urgent need to understand its impact on neurobiological development and mental health. Extant literature indicates that using social media promotes social comparison and feedback seeking (SCFS) behaviors in youth, which portend increased risk for mental health disorders, but little is known about its impact on neurobiological development. We assessed social media behaviors, mental health symptoms, and spontaneous cortical activity using magnetoencephalography (MEG) in 80 typically developing youth (8–16 years) and tested how self-reported pubertal stage moderates their relationship. More mature adolescents who engaged in more SCFS showed weaker fusiform/parahippocampal alpha and medial prefrontal beta activity, and increased symptoms of anxiety and attention problems. Engaging in SCFS on social media during adolescence may thus relate to developmental differences in brain regions that undergo considerable development during puberty. These results are consistent with works indicating altered neurodevelopmental trajectories within association cortices surrounding the onset of many mental health disorders. Importantly, later pubertal stages may be most sensitive to the detrimental effects of social media use.

1. Introduction

In the past decade, access to social media has exploded, creating an unprecedented landscape of peer interactions for youth and a rising concern of risk for concomitant mental health problems. Recent estimates indicate that 97 % of adolescents regularly use at least one of the predominant social media platforms (e.g., Twitter, Snapchat, Instagram), and that over 90 % use social media multiple times per day (Anderson and Jiang, 2018; Hill et al., 2016). Approximately 45 % of adolescents report that they are online “near constantly” (Anderson and Jiang, 2018; Hill et al., 2016). Moreover, on average, adolescents engage with screens a staggering 7.7 hours per day outside of school (Nagata et al., 2022). Given that adolescence is a period of profound biopsychosocial development (Crone and Dahl, 2012), whereby acquisition of core social developmental tasks is shaped through peer relationships (Roisman et al., 2004; Zimmer-Gembeck, 2002), it stands to reason that social media is now a common context where these peer interactions and relationships occur (Nesi et al., 2018). In concert, a major instigator of neurobiological changes and reorientation toward peers observed during adolescence is pubertal development (Picci and Scherf, 2016; Saxbe et al., 2015), which coincides with increases in most major mental health disorders (Dehestani et al., 2023; Solmi et al., 2022). Crucially, beyond the near ubiquitous use of screens and social media, studies suggest that there are links between such use and a myriad of physical

* Corresponding author at: Institute for Human Neuroscience, Boys Town National Research Hospital, Boys Town, NE, USA.
E-mail address: giorgia.picci@boystown.org (G. Picci).

[1] Shared first authorship

https://doi.org/10.1016/j.dcn.2024.101479
Received 5 July 2024; Received in revised form 18 November 2024; Accepted 19 November 2024
Available online 22 November 2024
1878-9293/

and mental health issues, including anxiety (Barry et al., 2017), depression (Fors and Barch, 2019), sleep problems (Lund et al., 2021), and substance use (Brunborg et al., 2017; Kaur et al., 2020). Thus, there is an urgent need to understand the impact of social media use on neurobiological development during potentially sensitive periods, for better or for worse. Unfortunately, the vast majority of social media studies have focused on mere screen time exposure, and not more nuanced aspects of engagement and attributions or emotional states related to such exposure.

To date, the strongest evidence for links between social media use and transdiagnostic symptomology in youth has been found for internalizing- and attention-related symptoms (Barry et al., 2017; Boer et al., 2020; Luijten et al., 2022; Ra et al., 2018). For instance, a recent meta-analysis of 143 studies found the strongest support for links between social media use and elevated internalizing symptoms (e.g., anxiety, depression) in clinical and community-based adolescent samples (Fassi et al., 2024). In two separate longitudinal studies in typically-developing adolescent samples, patterns of social media use were predictive of increased attention-deficit symptoms in youth who were otherwise healthy (Boer et al., 2020; Ra et al., 2018). In the study from Boer and colleagues (2020), problematic social media use (i.e., dependence-like behaviors), not mere amount of time spent on social media platforms, was unidirectionally predictive of an influx of attention-related problems, suggesting that more nuanced approaches to social media use are important to disentangling the nature of these associations on mental health. Other features of social media use, including social comparison and feedback seeking (SCFS) behaviors have been shown to predict increases in depressive symptoms in youth across one year, above and beyond mere frequency of use (Nesi and Prinstein, 2015). Importantly, findings suggest that during adolescence, the extent to which social media affects emotional states (Sánchez-Hernández et al., 2021) and body image satisfaction (Martinac Dorčić et al., 2023) are dependent upon how much SCFS teens are engaging in on social media. Researchers have suggested that engaging in SCFS behaviors are likely to be intensified through social media platforms and may put youths at greater risk of more internalizing-based problems (Feinstein et al., 2013; Moroney et al., 2023; Venta et al., 2019), as peer-based interactions are crucial for sculpting self-esteem and identity formation during adolescence and beyond (Gruenenfelder-Steiger et al., 2016).

Attempts to identify the developmental windows in which adolescents are most profoundly vulnerable to the effects of social media have been made (Orben et al., 2022). However, these studies have exclusively focused on chronological age and not pubertal development, which could provide more information about the developmental stage that individuals are in and potential sensitivity to the harms or benefits of social media. With the major influx of hormones that occurs during puberty, one of the most marked changes is increased neurobiological and behavioral sensitivity to social evaluation, feedback, and exclusion, especially from peer contexts (Lindberg et al., 2007; Pfeifer et al., 2013; Pfeifer and Allen, 2021; Silk et al., 2014). Theories and supporting data suggest that pubertal hormones instigate motivation to seek out and form intimate and confiding relationships with peers, which is thought to be integral in the neural reorganization that occurs during puberty (Nelson et al., 2016; Scherf et al., 2013). In fact, the most convergent set of findings from functional neuroimaging studies examining pubertal effects on brain development can be found in networks involved in social information processing (Dai and Scherf, 2019). Crucially, while this "social reorientation" toward peers is adaptive to achieving successful transition into adult levels of social functioning (Nelson et al., 2005), it also carries elevated risk for psychopathology, especially symptom sets characterized by internalizing behaviors (Pfeifer and Allen, 2021). Thus, it stands to reason that puberty, above and beyond age, is a critical factor in understanding how the developing brain responds to the newly found context of social media, especially with respect to mental health issues known to arise during the pubertal window (Solmi et al., 2022). Although very limited, one existing study suggests that during later stages of puberty, adolescents are more likely to engage in more performative and lurking behaviors on social media platforms, suggesting that puberty may be a time when youth are particularly susceptible to developing use patterns that propagate risk for internalizing problems (Swirsky et al., 2022). Indeed, advanced pubertal development is a potent predictor of increased social comparisons (e.g., comparing physical attributes), which have the potential to be amplified through social media use due to more opportunity for upward social comparisons and attempts to create idealized self-presentations (Chou and Edge, 2012; Meeus et al., 2019). Thus, the current study sought to investigate whether pubertal stage, particularly the later stages, may create risk for maladaptive social media use (e.g., elevated SCFS behaviors) and mental health problems.

Despite social media fundamentally changing the way adolescents engage socially, the field's understanding of how social media affects brain development is severely limited. Existing studies have mostly used structural MRI approaches, with evidence of accelerated cortical thinning in sensory and association brain regions (Achterberg et al., 2022; Paulus et al., 2019), and decreased grey matter volume in regions central to reward and social-affective processing (e.g., ventral striatum, amygdala, orbitofrontal cortex; He et al., 2017; Hong et al., 2013; Zhou et al., 2011). Functional MRI studies have documented altered activation and connectivity patterns across cognitive control and reward networks in youth with internet addiction compared to peers, suggesting distinct effects of excessive digital media use on the developing brain (Hong, Zalesky, et al., 2013; Li et al., 2014; Lin et al., 2015). There is also work linking social media and smart phone addiction to altered resting-state functional connectivity in sensory networks (e.g., visual and sensorimotor; Áfra et al., 2024), as well as task-based fMRI research showing age-related increases in activation within reward circuitry (i.e., nucleus accumbens) in response to photos with greater Instagram likes (Sherman, Greenfield, et al., 2018). An early study also showed that adolescents exhibit diminished activity in cognitive control network regions when viewing riskier photos (Sherman et al., 2016). Taken together, these findings provide some initial insight into how developing brain networks are sensitive to social media use patterns. Although several studies have examined age-related effects in adolescent samples, no study to date has examined how potentially harmful patterns of use differ across pubertal development, when the most extensive reorganization is happening in association cortices, and when vulnerability to mental health issues are accentuated.

While not as widely used as fMRI, magnetoencephalography (MEG) is a particularly useful tool for studying adolescent functional brain development. The MEG recording environment is silent, noninvasive, and allows participants to be comfortably seated throughout the recording period, making the environment more ideal for children and others. Like other electrophysiological methods, the temporal resolution of MEG is excellent (1 ms) and enables the direct detection of ongoing neural activity with good spatial precision (~3–5 mm). Resting-state MEG recordings generally focus on the local power of spontaneous cortical rhythms. Briefly, neurons in the human cerebral cortex exhibit spontaneous discharges and dendritic current fluctuations, which locally summate to produce population-level rhythmic activity that can be quantified using MEG and various neurophysiological methods (Buzsáki et al., 2012; Mountcastle, 1998). The amplitude and spectral content of these "spontaneous" rhythms are known to vary across different brain areas based partially on the organization of local cortical circuits (Bollimunta et al., 2008; Steriade et al., 1990), thalamic inputs and neurotransmitter distribution (Edden et al., 2009; Flint and Connors, 1996), and such rhythms play a critical role in the neural computations and oscillations that underlie perceptual, cognitive, and motor processing (Cohen, 2017; Heinrichs-Graham et al., 2018; Schantell et al., 2024; Springer et al., 2023). In fact, such neural oscillatory activity has been tied to specific psychological functions (Siegel et al., 2012), with alpha (8–12 Hz) being strongly tied to visuoperceptual and attention processes (Klimesch, 2012; Wiesman et al., 2017), and beta tending to reflect motor activity in the sensorimotor strip and higher-level cognitive processing in prefrontal and other association cortices (Engel and Fries, 2010; Lundqvist et al., 2024). Further, neural activity in both of these spectral bands is known to underlie aspects of social cognition (Campagnoli et al., 2019; Güntekin and Başar, 2014).

In general, spontaneous activity in lower frequencies (delta, theta) becomes weaker while that in higher frequencies (alpha, beta, gamma) becomes stronger from childhood into early adulthood (Gómez et al., 2013; Hoshi and Shigihara, 2020; Ott et al., 2021; Rempe et al., 2023; Segalowitz et al., 2010). These developmental effects occur predominantly in association cortices (Hoshi and Shigihara, 2020; Ott et al., 2021; Petro et al., 2022), which are particularly sensitive to adolescent development vis-à-vis increased neural plasticity (Larsen et al., 2022; Sydnor et al., 2021; Thompson et al., 2001; van Wingen et al., 2011), and tied to the release of sex hormones during puberty (Penhale et al., 2022; Picci, Ott, Penhale, et al., 2023). This shift in balance from lower to higher frequency rhythms is thought to at least partially reflect changes in the activity of cortical interneurons (McKeon et al., 2024; Voytek et al., 2015) and be linked to developmentally sensitive increases in plasticity (Froemke, 2015; Hensch, 2005; Juraska, 2024). Taken together, analyses of multispectral spontaneous activity during rest may provide critical insights into neurobiological, cognitive, and emotional development during childhood and adolescence.

In the present study, we assessed social media behaviors, perceived pubertal stage, mental health symptoms, and resting-state brain activity using MEG across a broad swath of development (i.e., 8–16-years-old). To probe potentially harmful social media behaviors, we targeted SCFS behaviors on social media platforms, as these motivational factors may be particularly consequential for youths' mental health beyond mere exposure (Nesi and Prinstein, 2015). The core research question we assessed was whether there are interactive effects between perceived pubertal stage and social media use on frequency-specific neuronal activity, and whether this activity relates to mental health symptomology (i.e., anxiety, depression, and attention problems) previously associated with social media use patterns in youth. Specifically, we expected that engaging in more SCFS would lead to spectral patterns of spontaneous brain activity that are inconsistent with typical developmental trajectories. In other words, we expected more mature adolescents who engage in more SCFS to exhibit weaker activity in the higher alpha and beta frequency bands. Since sensitivity to social feedback becomes more salient and fundamental during the later stages of puberty, we hypothesized that more aberrant associations between SCFS behaviors and spontaneous neural activity would emerge during more advanced stages of puberty.

2. Methods

2.1. Participants

The current cross-sectional sample consisted of 92 participants who were already enrolled in an ongoing longitudinal study. These participants were selected from the entire sample based on their age (i.e., youth younger than eight were excluded) and ownership of a cell phone. Each participant completed an online social media use questionnaire, which was administered between years 2 and 3 of a five year longitudinal study with annual visits. Of those 92, four did not complete the MEG resting state recording, six had unusable MEG resting state recordings, and two were excluded because they indicated that they did not use social media on our questionnaire. Thus, 80 youth (38 females, 8 – 16 years, $M_{age} = 12.23$, SD = 2.29) completed all aspects of this sub-study, including a recent resting-state MEG scan and structural MRI, behavioral and puberty questionnaires, and the social media questionnaire. Prospective participants were excluded from the parent longitudinal study if, at the time of initial enrollment, they had any current or previous diagnoses of psychiatric or neurological conditions, a history of significant head trauma, active drug or alcohol use, the inability to commit to the longitudinal study, current use of medications known to affect CNS function (e.g., psychotropics, antidepressants, antipsychotics, anticonvulsants, etc.), or the presence of any ferrous metal implant, including orthodonture. After a complete description of the study, written informed assent and consent were obtained from the child and the child's parent or legal guardian, respectively. All procedures were approved by the Institutional Review Board (IRB).

2.2. Perceived pubertal stage questionnaire

Perceived pubertal stage was assessed using the Pubertal Development Scale (Petersen et al., 1988), which is composed of questions about participants' progress through physical changes indicative of both adrenarche (i.e., body hair, skin changes) and gonadarche (i.e., growth spurt, voice changes and facial hair in boys, breast development and menarche in girls). This questionnaire was completed by the youth aged 11 and older (n = 50), or by the parent if younger than 11 (n = 30). Crucially, recent work has shown that there is high internal consistency and test-retest reliability between parent and child PDS reports (Koopman-Verhoeff et al., 2020). This questionnaire was scored using a coding system developed by Shirtcliff and colleagues (Shirtcliff et al., 2009), which parallels the Tanner stages of pubertal development (i.e., stages 1 – 5; 1 = prepubescent, 5 = sexually mature). Cronbach's alphas indicated good reliability in the current sample (boys α =.91, girls α =.89). The percentage of sample participants in each perceived pubertal stage are reported in supplemental Table S7.

2.3. Mental health symptoms questionnaire

Participants completed the self-report version of the Behavior Assessment for Children Scale (third edition; BASC-3; Reynolds and Kamphaus, 2015). The BASC-3 scale is a validated measure that comprehensively assesses behaviors and emotions in children and adolescents related to psychopathology and well-being (Canivez et al., 2021). The current study was focused on assessing anxiety, depression, and attention problems, which are all measured as subscales in the BASC-3. Participants were asked to read statements describing different behaviors or symptoms, and to respond how often they exhibit each behavior (i.e., 0 = never, 1 = sometimes, 2 = often, or 3 = almost always). The BASC-3 self-report clinical and adaptive scales have good internal (α =.82 – 84) and test-retest reliability (α =.78 –.83). Given that the current sample is typically developing and because age and sex were controlled for in statistical models, raw scores were used in the current analyses.

2.4. Social media questionnaire

Participants completed an online questionnaire virtually, which probed their social media use patterns and emotional responses to social media use. This questionnaire was administered between years 2 and 3 of the longitudinal study. Specifically, participants reported on when they started using social media, which applications they typically use, and characteristics of daily use for specific apps (e.g., amount of time used per day, use after bedtime, number of app checks per day). In addition, participants completed a series of questions related to both active and passive social media use. Here, passive use was the sum of all consuming items, and active use was the sum of all communicating, sharing, and creating items from the questionnaire. All items from this survey are listed in the Supplemental Materials. To assess the extent to which youth engage in social comparison and feedback seeking (SCFS) behaviors on social media, we utilized a modified version of the Motivations for Electronic Interaction Scale (Nesi and Prinstein, 2015), which was originally validated on older youth (8th and 9th graders). Specifically, to be developmentally appropriate and relevant to the social behaviors of this age-range, we removed items 18–22, which were related to sexual activity and rephrased certain items to refer to "friends" instead of "dating partners" (see Supplemental Materials). Participants read statements describing motivations for using social media (i.e., "*I use social media to…*") and reported how true each statement was to their experience (i.e., 1 = not at all true, 5 = extremely true). The questionnaire included 17 items, such as "*to check out the way others look*", "*to get feedback from others on the things I send/post*", "*to see what others think about how I look*", "*to feel less lonely*". The questionnaire items included in the current study are reported in the Supplemental Materials. The SCFS scale had excellent reliability in our sample (Cronbach's α =.90).

2.5. MEG data acquisition

The MEG recordings were conducted in a two-layer magnetically-shielded VACOSHIELD room. Neuromagnetic responses were sampled continuously at 1 kHz, with an acquisition bandwidth of 0.1–330 Hz, using a MEGIN Triux Neo MEG system with 306 magnetic sensors (Helsinki, Finland). During six-minutes of data acquisition, participants were seated with their eyes-open and maintained gaze on a fixation, while being monitored via real-time audio-visual feeds from inside the shielded room.

2.6. Structural MRI acquisition, processing, and MEG-MRI coregistration

Individual structural MRI data for each participant were acquired using a Siemens Prisma 3 T scanner (Siemens Medical Solutions) with a 32-channel head coil and consisted of one T1 weighted 3D isotropic sequence with the following parameters: TR = 2.4 s, TE = 2.05 ms, flip angle = 8°, FOV = 256 mm, voxel size = 1×1×1 mm, slices = 192. All T1-weighted sMRI data were segmented with the computational anatomy toolbox (CAT12 v12.6 (Gaser and Dahnke, 2016)) within SPM12. Here, segmented T1 images underwent noise reduction using a spatially-adaptive non-local means denoising filter (Manjón et al., 2010) and a classical Markov Random Field approach (Rajapakse et al., 1997). An affine registration and a local intensity transformation were then applied to the bias corrected images. These preprocessed images were segmented based on an adaptive maximum *a posteriori* technique (Ashburner and Friston, 2005) and a partial volume estimation with a simplified mixed model of a maximum of two tissue types. Lastly, the segmented images were normalized to MNI template space and imported into Brainstorm for co-registration.

Preceding MEG recording, five head position indicator (HPI) coils were attached to the participant's head and localized, together with three fiducial points and at least 100 scalp surface points, with a 3D digitizer (Fastrak, Polhemus Navigator Sciences, Colchester, VT, USA). Once in the MEG, electrical currents with unique frequency labels (e.g., 322 Hz) were fed into each of the HPI coils, which induced measurable magnetic fields and allowed the position of the coils to be actively tracked relative to the MEG sensors throughout the recording. Since the HPI coil locations were also known in head coordinates, all MEG measurements could be transformed into a common coordinate system. With this coordinate system, participant-wise MEG data were coregistered with the participant's high-resolution structural T1-weighted MRI data prior to source reconstruction in Brainstorm.

2.7. MEG data processing

Each set of MEG data was individually corrected for head motion and underwent noise reduction using the signal space separation method with a temporal extension (tSSS; Taulu and Simola, 2006). These noise-reduced MEG data then underwent standard data preprocessing using the Brainstorm software. This process included a high pass filter of 1 Hz, a low pass filter of 200 Hz and a notch filter of 60 Hz and its harmonics to eliminate line noise. Cardiac artifacts were identified and removed using signal-space projection (SSP), which was subsequently accounted for during source reconstruction (Ille et al., 2002; Uusitalo and Ilmoniemi, 1997). Data were split into 4 s epochs for the detection and rejection of bad segments of MEG data. Amplitude and gradient metrics for each 4 s epoch were computed using custom Matlab code, and epochs that contained outliers were rejected using thresholds determined per participant, given the impact of head position on signal strength (i.e., magnetic field strength falls off exponentially with distance from the current source; Baillet, 2017; Wiesman and Wilson, 2020; Wilson, 2014; Wilson et al., 2016). Following this artifact rejection step, the mean number of accepted epochs was 87.81 (SD = 3.00, min = 77, max = 95). The total number of accepted epochs did not statistically covary as a function of age or perceived pubertal stage.

2.8. MEG source imaging and frequency power maps

The procedures used to source image MEG data followed the analysis pipeline outlined by Wiesman and colleagues (2021) and also used in a recent large-scale lifespan study (Rempe et al., 2023). Using an overlapping-spheres model that is not constrained to the cortical surface (Huang et al., 1999), this analysis models a single sphere for each of the 204 gradiometers (minus any channels previously labeled as bad). A linearly constrained minimum variance (LCMV) beamformer was then used to spatially filter the data based on the data covariance, computed from the resting-state recordings, and the noise covariance, computed from empty room recordings. Note, except for the removal of cardiac artifacts, the empty room recordings underwent preprocessing steps identical to the recordings of spontaneous cortical activity.

The resulting data were then used to estimate the power of cortical activity in each of the canonical frequency bands (delta: 2–4 Hz, theta: 5–7 Hz, alpha: 8–12 Hz, beta: 15–29 Hz, low gamma: 30–59 Hz, high gamma: 60–90 Hz). Using Welch's method (Welch, 1967), power spectrum densities (PSD) were estimated for each 4 s epoch across each MEG recording, with a 1 s sliding hamming window that overlapped at 50 %. These raw PSD maps were averaged across epochs to obtain one absolute PSD map per participant, with units corresponding to the Pseudo Neural Activity Index (PNAI), which is a modified version of Van Veen's Neural Activity Index (Robinson, 2004). Lastly, the norm of the three unconstrained orientations per location were then projected onto a common MNI ICBM152 brain template (Fonov et al., 2009) surface and a 3 mm FWHM smoothing kernel was applied before further statistical analysis.

2.9. Data analytic plan

We computed descriptive statistics on demographics and all study variables, including social media use. Next, we tested if the relationship between SCFS and brain activity differed as a function of perceived pubertal stage using a vertex-wise multiple regression implemented in SPM12. Here, the spontaneous power during rest, separately for each vertex and frequency band, was submitted as the outcome in a multiple regression across subjects, with SCFS behavior, pubertal stage, and their interaction serving as separate predictors; in addition, age, sex, and time between visits served as covariates of no interest. Notably, time between visits was included to control for confounds related to the timing of data collection, given that the social media questionnaire was administered virtually at a different time relative to each participant's annual in-person visit where all other data were collected. To correct for multiple comparisons, threshold free cluster enhancement (TFCE; E = 1, H = 2; 5000 permutations; (Smith and Nichols, 2009)) was applied to each of the resulting statistical maps. Following permutations, these TFCE maps were assessed with a cluster-wise threshold of $p_{FWE} < .05$ and a cluster forming threshold of $k > 100$ vertices. Data from the peak vertices were used to display and interpret the corresponding moderating effects of puberty on the relationship between SCFS and neural activity. Specifically, the regression coefficients were used to calculate the regression slope of the SCFS to neural activity relationship at each level of perceived pubertal status; the level at which these slopes reach significance is reported.

We next tested whether there was a similar moderating effect of pubertal stage on the relationship between SCFS and symptoms of mental health. Based upon prior literature, we were specifically interested in symptoms of attention, anxiety, and depression. This was conducted in a multiple regression framework where comparison and feedback seeking behavior, pubertal stage, and their interaction served as separate predictors; in addition, age, sex, and time between visits served as covariates of no interest. This model was computed separately with attention problems, anxiety, and depression as the outcome variables. The regression coefficients associated with the interaction term were assessed to determine the moderating effect of pubertal stage on the relationship between SCFS and mental health symptoms. As with the analyses of neural activity described above, these moderating effects were interpreted by calculating the relationship between SCFS and mental health symptoms at each level of puberty; the level at which these slopes reach significance is reported.

Two additional exploratory analyses were conducted, which are reported in full in the supplemental materials (sections S1 and S2). First, potential sex differences in the moderation effects were investigated. Second, to fully characterize the relationship between brain activity and all variables of interest, we investigated the relationship (i.e., main effect) between each behavioral variable and spontaneous brain activity controlling for pubertal stage (and all other covariates of no interest indicated in the aforementioned analyses). These exploratory analyses appear in the supplemental materials.

3. Results

3.1. Descriptive statistics, social media use, and perceived pubertal stage

Descriptive statistics of all variables and demographic characteristics are reported in Table 1. Of the 80 participants included in this substudy, three did not complete the BASC-3 survey and were excluded from the analyses of mental health symptoms. Overall, youth with a higher perceived pubertal stage reported more active (r_{78} =.38, p <.001) and passive (r_{78} =.61, p <.001) social media use, and endorsed greater amounts of SCFS (Fig. 1; r_{78} =.40, p <.001). Perceived pubertal stage did not relate to reported symptoms of anxiety (r_{77} =.03, p >.05), attention problems (r_{77} = −.05, p >.05), or depression (r_{78} =.13, p >.05). The correlations among behavioral variables are reported in the Supplemental Materials (Table S1).

3.2. Moderation analyses

3.2.1. Spontaneous cortical activity

Whole-brain vertex-wise regressions revealed an interaction between SCFS and pubertal stage on alpha and beta power, controlling for age, sex, and time between visits (Fig. 2).

Table 1
Participant Demographics.

	Sample n = 80
Age (in years)	8 – 16; 12.23 (2.29)
Sex (Male/Female)	42/38
Race (White/Black or AA/Asian/AIAN/Multiple)	67/3/1/0/9
Ethnicity (Not HL/HL/Unknown)	76/3/1
Perceived Pubertal Stage	1 – 5; 2.89 (1.45)
Social Media Comparison & Feedback Seeking	17 – 68; 31.31 (10.77)
Active Social Media Use (Z-Score)	−1.36 – 2.97; 0 (1.00)
Passive Social Media Use (Z-Score)	−1.86 – 2.12; 0 (1.00)
Anxiety Symptoms (BASC)	0 – 32; 11.04 (7.49)
Depression Symptoms (BASC)	0 – 24; 4.60 (4.45)
Attention Problems (BASC)	0 – 21; 7.44 (5.07)

Note. Ranges, means, and standard deviations are reported for continuous variables. Counts for categorical grouping variables are reported. AA – African American; AIAN – American Indian/Alaska Native; HL – Hispanic or Latino.

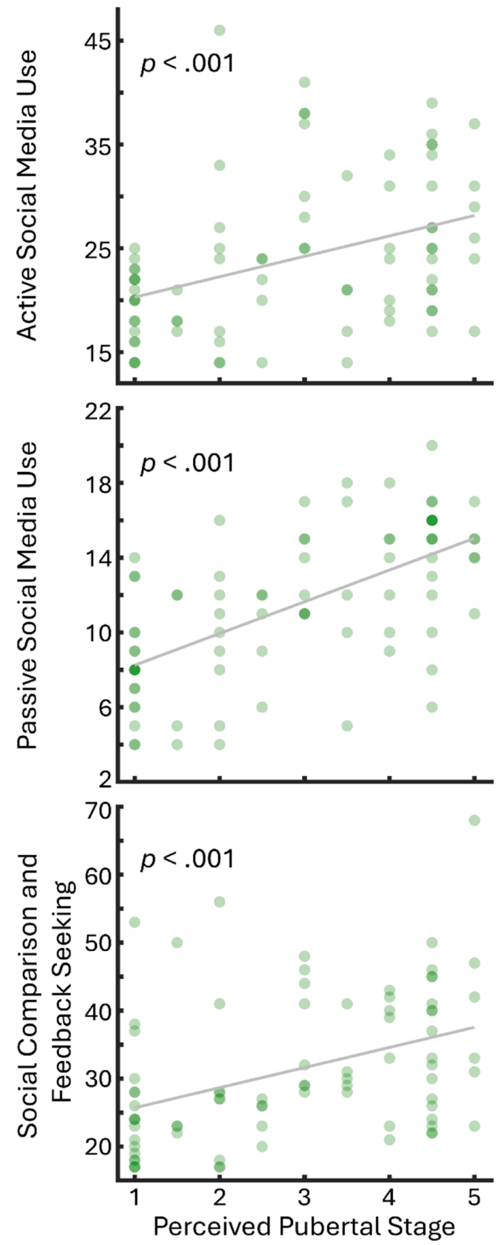

Fig. 1. Relationship between perceived pubertal stage and social media behavior. Scatterplots illustrate the relationship between perceived pubertal stage (*x*-axes) and social media behaviors (*y*-axes), including active social media use (top), passive social media use (middle), and social comparison and feedback seeking (SCFS; bottom). Each data point is shown with 30 % transparency to depict the density of overlapping data points. The trend lines (gray) illustrate the least square fit for each comparison.

In the alpha band, the interaction between SCFS and pubertal stage was significant at one cluster (t_{73} = −3.62, p_{FWE} <.05), which peaked in the left fusiform gyrus and extended medially into the parahippocampal gyrus and laterally to include the left occipitotemporal notch (see supplemental Table S2 for all regression coefficients). To further examine this moderation effect, the relationship between SCFS and alpha power was calculated at each pubertal stage. In pubertal stages 4–5 (i.e., most mature), a significant negative relationship was found (ps <.05). Conversely, at pubertal stages 1 (i.e., prepubertal) to 1.5, there was a significant positive relationship (ps <.05).

In the beta band, the interaction between SCFS and pubertal stage was significant in two bilateral prefrontal clusters, which peaked in the medial frontal gyrus (t_{73} = −3.40, p_{FWE} <.05) and included bilateral

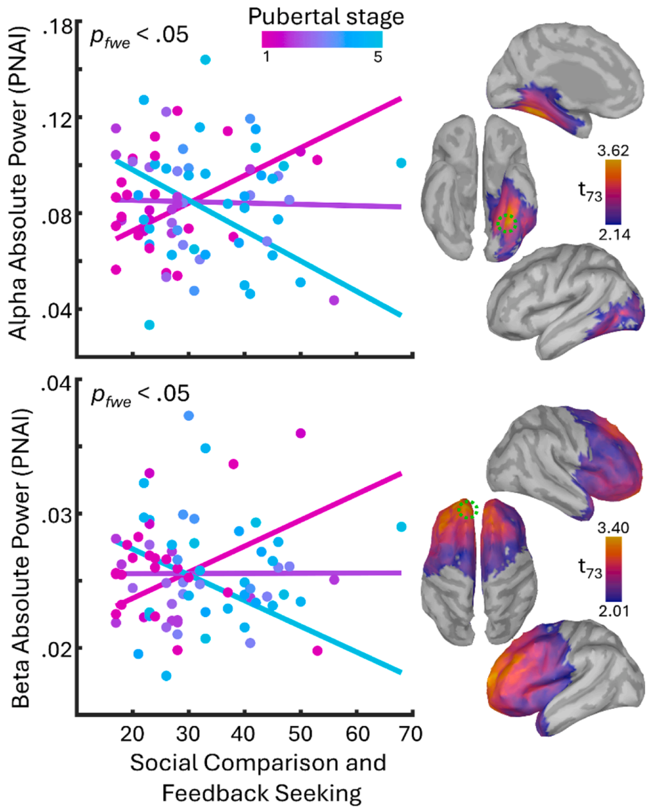

Fig. 2. Moderating effect of perceived pubertal stage on the relationship between social comparison and feedback seeking (SCFS) and spontaneous cortical activity. Cortical surface maps (right) display the vertex-wise *t*-values representing the interaction between SCFS and perceived pubertal stage on alpha (top) and beta (bottom) spontaneous cortical activity. Green dashed circles denote the vertices containing the strongest interaction effect. Absolute power from these peak vertices are plotted in the scatterplots (left, *y*-axes) against SCFS (*x*-axes), after adjustment for all predictors and nuisance variables (i.e., age, sex, and time between visits). Each data point is shaded according to perceived pubertal stage, where magenta indicates the lowest pubertal stage (i.e., prepubertal) and cyan the highest pubertal stage (i.e., fully or nearly fully mature). To illustrate the moderation effects, the trend lines depict the relationship between SCFS and brain activity at the minimum (pubertal stage = 1; magenta), middle (pubertal stage = 3; purple), and maximum (pubertal stage = 5; cyan) pubertal stage, calculated from the regression coefficients. *P*-values correspond to the cluster-level FWE statistic.

orbitofrontal, anterior cingulate, anterior insula, and anterior temporal cortices (see supplemental Table S3 for all regression coefficients). To further examine this moderation effect, the relationship between SCFS and beta power was calculated at each pubertal stage. In pubertal stages 4.5–5 there was a significant negative relationship (*ps* <.05), while this relationship was positive during pubertal stages 1 and 1.5 (*ps* <.05).

3.2.2. *Mental health symptoms*

Regression models were used to assess the moderating role of puberty on the relationship between SCFS and mental health symptoms (Fig. 3). These models indicated that pubertal stage moderated the relationship between SCFS and both attention problems ($t_{70} = 2.14$, $p < .05$) and anxiety ($t_{70} = 2.10$, $p < .05$), but not depression ($t_{70} = 1.54$, $p = .13$); see supplemental Tables S4, S5, and S6 for all regression coefficients from each moderation analysis, respectively. For attention problems and anxiety symptoms, greater symptomology was related to more advanced puberty.

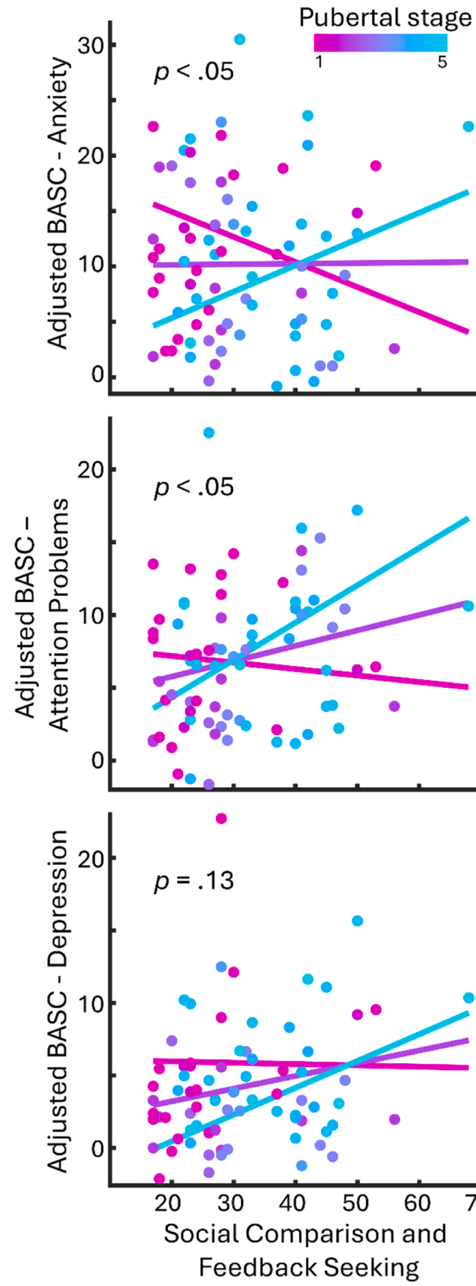

Fig. 3. Moderating effect of perceived pubertal stage on the relationship between social comparison and feedback seeking (SCFS) and mental health symptoms. Scatterplots illustrate the relationship between SCFS (x-axis) and the BASC-3 outcome measures (y-axis) of anxiety (top), attention problems (middle), and depression (bottom). The outcome measures are adjusted for all predictors and nuisance variables (i.e., age, sex, and time between visits). Each data point is shaded according to perceived pubertal stage, where magenta indicates the lowest pubertal stage and cyan the highest pubertal stage. The trend lines illustrate the relationship between SCFS and mental health symptoms at the minimum (magenta), middle (purple), and maximum (cyan) pubertal stage, calculated from the regression coefficients.

4. Discussion

The profound biopsychosocial development that occurs during adolescence instigates motivational changes toward social interactions with peers while concurrently conferring risk for mental health disorders. Pubertal development is a major catalyst for these changes, including the concomitant neuronal development that supports the behavioral changes characteristic of adolescence (Goddings et al., 2019). Currently, access to social media has become a central developmental context for youth, pointing to an urgent need to understand the impact of social media use on brain development during the pubertal transition. In the current study, we examined the relationship between social media behavior, spontaneous cortical activity, and mental health symptoms across different levels of perceived pubertal stage. Among more mature adolescents, spontaneous cortical activity within both the alpha and beta range were weaker with increasing SCFS behavior. In addition, more mature adolescents who endorsed more SCFS also endorsed having more symptoms of anxiety and attention problems. These findings suggest that social media may help build an environment that amplifies exposure to interactions that have the potential to be detrimental for adolescents. Below, we discuss the impact and implications of each finding in detail.

Alpha and beta power showed similar effects whereby power was diminished in more mature adolescents who endorsed more SCFS. Both alpha and beta power during rest typically increase throughout childhood and into adulthood (Doval et al., 2024; Hardy et al., 2024; Ott et al., 2021; Rempe et al., 2023). In addition, task induced alpha and beta activity has been associated with adolescent developmental differences in working memory (Embury et al., 2019; Killanin et al., 2022, 2024b, 2024a) and visual attention (Picci, Ott, Petro, et al., 2023; Pulliam et al., 2024; Taylor et al., 2021). Increased pubertal testosterone and DHEA have also been shown to be drivers of developmental shifts in both alpha (Fung et al., 2020; Penhale et al., 2022) and beta activity (Fung et al., 2022; Killanin et al., 2023; Penhale et al., 2022; Picci, Ott, Penhale, et al., 2023). The current results corroborate and extend this extant literature by linking other aspects of pubertal development (i.e., perceived stage) to alterations in alpha and beta, irrespective of age. Interestingly, weaker alpha and beta activity has been linked to increased internalizing problems (Alamian et al., 2017; Calzada-Reyes et al., 2017; Franzen et al., 2013; Newson and Thiagarajan, 2019; Wilson et al., 2011). Taken together, the present results suggest that more mature adolescents who engage in greater levels of social comparison and feedback seeking on social media may deviate from this typical trajectory, which may underlie increased risk for emerging internalizing symptoms and attention problems.

The effect in the beta band spanned a large portion of the prefrontal cortex and peaked in a dorsal portion of the medial prefrontal cortex (PFC). Across species, structural and functional features of the medial PFC continue to be shaped during puberty (Delevich et al., 2021; Juraska, 2024), suggesting targeted effects of pubertal processes (e.g., hormones) on this particular region (Vijayakumar et al., 2018). This also replicates prior MEG findings showing sex steroid effects on beta activity at rest in youth, which are also pronounced in the PFC (Picci, Ott, Penhale, et al., 2023). The medial PFC is a part of the default mode network (Shulman et al., 1997), and has consistently been implicated in mentalizing processes (Andrews-Hanna, 2012; Van Overwalle, 2008), which undergo marked refinement during adolescence (Blakemore, 2008). Of relevance to the current study, the medial PFC is reliably active across a variety tasks requiring the inference of others' intentions (Ochsner et al., 2005; Schurz et al., 2014, 2021), pointing to its critical role in social cognition (Amodio and Frith, 2006; Denny et al., 2012; Frith and Frith, 2006). Furthermore, there is growing evidence that activation of this region during mentalizing tasks strengthens during adolescence into adulthood (Fehlbaum et al., 2022; Overgaauw et al., 2015). In the context of this literature, our results suggest that engaging in elevated levels of SCFS behaviors on social media during specific stages of puberty may be associated with altered neural activity in regions integral to the social and cognitive skills that are known to develop during adolescence (Blakemore, 2008; Crone and Steinbeis, 2017). Thus, while social media in and of itself may not be harmful, it may create contexts during puberty that amplify the risk for negative social comparison behaviors that are known to exacerbate mental health symptoms during adolescence (Nesi and Prinstein, 2015). However, this interpretation should be followed up with work examining whether task-based neurophysiological activity in this circuitry is related to such patterns of social media use.

Similarly, spontaneous alpha activity observed in the fusiform and parahippocampal regions has been linked to complex social cognition and implicated in prior social media use studies. Both regions are integral to lower (i.e., visuoperceptual) and higher-order aspects of social cognition (Aminoff et al., 2013; Gobbini and Haxby, 2007; Haxby et al., 2002; Kanwisher and Yovel, 2006; Kveraga et al., 2011) and continue to develop well into adolescence (Golarai et al., 2010; Haist and Anzures, 2017; Moore et al., 2012). Prior literature has linked activation and connectivity patterns in these regions with aspects of social media use in teens (Sherman, Hernandez, et al., 2018; Zou et al., 2022). Specifically, increased activity in fusiform and parahippocampal gyrus has been reported when adolescents provided "likes" for photos in an Instagram-like interface during an fMRI experiment (Sherman, Hernandez, et al., 2018), suggesting that engagement on social media platforms drives activity in crucial social-affective regions. Moreover, functional connectivity patterns between the parahippocampal gyrus and middle temporal gyrus have been linked to problematic social media use and depressive symptoms in adolescents (Zou et al., 2022). Thus, similar to the effects observed in medial prefrontal beta activity, these alpha effects in the fusiform and parahippoocampal cortices may reflect puberty-related alterations in regions that support complex social cognition and are sensitive to potentially problematic social media use. An alternative possibility is that, given their strong involvement in perceptual processes, engaging in SCFS behaviors on social media may lead to experience driven differences in these brain regions.

Taken together, the social media and puberty-related effects on spontaneous brain activity were generally restricted to high-tier association cortices, rather than low-level sensory regions. This is consistent with the prevailing view and mounting evidence that adolescence is a sensitive period for the development of association cortices (Larsen et al., 2022; Sydnor et al., 2021; Thompson et al., 2001; van Wingen et al., 2011), where pubertal hormones induce increased experience-driven neuroplasticity (Fuhrmann et al., 2015; Kaczkurkin, Raznahan, et al., 2019; Larsen et al., 2022; Larsen and Luna, 2018). While puberty sparks a time of tremendous social and cognitive growth, it also presents a time of increased risk for the development of neuropathology (Kaczkurkin, Park, et al., 2019; McTeague et al., 2017; Sydnor et al., 2021). The current results indicate that the deleterious effects of SCFS are present for adolescents in later stages of puberty. This suggests that the pubertally-driven state of increased neuroplasticity creates an environment in which specific types of social media behavior that increase social comparison may promote additional vulnerabilities for elevated mental health symptoms.

The current results may reflect developmental processes in the activity of cortical interneurons that are essential for adolescent neurodevelopment. Whereas alpha and beta activity typically strengthen from adolescence into adulthood, in the current results, more mature adolescents who exhibited elevated SCFS behaviors showed weaker activity in these frequencies. Importantly, the typically increased dominance of higher alpha and beta frequencies in older adolescents is in part reflective of changes in interneuronal activity within cortical ensembles (McKeon et al., 2024; Voytek et al., 2015). Such changes in the activity of GABA-gated parvalbumin interneurons in particular are a feature of the increased neuroplasticity (Froemke, 2015; Hensch, 2005; Juraska, 2024) that drives pubertal brain development in association cortices as discussed above (Larsen et al., 2022; Sydnor et al., 2021). Moreover, outside the context of development, GABA-gated interneurons are thought to be essential for synchronizing neural ensembles within discrete frequencies (Buzsáki et al., 2012), including cortical alpha (Bollimunta et al., 2008; Karameh et al., 2006), beta (Hall et al., 2010, 2011; Rossiter et al., 2014), and gamma rhythms (Buzsáki and Wang, 2012; Kujala et al., 2015; Muthukumaraswamy et al., 2009). In the context of this literature, the current results suggest that engaging in more SCFS during adolescence may be an influencing factor on at least the timing of the neuroplastic changes that are essential to reaching the typical patterns seen in mature brain functioning.

The effects observed in the brain were accompanied by similar moderating effects of puberty on the relationship between SCFS and symptoms of anxiety and attention problems. These results are comparable to prior literature establishing links between SCFS and mental health in adolescent samples, with the current study contributing pertinent information about puberty-specific effects. That is, existing work has shown that the more adolescents tend to engage in SCFS behaviors, the more internalizing symptoms emerge across time (Nesi and Prinstein, 2015), even in otherwise healthy adolescents. Other work also suggests that elevated SCFS is highly disruptive to youths' self-esteem and emotional health (Martinac Dorčić et al., 2023; Sánchez-Hernández et al., 2021), which could promote the emergence of internalizing symptoms. The literature showing increases in attention problems has mostly focused on amount of social media use and dependence-like behaviors (Boer et al., 2020; Ra et al., 2018). Thus, our results build upon the literature by underscoring that puberty, controlling for age, provides additional contextualization of the developmental factors that could contribute to detrimental social media use behaviors. That is, we show that adolescents in the later stages of puberty engaging in more SCFS behaviors are at the greatest risk of having anxiety symptoms and attention problems. This is in agreement with extensive work, as it is known that adolescents in more advanced stages of puberty are especially sensitive to social evaluative feedback (Sumter et al., 2010; van den Bos et al., 2014); this sensitivity, coupled with greater SCFS tendencies, could put more mature youth at risk of developing corresponding mental health symptoms. Indeed, many major mental health disorders emerge during late adolescence and emerging adulthood (Solmi et al., 2022). While we also expected depression symptoms to have interactive effects with puberty on elevated SCFS behaviors, it may be that the timing of our assessment was a limiting factor. That is, while our sample was otherwise healthy, it is important to consider that the emergence of depressive disorders tends to occur much later (~19.5 years old) than anxiety (14–15 years old) and attention-related disorders (~9.5 years old; Solmi et al., 2022). Altogether, these behavioral findings provide a springboard for future work to examine how other pubertal indicators (e.g., hormones) relate to problematic social media use patterns and mental health.

Before closing, several limitations should be considered when interpreting the results. First and foremost, this study is cross-sectional; longitudinal designs would greatly strengthen the developmental conclusions that can be drawn. Along these lines, future studies may seek to use more complex modeling schemes, such as mediation or moderated mediation models. The current study performed moderation models in order to utilize whole brain approaches, given that no analytic toolboxes exist at this time for whole-brain moderated mediation. An exploratory analysis of sex differences (reported in the supplemental materials) pointed to interesting effects in the temporoparietal junction and ventral visual cortex, regions implicated in social cognition (Kastner et al., 2017; Kim et al., 2018) and social perception (Fusar-Poli et al., 2009; Haxby et al., 2002; Kanwisher and Yovel, 2006), respectively. However, caution is warranted as this analysis was exploratory and potentially underpowered given the small sample sizes when the sample was split by sex. Thus, future studies using larger sample-sizes should be pursued, as these would permit the rigorous analysis of potential sex-related differences, which have been observed when examining the effects of social media use on mental health (Orben et al., 2022), and associated with differential risk for internalizing symptoms during puberty more generally (Pfeifer and Allen, 2021). Next, social media use was measured via self-report, which is not an objective measure of use (e.g., recorded directly from the device or application). While subjective measures have their limitations, it should be noted that the present study was especially concerned with youths' perceptions of motivational factors driving their social media use. Nonetheless, future work should measure more nuanced patterns of social media use (e.g., social information processing, use patterns among peer groups, status-seeking behaviors, etc.). In addition, the current study focused only on SCFS behaviors, a particularly harmful aspect of social media use. Subsequent studies should attempt to take on a more strengths-based approach to other aspects of social media use, including those that may be beneficial to social development and potentially combat damaging effects of social media; such work is essential for future interventions. Lastly, the extent to which brain activity during resting conditions can be tied to task-based activity is limited. Thus, future studies should test if these results extend to task-based findings, including those directly testing attention and social cognition, and in paradigms with high ecological validity for social media use.

In sum, the current study found that adolescents in later pubertal stages who endorsed a higher amount of SCFS reported more symptoms of anxiety and attention problems and exhibited alpha and beta cortical activity counter to typical developmental patterns reported in the literature. Consistent with extant literature, these findings point to a potentially disadvantageous effect of specific types of social media use on neural circuitry known to support social-affective processing, which is also known to undergo a protracted developmental course that stretches well into adolescence (i.e., fusiform, medial prefrontal cortex). Thus, this work suggests that youth within specific stages of pubertal development may be most sensitive to the deleterious effects of social media use. The nature of youths' engagement with social media platforms constitutes an environmental risk factor that could influence the pathways away from expected patterns of brain development and confer increased mental health risks.

Funding acknowledgments

This study was supported by the National Institutes of Health through grants R01-MH121101 (TWW), P20-GM144641 (TWW, GP), S10-OD028751 (TWW), F31-DA056296 (MS), F30-MH134713 (JJS), and F30-MH130150 (ADK). The funders had no role in the study design, collection, analysis, or interpretation of data, nor did they influence writing the report or the decision to submit this work for publication.

CRediT authorship contribution statement

Grace C. Ende: Writing – review & editing, Investigation, Data curation. **Danielle L. Rice:** Writing – review & editing, Investigation, Data curation. **Abraham D. Killanin:** Writing – review & editing, Methodology. **Cooper L. Livermore:** Writing – review & editing, Methodology. **Kellen McDonald:** Writing – review & editing, Methodology. **Thomas W. Ward:** Writing – review & editing, Methodology. **Jake J. Son:** Writing – review & editing, Methodology, Data curation. **Mikki Schantell:** Writing – review & editing, Methodology, Data curation. **Tony W. Wilson:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Lauren K. Webert:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Erica Steiner:** Investigation, Data curation. **Giorgia Picci:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Anna T. Coutant:** Writing – review & editing, Investigation, Data curation. **Nathan Martin Petro:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2024.101479.

Data availability

Data will be made available on request.

References

Achterberg, M., Becht, A., van der Cruijsen, R., van de Groep, I.H., Spaans, J.P., Klapwijk, E., Crone, E.A., 2022. Longitudinal associations between social media use, mental well-being and structural brain development across adolescence. Dev. Cogn. Neurosci. 54, 101088. https://doi.org/10.1016/j.dcn.2022.101088.

Áfra, E., Janszky, J., Perlaki, G., Orsi, G., Nagy, S.A., Arató, Á., Szente, A., Alhour, H.A. M., Kis-Jakab, G., Darnai, G., 2024. Altered functional brain networks in problematic smartphone and social media use: Resting-state fMRI study. Brain Imaging Behav. 18 (2), 292–301. https://doi.org/10.1007/s11682-023-00825-y.

Alamian, G., Hincapié, A.-S., Combrisson, E., Thiery, T., Martel, V., Althukov, D., Jerbi, K., 2017. Alterations of intrinsic brain connectivity patterns in depression and bipolar disorders: a critical assessment of magnetoencephalography-based evidence. Front. Psychiatry 8. https://doi.org/10.3389/fpsyt.2017.00041.

Aminoff, E.M., Kveraga, K., Bar, M., 2013. The role of the parahippocampal cortex in cognition. Trends Cogn. Sci. 17 (8), 379–390. https://doi.org/10.1016/j.tics.2013.06.009.

Amodio, D.M., Frith, C.D., 2006. Meeting of minds: the medial frontal cortex and social cognition. Nat. Rev. Neurosci. 7 (4), 268–277. https://doi.org/10.1038/nrn1884.

Anderson, M., & Jiang, J. (2018). Teens, social media & technology 2018 (United States of America) [Report]. Pew Research Center. ⟨https://apo.org.au/node/175701⟩.

Andrews-Hanna, J.R., 2012. The Brain's Default Network and its Adaptive Role in Internal Mentation. Neurosci.: A Rev. J. Bringing Neurobiol., Neurol. Psychiatry 18 (3), 251–270. https://doi.org/10.1177/1073858411403316.

Ashburner, J., Friston, K.J., 2005. Unified segmentation. NeuroImage 26 (3), 839–851. https://doi.org/10.1016/j.neuroimage.2005.02.018.

Baillet, S., 2017. Magnetoencephalography for brain electrophysiology and imaging. Nat. Neurosci. 20 (3), 327–339. https://doi.org/10.1038/nn.4504.

Barry, C.T., Sidoti, C.L., Briggs, S.M., Reiter, S.R., Lindsey, R.A., 2017. Adolescent social media use and mental health from adolescent and parent perspectives. J. Adolesc. 61 (1), 1–11. https://doi.org/10.1016/j.adolescence.2017.08.005.

Blakemore, S.-J., 2008. The social brain in adolescence. Nat. Rev. Neurosci. 9 (4), 267–277. https://doi.org/10.1038/nrn2353.

Boer, M., Stevens, G., Finkenauer, C., van den Eijnden, R., 2020. Attention deficit hyperactivity disorder-symptoms, social media use intensity, and social media use problems in adolescents: investigating directionality. Child Dev. 91 (4), e853–e865. https://doi.org/10.1111/cdev.13334.

Bollimunta, A., Chen, Y., Schroeder, C.E., Ding, M., 2008. Neuronal mechanisms of cortical alpha oscillations in awake-behaving macaques. J. Neurosci. 28 (40), 9976–9988. https://doi.org/10.1523/JNEUROSCI.2699-08.2008.

Brunborg, G.S., Andreas, J.B., Kvaavik, E., 2017. Social media use and episodic heavy drinking among adolescents. Psychol. Rep. 120 (3), 475–490. https://doi.org/10.1177/0033294117697090.

Buzsáki, G., Anastassiou, C.A., Koch, C., 2012. The origin of extracellular fields and currents—EEG, ECoG, LFP and spikes. Article 6. Nat. Rev. Neurosci. 13 (6). https://doi.org/10.1038/nrn3241.

Buzsáki, G., Wang, X.-J., 2012. Mechanisms of gamma oscillations. Annu. Rev. Neurosci. 35 (1), 203–225. https://doi.org/10.1146/annurev-neuro-062111-150444.

Calzada-Reyes, A., Alvarez-Amador, A., Galán-García, L., Valdés-Sosa, M., 2017. QEEG and LORETA in teenagers with conduct disorder and psychopathic traits. Clin. EEG Neurosci. 48 (3), 189–199. https://doi.org/10.1177/1550059416645712.

Campagnoli, R.R., Wieser, M.J., Gruss, L.F., McTeague, L.M., Boylan, M.R., Keil, A., 2019. How the visual brain detects emotional changes in facial expressions: evidence from driven and intrinsic brain oscillations. Cortex; a J. Devoted Study Nerv. Syst. Behav. 111, 35–50. https://doi.org/10.1016/j.cortex.2018.10.006.

Canivez, G.L., von der Embse, N.P., McGill, R.J., 2021. Construct validity of the BASC-3 teacher rating scales: independent hierarchical exploratory factor analyses with the normative sample. Sch. Psychol. 36 (4), 235–254. https://doi.org/10.1037/spq0000444.

Chou, H.-T.G., Edge, N., 2012. They are happier and having better lives than i am": the impact of using facebook on perceptions of others' lives. Cyber, Behav., Soc. Netw. 15 (2), 117–121. https://doi.org/10.1089/cyber.2011.0324.

Cohen, M.X., 2017. Where Does EEG come from and what does it mean? Trends Neurosci. 40 (4), 208–218. https://doi.org/10.1016/j.tins.2017.02.004.

Crone, E.A., Dahl, R.E., 2012. Understanding adolescence as a period of social–affective engagement and goal flexibility. Article 9. Nat. Rev. Neurosci. 13 (9). https://doi.org/10.1038/nrn3313.

Crone, E.A., Steinbeis, N., 2017. Neural perspectives on cognitive control development during childhood and adolescence. Trends Cogn. Sci. 21 (3), 205–215. https://doi.org/10.1016/j.tics.2017.01.003.

Dai, J., Scherf, K.S., 2019. Puberty and functional brain development in humans: convergence in findings? Dev. Cogn. Neurosci. 39, 100690. https://doi.org/10.1016/j.dcn.2019.100690.

Dehestani, N., Whittle, S., Vijayakumar, N., Silk, T.J., 2023. Developmental brain changes during puberty and associations with mental health problems. Dev. Cogn. Neurosci. 60, 101227. https://doi.org/10.1016/j.dcn.2023.101227.

Delevich, K., Klinger, M., Okada, N.J., Wilbrecht, L., 2021. Coming of age in the frontal cortex: the role of puberty in cortical maturation. Semin. Cell Dev. Biol. 118, 64–72. https://doi.org/10.1016/j.semcdb.2021.04.021.

Denny, B.T., Kober, H., Wager, T.D., Ochsner, K.N., 2012. A meta-analysis of functional neuroimaging studies of self and other judgments reveals a spatial gradient for mentalizing in medial prefrontal cortex. J. Cogn. Neurosci. 24 (8), 1742–1752. https://doi.org/10.1162/jocn_a_00233.

Doval, S., López-Sanz, D., Bruña, R., Cuesta, P., Antón-Toro, L., Taguas, I., Torres-Simón, L., Chino, B., Maestú, F., 2024. When maturation is not linear: brain oscillatory activity in the process of aging as measured by electrophysiology. Brain Topogr. https://doi.org/10.1007/s10548-024-01064-0.

Edden, R.A.E., Muthukumaraswamy, S.D., Freeman, T.C.A., Singh, K.D., 2009. Orientation discrimination performance is predicted by gaba concentration and gamma oscillation frequency in human primary visual cortex. J. Neurosci. 29 (50), 15721–15726. https://doi.org/10.1523/JNEUROSCI.4426-09.2009.

Embury, C.M., Wiesman, A.I., Proskovec, A.L., Mills, M., Heinrichs-Graham, E., Wang, Y.-P., Calhoun, V.D., Stephen, J.M., Wilson, T.W., 2019. Neural dynamics of verbal working memory processing in children and adolescents. NeuroImage 185, 191–197. https://doi.org/10.1016/j.neuroimage.2018.10.038.

Engel, A.K., Fries, P., 2010. Beta-band oscillations—signalling the status quo? Article 2. Curr. Opin. Neurobiol. 20 (2). https://doi.org/10.1016/j.conb.2010.02.015.

Fassi, L., Thomas, K., Parry, D.A., Leyland-Craggs, A., Ford, T.J., Orben, A., 2024. SociAl Media Use and Internalizing Symptoms in Clinical and Community Adolescent Samples: A Systematic Review and Meta-analysis. JAMA Pediatr. https://doi.org/10.1001/jamapediatrics.2024.2078.

Fehlbaum, L.V., Borbás, R., Paul, K., Eickhoff, S.B., Raschle, N.M., 2022. Early and late neural correlates of mentalizing: ALE meta-analyses in adults, children and adolescents. Soc. Cogn. Affect. Neurosci. 17 (4), 351–366. https://doi.org/10.1093/scan/nsab105.

Feinstein, B.A., Hershenberg, R., Bhatia, V., Latack, J.A., Meuwly, N., Davila, J., 2013. Negative social comparison on Facebook and depressive symptoms: rumination as a mechanism. Psychol. Pop. Media Cult. 2 (3), 161–170. https://doi.org/10.1037/a0033111.

Flint, A.C., Connors, B.W., 1996. Two types of network oscillations in neocortex mediated by distinct glutamate receptor subtypes and neuronal populations. J. Neurophysiol. 75 (2), 951–957. https://doi.org/10.1152/jn.1996.75.2.951.

Fonov, V., Evans, A., McKinstry, R., Almli, C., Collins, D., 2009. Unbiased nonlinear average age-appropriate brain templates from birth to adulthood. NeuroImage 47, S102. https://doi.org/10.1016/S1053-8119(09)70884-5.

Fors, P.Q., Barch, D.M., 2019. Differential relationships of child anxiety and depression to child report and parent report of electronic media use. Child Psychiatry Hum. Dev. 50 (6), 907–917. https://doi.org/10.1007/s10578-019-00892-7.

Franzen, J., Heinrichs-Graham, E., White, M., Wetzel, M., Knott, N., Wilson, T., 2013. Atypical coupling between posterior regions of the default mode network in attention-deficit/hyperactivity disorder: a pharmaco-magnetoencephalography study. J. Psychiatry Neurosci. 38 (5), 333–340. https://doi.org/10.1503/jpn.120054.

Frith, C.D., Frith, U., 2006. The neural basis of mentalizing. Neuron 50 (4), 531–534. https://doi.org/10.1016/j.neuron.2006.05.001.

Froemke, R.C., 2015. Plasticity of cortical excitatory-inhibitory balance. Annu. Rev. Neurosci. 38, 195–219. https://doi.org/10.1146/annurev-neuro-071714-034002.

Fuhrmann, D., Knoll, L.J., Blakemore, S.-J., 2015. Adolescence as a sensitive period of brain development. Trends Cogn. Sci. 19 (10), 558–566. https://doi.org/10.1016/j.tics.2015.07.008.

Fung, M.H., Heinrichs-Graham, E., Taylor, B.K., Frenzel, M.R., Eastman, J.A., Wang, Y.-P., Calhoun, V.D., Stephen, J.M., Wilson, T.W., 2022. The development of sensorimotor cortical oscillations is mediated by pubertal testosterone. NeuroImage 264, 119745. https://doi.org/10.1016/j.neuroimage.2022.119745.

Fung, M.H., Taylor, B.K., Frenzel, M.R., Eastman, J.A., Wang, Y.-P., Calhoun, V.D., Stephen, J.M., Wilson, T.W., 2020. Pubertal testosterone tracks the developmental trajectory of neural oscillatory activity serving visuospatial processing. Cereb. Cortex 30 (11), 5960–5971. https://doi.org/10.1093/cercor/bhaa169.

Fusar-Poli, P., Placentino, A., Carletti, F., Landi, P., Allen, P., Surguladze, S., Benedetti, F., Abbamonte, M., Gasparotti, R., Barale, F., Perez, J., McGuire, P., Politi, P., 2009. Functional atlas of emotional faces processing: a voxel-based meta-analysis of 105 functional magnetic resonance imaging studies. J. Psychiatry Neurosci. 34 (6), 418–432.

Gaser, C., & Dahnke, R. (2016). CAT - A Computational Anatomy Toolbox for the Analysis of Structural MRI Data. 1.

Gobbini, M.I., Haxby, J.V., 2007. Neural systems for recognition of familiar faces. Neuropsychologia 45 (1), 32–41. https://doi.org/10.1016/j.neuropsychologia.2006.04.015.

Goddings, A.-L., Beltz, A., Peper, J.S., Crone, E.A., Braams, B.R., 2019. Understanding the role of puberty in structural and functional development of the adolescent brain. J. Res. Adolesc. 29 (1), 32–53. https://doi.org/10.1111/jora.12408.

Golarai, G., Liberman, A., Yoon, J.M., Grill-Spector, K., 2010. Differential development of the ventral visual cortex extends through adolescence. Front. Hum. Neurosci. 3. https://doi.org/10.3389/neuro.09.080.2009.

Gómez, C., Pérez-Macías, J.M., Poza, J., Fernández, A., Hornero, R., 2013. Spectral changes in spontaneous MEG activity across the lifespan. Article 6. J. Neural Eng. 10 (6). https://doi.org/10.1088/1741-2560/10/6/066006.

Gruenenfelder-Steiger, A.E., Harris, M.A., Fend, H.A., 2016. Subjective and objective peer approval evaluations and self-esteem development: a test of reciprocal,

prospective, and long-term effects. Dev. Psychol. 52 (10), 1563–1577. https://doi.org/10.1037/dev0000147.
Güntekin, B., Başar, E., 2014. A review of brain oscillations in perception of faces and emotional pictures. Neuropsychologia 58, 33–51. https://doi.org/10.1016/j.neuropsychologia.2014.03.014.
Haist, F., Anzures, G., 2017. Functional development of the brain's face-processing system. WIREs Cogn. Sci. 8 (1–2), e1423. https://doi.org/10.1002/wcs.1423.
Hall, S.D., Barnes, G.R., Furlong, P.L., Seri, S., Hillebrand, A., 2010. Neuronal network pharmacodynamics of GABAergic modulation in the human cortex determined using pharmaco-magnetoencephalography. Hum. Brain Mapp. 31 (4), 581–594. https://doi.org/10.1002/hbm.20889.
Hall, S.D., Stanford, I.M., Yamawaki, N., McAllister, C.J., Rönnqvist, K.C., Woodhall, G. L., Furlong, P.L., 2011. The role of GABAergic modulation in motor function related neuronal network activity. NeuroImage 56 (3), 1506–1510. https://doi.org/10.1016/j.neuroimage.2011.02.025.
Hardy, S., Roberts, G., Ventresca, M., Dunkley, B.T., 2024. Predicting brain age across the adult lifespan with spontaneous oscillations and functional coupling in resting brain networks captured with magnetoencephalography. Imaging Neurosci. 2, 1–17. https://doi.org/10.1162/imag_a_00195.
Haxby, J.V., Hoffman, E.A., Gobbini, M.I., 2002. Human neural systems for face recognition and social communication. Biol. Psychiatry 51 (1), 59–67. https://doi.org/10.1016/S0006-3223(01)01330-0.
He, Q., Turel, O., Brevers, D., Bechara, A., 2017. Excess social media use in normal populations is associated with amygdala-striatal but not with prefrontal morphology. Psychiatry Res.: Neuroimaging 269, 31–35. https://doi.org/10.1016/j.pscychresns.2017.09.003.
Heinrichs-Graham, E., McDermott, T.J., Mills, M.S., Wiesman, A.I., Wang, Y.-P., Stephen, J.M., Calhoun, V.D., Wilson, T.W., 2018. The lifespan trajectory of neural oscillatory activity in the motor system. Dev. Cogn. Neurosci. 30, 159–168. https://doi.org/10.1016/j.dcn.2018.02.013.
Hensch, T.K., 2005. Critical period plasticity in local cortical circuits. Nat. Rev. Neurosci. 6 (11), 877–888. https://doi.org/10.1038/nrn1787.
Hill, D., Ameenuddin, N., Chassiakos, Y.L.R., Cross, C., Radesky, J., Hutchinson, J., Swanson, W.S., 2016. Media use in school-aged children and adolescents. Pediatrics 138 (5).
Hong, S.-B., Zalesky, A., Cocchi, L., Fornito, A., Choi, E.-J., Kim, H.-H., Suh, J.-E., Kim, C.-D., Kim, J.-W., Yi, S.-H., 2013. Decreased functional brain connectivity in adolescents with internet addiction. PloS One 8 (2), e57831. https://doi.org/10.1371/journal.pone.0057831.
Hoshi, H., Shigihara, Y., 2020. Age- and gender-specific characteristics of the resting-state brain activity: a magnetoencephalography study. Aging 12 (21), 21613–21637. https://doi.org/10.18632/aging.103956.
Huang, M.X., Mosher, J.C., Leahy, R.M., 1999. A sensor-weighted overlapping-sphere head model and exhaustive head model comparison for MEG. Phys. Med. Biol. 44 (2), 423–440. https://doi.org/10.1088/0031-9155/44/2/010.
Ille, N., Berg, P., Scherg, M., 2002. Artifact correction of the ongoing EEG using spatial filters based on artifact and brain signal topographies. J. Clin. Neurophysiol. 19 (2), 113–124. https://doi.org/10.1097/00004691-200203000-00002.
Juraska, J.M., 2024. The last stage of development: the restructuring and plasticity of the cortex during adolescence especially at puberty. Dev. Psychobiol. 66 (2), e22468. https://doi.org/10.1002/dev.22468.
Kaczkurkin, A.N., Park, S.S., Sotiras, A., Moore, T.M., Calkins, M.E., Cieslak, M., Rosen, A.F.G., Ciric, R., Xia, C.H., Cui, Z., Sharma, A., Wolf, D.H., Ruparel, K., Pine, D.S., Shinohara, R.T., Roalf, D.R., Gur, R.C., Davatzikos, C., Gur, R.E., Satterthwaite, T.D., 2019. Evidence for dissociable linkage of dimensions of psychopathology to brain structure in youths. Am. J. Psychiatry 176 (12), 1000–1009. https://doi.org/10.1176/appi.ajp.2019.18070835.
Kaczkurkin, A.N., Raznahan, A., Satterthwaite, T.D., 2019. Sex differences in the developing brain: Insights from multimodal neuroimaging. Neuropsychopharmacol.: Off. Publ. Am. Coll. Neuropsychopharmacol. 44 (1), 71–85. https://doi.org/10.1038/s41386-018-0111-z.
Kanwisher, N., Yovel, G., 2006. The fusiform face area: a cortical region specialized for the perception of faces. Philos. Trans. R. Soc. B: Biol. Sci. 361 (1476), 2109–2128. https://doi.org/10.1098/rstb.2006.1934.
Karameh, F.N., Dahleh, M.A., Brown, E.N., Massaquoi, S.G., 2006. Modeling the contribution of lamina 5 neuronal and network dynamics to low frequency EEG phenomena. Biol. Cybern. 95 (4), 289–310. https://doi.org/10.1007/s00422-006-0090-8.
Kastner, S., Chen, Q., Jeong, S.K., Mruczek, R.E.B., 2017. A brief comparative review of primate posterior parietal cortex: A novel hypothesis on the human toolmaker. Neuropsychologia 105, 123–134. https://doi.org/10.1016/j.neuropsychologia.2017.01.034.
Kaur, N., Rutherford, C.G., Martins, S.S., Keyes, K.M., 2020. Associations between digital technology and substance use among U.S. adolescents: results from the 2018 monitoring the future survey. Drug Alcohol Depend. 213, 108124. https://doi.org/10.1016/j.drugalcdep.2020.108124.
Killanin, A.D., Embury, C.M., Picci, G., Heinrichs-Graham, E., Wang, Y.-P., Calhoun, V. D., Stephen, J.M., Wilson, T.W., 2022. Trauma moderates the development of the oscillatory dynamics serving working memory in a sex-specific manner. Cereb. Cortex (N. Y., NY) 32 (22), 5206–5215. https://doi.org/10.1093/cercor/bhac008.
Killanin, A.D., Taylor, B.K., Embury, C.M., Picci, G., Wang, Y.-P., Calhoun, V.D., Stephen, J.M., Heinrichs-Graham, E., Wilson, T.W., 2023. Testosterone levels mediate the dynamics of motor oscillatory coding and behavior in developing youth. Dev. Cogn. Neurosci. 61, 101257. https://doi.org/10.1016/j.dcn.2023.101257.
Killanin, A.D., Ward, T.W., Embury, C.M., Calhoun, V.D., Wang, Y.-P., Stephen, J.M., Picci, G., Heinrichs-Graham, E., Wilson, T.W., 2024a. Better with age: developmental changes in oscillatory activity during verbal working memory encoding and maintenance. Dev. Cogn. Neurosci. 66, 101354. https://doi.org/10.1016/j.dcn.2024.101354.
Killanin, A.D., Ward, T.W., Embury, C.M., Calhoun, V.D., Wang, Y.-P., Stephen, J.M., Picci, G., Heinrichs-Graham, E., Wilson, T.W., 2024b. Effects of endogenous testosterone on oscillatory activity during verbal working memory in youth. Hum. Brain Mapp. 45 (10), e26774. https://doi.org/10.1002/hbm.26774.
Kim, S.-Y., Shin, J.E., Lee, Y.I., Kim, H., Jo, H.J., Choi, S.-H., 2018. Neural evidence for persistent attentional bias to threats in patients with social anxiety disorder. Soc. Cogn. Affect. Neurosci. 13 (12), 1327–1336. https://doi.org/10.1093/scan/nsy101.
Klimesch, W., 2012. Alpha-band oscillations, attention, and controlled access to stored information. Article 12. Trends Cogn. Sci. 16 (12). https://doi.org/10.1016/j.tics.2012.10.007.
Koopman-Verhoeff, M.E., Gredvig-Ardito, C., Barker, D.H., Saletin, J.M., Carskadon, M. A., 2020. Classifying pubertal development using child and parent report: comparing the pubertal development scales to tanner staging. J. Adolesc. Health 66 (5), 597–602. https://doi.org/10.1016/j.jadohealth.2019.11.308.
Kujala, J., Jung, J., Bouvard, S., Lecaignard, F., Lothe, A., Bouet, R., Ciumas, C., Ryvlin, P., Jerbi, K., 2015. Gamma oscillations in V1 are correlated with GABAA receptor density: a multi-modal MEG and Flumazenil-PET study. Article 1. Sci. Rep. 5 (1). https://doi.org/10.1038/srep16347.
Kveraga, K., Ghuman, A.S., Kassam, K.S., Aminoff, E.A., Hämäläinen, M.S., Chaumon, M., Bar, M., 2011. Early onset of neural synchronization in the contextual associations network. Proc. Natl. Acad. Sci. 108 (8), 3389–3394. https://doi.org/10.1073/pnas.1013760108.
Larsen, B., Cui, Z., Adebimpe, A., Pines, A., Alexander-Bloch, A., Bertolero, M., Calkins, M.E., Gur, R.E., Gur, R.C., Mahadevan, A.S., Moore, T.M., Roalf, D.R., Seidlitz, J., Sydnor, V.J., Wolf, D.H., Satterthwaite, T.D., 2022. A developmental reduction of the excitation:inhibition ratio in association cortex during adolescence. Sci. Adv. 8 (5), eabj8750. https://doi.org/10.1126/sciadv.abj8750.
Larsen, B., Luna, B., 2018. Adolescence as a neurobiological critical period for the development of higher-order cognition. Neurosci. Biobehav. Rev. 94, 179–195. https://doi.org/10.1016/j.neubiorev.2018.09.005.
Li, B., Friston, K.J., Liu, J., Liu, Y., Zhang, G., Cao, F., Su, L., Yao, S., Lu, H., Hu, D., 2014. Impaired frontal-basal ganglia connectivity in adolescents with internet addiction. Sci. Rep. 4 (1), 5027. https://doi.org/10.1038/srep05027.
Lin, F., Zhou, Y., Du, Y., Zhao, Z., Qin, L., Xu, J., Lei, H., 2015. Aberrant corticostriatal functional circuits in adolescents with internet addiction disorder. Front. Hum. Neurosci. 9. ⟨https://www.frontiersin.org/articles/10.3389/fnhum.2015.00356⟩.
Lindberg, S.M., Grabe, S., Hyde, J.S., 2007. Gender, pubertal development, and peer sexual harassment predict objectified body consciousness in early adolescence. J. Res. Adolesc. 17 (4), 723–742. https://doi.org/10.1111/j.1532-7795.2007.00544.x.
Luijten, C.C., Van De Bongardt, D., Nieboer, A.P., 2022. The roles of social media use and friendship quality in adolescents' internalizing problems and well-being. J. Happiness Stud. 23 (7), 3161–3178. https://doi.org/10.1007/s10902-022-00539-w.
Lund, L., Sølvhøj, I.N., Danielsen, D., Andersen, S., 2021. Electronic media use and sleep in children and adolescents in western countries: a systematic review. BMC Public Health 21 (1), 1598. https://doi.org/10.1186/s12889-021-11640-9.
Lundqvist, M., Miller, E.K., Nordmark, J., Liljefors, J., Herman, P., 2024. Beta: bursts of cognition. Trends Cogn. Sci. 28 (7), 662–676. https://doi.org/10.1016/j.tics.2024.03.010.
Manjón, J.V., Coupé, P., Martí-Bonmatí, L., Collins, D.L., Robles, M., 2010. Adaptive non-local means denoising of MR images with spatially varying noise levels. Article 1. J. Magn. Reson. Imaging 31 (1). https://doi.org/10.1002/jmri.22003.
Martinac Dorčić, T., Smojver-Ažić, S., Božić, I., Malkoč, I., 2023. Effects of social media social comparisons and identity processes on body image satisfaction in late adolescence. Eur. 'S. J. Psychol. 19 (2), 220–231. https://doi.org/10.5964/ejop.9885.
McKeon, S.D., Perica, M.I., Parr, A.C., Calabro, F.J., Foran, W., Hetherington, H., Moon, C.-H., Luna, B., 2024. Aperiodic EEG and 7T MRSI evidence for maturation of E/I balance supporting the development of working memory through adolescence. Dev. Cogn. Neurosci. 66, 101373. https://doi.org/10.1016/j.dcn.2024.101373.
McTeague, L.M., Huemer, J., Carreon, D.M., Jiang, Y., Eickhoff, S.B., Etkin, A., 2017. Identification of common neural circuit disruptions in cognitive control across psychiatric disorders. Am. J. Psychiatry 174 (7), 676–685. https://doi.org/10.1176/appi.ajp.2017.16040400.
Meeus, A., Beullens, K., Eggermont, S., 2019. Like me (please?): connecting online self-presentation to pre- and early adolescents' self-esteem. N. Media Soc. 21 (11–12), 2386–2403. https://doi.org/10.1177/1461444819847447.
Moore, W.E., Pfeifer, J.H., Masten, C.L., Mazziotta, J.C., Iacoboni, M., Dapretto, M., 2012. Facing puberty: Associations between pubertal development and neural responses to affective facial displays. Soc. Cogn. Affect. Neurosci. 7 (1), 35–43. https://doi.org/10.1093/scan/nsr066.
Moroney, E., Lee, S.S., Ebbert, A.M., Luthar, S.S., 2023. Digital media use frequency, online behaviors, and risk for negative mental health in adolescents in high-achieving schools. Clin. Child Psychol. Psychiatry 28 (1), 237–254. https://doi.org/10.1177/13591045221108834.
Mountcastle, V.B. (1998). Perceptual Neuroscience. Harvard University Press.
Muthukumaraswamy, S.D., Edden, R.A.E., Jones, D.K., Swettenham, J.B., Singh, K.D., 2009. Resting GABA concentration predicts peak gamma frequency and fMRI amplitude in response to visual stimulation in humans. Proc. Natl. Acad. Sci. 106 (20), 8356–8361. https://doi.org/10.1073/pnas.0900728106.
Nagata, J.M., Cortez, C.A., Cattle, C.J., Ganson, K.T., Iyer, P., Bibbins-Domingo, K., Baker, F.C., 2022. Screen time use among US adolescents during the COVID-19

pandemic. JAMA Pediatr. 176 (1), 94–96. https://doi.org/10.1001/jamapediatrics.2021.4334.
Nelson, E.E., Jarcho, J.M., Guyer, A.E., 2016. Social re-orientation and brain development: an expanded and updated view. Dev. Cogn. Neurosci. 17, 118–127. https://doi.org/10.1016/j.dcn.2015.12.008.
Nelson, E.E., Leibenluft, E., McClure, E.B., Pine, D.S., 2005. The social re-orientation of adolescence: a neuroscience perspective on the process and its relation to psychopathology. Psychol. Med. 35 (2), 163–174. https://doi.org/10.1017/s0033291704003915.
Nesi, J., Choukas-Bradley, S., Prinstein, M.J., 2018. Transformation of adolescent peer relations in the social media context: part 1-A theoretical framework and application to dyadic peer relationships. Clin. Child Fam. Psychol. Rev. 21 (3), 267–294. https://doi.org/10.1007/s10567-018-0261-x.
Nesi, J., Prinstein, M.J., 2015. Using social media for social comparison and feedback-seeking: gender and popularity moderate associations with depressive symptoms. J. Abnorm. Child Psychol. 43 (8), 1427–1438. https://doi.org/10.1007/s10802-015-0020-0.
Newson, J.J., Thiagarajan, T.C., 2019. EEG frequency bands in psychiatric disorders: a review of resting state studies. Front. Hum. Neurosci. 12. ⟨https://www.frontiersin.org/articles/10.3389/fnhum.2018.00521⟩.
Ochsner, K.N., Beer, J.S., Robertson, E.R., Cooper, J.C., Gabrieli, J.D.E., Kihsltrom, J.F., D'Esposito, M., 2005. The neural correlates of direct and reflected self-knowledge. NeuroImage 28 (4), 797–814. https://doi.org/10.1016/j.neuroimage.2005.06.069.
Orben, A., Przybylski, A.K., Blakemore, S.-J., Kievit, R.A., 2022. Windows of developmental sensitivity to social media. Article 1. Nat. Commun. 13 (1). https://doi.org/10.1038/s41467-022-29296-3.
Ott, L.R., Penhale, S.H., Taylor, B.K., Lew, B.J., Wang, Y.-P., Calhoun, V.D., Stephen, J. M., Wilson, T.W., 2021. Spontaneous cortical MEG activity undergoes unique age- and sex-related changes during the transition to adolescence. NeuroImage 244, 118552. https://doi.org/10.1016/j.neuroimage.2021.118552.
Overgaauw, S., van Duijvenvoorde, A.C.K., Gunther Moor, B., Crone, E.A., 2015. A longitudinal analysis of neural regions involved in reading the mind in the eyes. Soc. Cogn. Affect. Neurosci. 10 (5), 619–627. https://doi.org/10.1093/scan/nsu095.
Paulus, M.P., Squeglia, L.M., Bagot, K., Jacobus, J., Kuplicki, R., Breslin, F.J., Bodurka, J., Morris, A.S., Thompson, W.K., Bartsch, H., Tapert, S.F., 2019. Screen media activity and brain structure in youth: Evidence for diverse structural correlation networks from the ABCD study. NeuroImage 185, 140–153. https://doi.org/10.1016/j.neuroimage.2018.10.040.
Penhale, S.H., Picci, G., Ott, L.R., Taylor, B.K., Frenzel, M.R., Eastman, J.A., Wang, Y.-P., Calhoun, V.D., Stephen, J.M., Wilson, T.W., 2022. Impacts of adrenarcheal DHEA levels on spontaneous cortical activity during development. Dev. Cogn. Neurosci. 57, 101153. https://doi.org/10.1016/j.dcn.2022.101153.
Petersen, A.C., Crockett, L., Richards, M., Boxer, A., 1988. A self-report measure of pubertal status: Reliability, validity, and initial norms. J. Youth Adolesc. 17 (2), 117–133. https://doi.org/10.1007/BF01537962.
Petro, N.M., Ott, L.R., Penhale, S.H., Rempe, M.P., Embury, C.M., Picci, G., Wang, Y.-P., Stephen, J.M., Calhoun, V.D., Wilson, T.W., 2022. Eyes-closed versus eyes-open differences in spontaneous neural dynamics during development. NeuroImage 258, 119337. https://doi.org/10.1016/j.neuroimage.2022.119337.
Pfeifer, J.H., Allen, N.B., 2021. Puberty initiates cascading relationships between neurodevelopmental, social, and internalizing processes across adolescence. Biol. Psychiatry 89 (2), 99–108. https://doi.org/10.1016/j.biopsych.2020.09.002.
Pfeifer, J.H., Kahn, L.E., Merchant, J.S., Peake, S.J., Veroude, K., Masten, C.L., Lieberman, M.D., Mazziotta, J.C., Dapretto, M., 2013. Longitudinal change in the neural bases of adolescent social self-evaluations: effects of age and pubertal development. J. Neurosci. 33 (17), 7415–7419. https://doi.org/10.1523/JNEUROSCI.4074-12.2013.
Picci, G., Ott, L.R., Penhale, S.H., Taylor, B.K., Johnson, H.J., Willett, M.P., Okelberry, H. J., Wang, Y.-P., Calhoun, V.D., Stephen, J.M., Wilson, T.W., 2023. Developmental changes in endogenous testosterone have sexually-dimorphic effects on spontaneous cortical dynamics. Hum. Brain Mapp. 44 (17), 6043–6054. https://doi.org/10.1002/hbm.26496.
Picci, G., Ott, L.R., Petro, N.M., Casagrande, C.C., Killanin, A.D., Rice, D.L., Coutant, A.T., Arif, Y., Embury, C.M., Okelberry, H.J., Johnson, H.J., Springer, S.D., Pulliam, H.R., Wang, Y.-P., Calhoun, V.D., Stephen, J.M., Heinrichs-Graham, E., Taylor, B.K., Wilson, T.W., 2023. Developmental alterations in the neural oscillatory dynamics underlying attentional reorienting. Dev. Cogn. Neurosci. 63, 101288. https://doi.org/10.1016/j.dcn.2023.101288.
Picci, G., Scherf, K.S., 2016. From caregivers to peers: puberty shapes human face perception. Psychol. Sci. 27 (11), 1461–1473. https://doi.org/10.1177/0956797616663142.
Pulliam, H.R., Springer, S.D., Rice, D.L., Ende, G.C., Johnson, H.J., Willett, M.P., Wilson, T.W., Taylor, B.K., 2024. Neurotoxic effects of home radon exposure on oscillatory dynamics serving attentional orienting in children and adolescents. NeuroImage 292, 120606. https://doi.org/10.1016/j.neuroimage.2024.120606.
Ra, C.K., Cho, J., Stone, M.D., De La Cerda, J., Goldenson, N.I., Moroney, E., Tung, I., Lee, S.S., Leventhal, A.M., 2018. Association of digital media use with subsequent symptoms of attention-deficit/hyperactivity disorder among adolescents. JAMA 320 (3), 255–263. https://doi.org/10.1001/jama.2018.8931.
Rajapakse, J.C., Giedd, J.N., Rapoport, J.L., 1997. Statistical approach to segmentation of single-channel cerebral MR images. IEEE Trans. Med. Imaging 16 (2), 176–186. https://doi.org/10.1109/42.563663.
Rempe, M.P., Ott, L.R., Picci, G., Penhale, S.H., Christopher-Hayes, N.J., Lew, B.J., Petro, N.M., Embury, C.M., Schantell, M., Johnson, H.J., Okelberry, H.J., Losh, K.L., Willett, M.P., Losh, R.A., Wang, Y.-P., Calhoun, V.D., Stephen, J.M., Heinrichs-Graham, E., Kurz, M.J., Wilson, T.W., 2023. Spontaneous cortical dynamics from the first years to the golden years. Proc. Natl. Acad. Sci. 120 (4), e2212776120. https://doi.org/10.1073/pnas.2212776120.
Reynolds, C.R., & Kamphaus, R.W. (2015). Behavior assessment for children: Third edition. (BASC-3). Pearson.
Robinson, S.E., 2004. Localization of event-related activity by SAM(erf). Neurol. Clin. Neurophysiol. 2004, 109.
Roisman, G.I., Masten, A.S., Coatsworth, J.D., Tellegen, A., 2004. Salient and emerging developmental tasks in the transition to adulthood. Child Dev. 75 (1), 123–133. https://doi.org/10.1111/j.1467-8624.2004.00658.x.
Rossiter, H.E., Davis, E.M., Clark, E.V., Boudrias, M.-H., Ward, N.S., 2014. Beta oscillations reflect changes in motor cortex inhibition in healthy ageing. NeuroImage 91, 360–365. https://doi.org/10.1016/j.neuroimage.2014.01.012.
Sánchez-Hernández, M.D., Herrera, M.C., Expósito, F., 2021. Does the number of likes affect adolescents' emotions? the moderating role of social comparison and feedback-seeking on instagram. J. Psychol. 156 (3), 200–223. https://doi.org/10.1080/00223980.2021.2024120.
Saxbe, D., Del Piero, L., Immordino-Yang, M.H., Kaplan, J., Margolin, G., 2015. Neural correlates of adolescents' viewing of parents' and peers' emotions: associations with risk-taking behavior and risky peer affiliations. Soc. Neurosci. 10 (6), 592–604. https://doi.org/10.1080/17470919.2015.1022216.
Schantell, M., Taylor, B.K., Mansouri, A., Arif, Y., Coutant, A.T., Rice, D.L., Wang, Y.-P., Calhoun, V.D., Stephen, J.M., Wilson, T.W., 2024. Theta oscillatory dynamics serving cognitive control index psychosocial distress in youth. Neurobiol. Stress 29, 100599. https://doi.org/10.1016/j.ynstr.2023.100599.
Scherf, K.S., Smyth, J.M., Delgado, M.R., 2013. The amygdala: an agent of change in adolescent neural networks. Horm. Behav. 64 (2), 298–313. https://doi.org/10.1016/j.yhbeh.2013.05.011.
Schurz, M., Radua, J., Aichhorn, M., Richlan, F., Perner, J., 2014. Fractionating theory of mind: a meta-analysis of functional brain imaging studies. Neurosci. Biobehav. Rev. 42, 9–34. https://doi.org/10.1016/j.neubiorev.2014.01.009.
Schurz, M., Radua, J., Tholen, M.G., Maliske, L., Margulies, D.S., Mars, R.B., Sallet, J., Kanske, P., 2021. Toward a hierarchical model of social cognition: a neuroimaging meta-analysis and integrative review of empathy and theory of mind. Psychol. Bull. 147 (3), 293–327. https://doi.org/10.1037/bul0000303.
Segalowitz, S.J., Santesso, D.L., Jetha, M.K., 2010. Electrophysiological changes during adolescence: a review. Article 1. Brain Cogn. 72 (1). https://doi.org/10.1016/j.bandc.2009.10.003.
Sherman, L.E., Greenfield, P.M., Hernandez, L.M., Dapretto, M., 2018. Peer influence via instagram: effects on brain and behavior in adolescence and young adulthood. Child Dev. 89 (1), 37–47. https://doi.org/10.1111/cdev.12838.
Sherman, L.E., Hernandez, L.M., Greenfield, P.M., Dapretto, M., 2018. What the brain 'Likes': neural correlates of providing feedback on social media. Soc. Cogn. Affect. Neurosci. 13 (7), 699–707. https://doi.org/10.1093/scan/nsy051.
Sherman, L.E., Payton, A.A., Hernandez, L.M., Greenfield, P.M., Dapretto, M., 2016. The power of the like in adolescence. Psychol. Sci. 27 (7), 1027–1035. https://doi.org/10.1177/0956797616645673.
Shirtcliff, E.A., Dahl, R.E., Pollak, S.D., 2009. Pubertal Development: correspondence between hormonal and physical development. Child Dev. 80 (2), 327–337. https://doi.org/10.1111/j.1467-8624.2009.01263.x.
Shulman, G.L., Fiez, J.A., Corbetta, M., Buckner, R.L., Miezin, F.M., Raichle, M.E., Petersen, S.E., 1997. Common blood flow changes across visual tasks: II. Decreases in cerebral cortex. J. Cogn. Neurosci. 9 (5), 648–663. https://doi.org/10.1162/jocn.1997.9.5.648.
Siegel, M., Donner, T.H., Engel, A.K., 2012. Spectral fingerprints of large-scale neuronal interactions. Nat. Rev. Neurosci. 13 (2), 121–134. https://doi.org/10.1038/nrn3137.
Silk, J.S., Siegle, G.J., Lee, K.H., Nelson, E.E., Stroud, L.R., Dahl, R.E., 2014. Increased neural response to peer rejection associated with adolescent depression and pubertal development. Soc. Cogn. Affect. Neurosci. 9 (11), 1798–1807. https://doi.org/10.1093/scan/nst175.
Smith, S., Nichols, T., 2009. Threshold-free cluster enhancement: addressing problems of smoothing, threshold dependence and localisation in cluster inference. NeuroImage 44 (1), 83–98. https://doi.org/10.1016/j.neuroimage.2008.03.061.
Solmi, M., Radua, J., Olivola, M., Croce, E., Soardo, L., Salazar de Pablo, G., Il Shin, J., Kirkbride, J.B., Jones, P., Kim, J.H., Kim, J.Y., Carvalho, A.F., Seeman, M.V., Correll, C.U., Fusar-Poli, P., 2022. Age at onset of mental disorders worldwide: large-scale meta-analysis of 192 epidemiological studies. Mol. Psychiatry 27 (1), 281–295. https://doi.org/10.1038/s41380-021-01161-7.
Springer, S.D., Spooner, R.K., Schantell, M., Arif, Y., Frenzel, M.R., Eastman, J.A., Wilson, T.W., 2023. Regular recreational cannabis users exhibit altered neural oscillatory dynamics during attention reorientation. Psychol. Med. 53 (4), 1205–1214. https://doi.org/10.1017/S0033291721002671.
Steriade, M., Gloor, P., Llinás, R.R., Lopes da Silva, F.H., Mesulam, M.-M., 1990. Basic mechanisms of cerebral rhythmic activities. Electroencephalogr. Clin. Neurophysiol. 76 (6), 481–508. https://doi.org/10.1016/0013-4694(90)90001-Z.
Sumter, S.R., Bokhorst, C.L., Miers, A.C., Van Pelt, J., Westenberg, P.M., 2010. Age and puberty differences in stress responses during a public speaking task: do adolescents grow more sensitive to social evaluation? Psychoneuroendocrinology 35 (10), 1510–1516. https://doi.org/10.1016/j.psyneuen.2010.05.004.
Swirsky, J.M., Rosie, M., Xie, H., 2022. Correlates of early adolescents' social media engagement: the role of pubertal status and social goals. J. Youth Adolesc. 51 (1), 74–85. https://doi.org/10.1007/s10964-021-01494-0.
Sydnor, V.J., Larsen, B., Bassett, D.S., Alexander-Bloch, A., Fair, D.A., Liston, C., Mackey, A.P., Milham, M.P., Pines, A., Roalf, D.R., Seidlitz, J., Xu, T., Raznahan, A., Satterthwaite, T.D., 2021. Neurodevelopment of the association cortices: patterns,

mechanisms, and implications for psychopathology. Neuron 109 (18), 2820–2846. https://doi.org/10.1016/j.neuron.2021.06.016.

Taulu, S., Simola, J., 2006. Spatiotemporal signal space separation method for rejecting nearby interference in MEG measurements. Phys. Med. Biol. 51 (7), 1759–1768. https://doi.org/10.1088/0031-9155/51/7/008.

Taylor, B.K., Eastman, J.A., Frenzel, M.R., Embury, C.M., Wang, Y.-P., Calhoun, V.D., Stephen, J.M., Wilson, T.W., 2021. Neural oscillations underlying selective attention follow sexually divergent developmental trajectories during adolescence. Dev. Cogn. Neurosci. 49, 100961. https://doi.org/10.1016/j.dcn.2021.100961.

Thompson, P.M., Vidal, C., Giedd, J.N., Gochman, P., Blumenthal, J., Nicolson, R., Toga, A.W., Rapoport, J.L., 2001. Mapping adolescent brain change reveals dynamic wave of accelerated gray matter loss in very early-onset schizophrenia. Proc. Natl. Acad. Sci. 98 (20), 11650–11655. https://doi.org/10.1073/pnas.201243998.

Uusitalo, M.A., Ilmoniemi, R.J., 1997. Signal-space projection method for separating MEG or EEG into components. Med. Biol. Eng. Comput. 35 (2), 135–140. https://doi.org/10.1007/BF02534144.

van den Bos, E., de Rooij, M., Miers, A.C., Bokhorst, C.L., Westenberg, P.M., 2014. Adolescents' Increasing Stress Response to Social Evaluation: Pubertal Effects on Cortisol and Alpha-Amylase During Public Speaking. Child Dev. 85 (1), 220–236. https://doi.org/10.1111/cdev.12118.

Van Overwalle, F., 2008. Social cognition and the brain: a meta-analysis. Hum. Brain Mapp. 30 (3), 829–858. https://doi.org/10.1002/hbm.20547.

van Wingen, G.A., Ossewaarde, L., Bäckström, T., Hermans, E.J., Fernández, G., 2011. Gonadal hormone regulation of the emotion circuitry in humans. Neuroscience 191, 38–45. https://doi.org/10.1016/j.neuroscience.2011.04.042.

Venta, A., Harmon, J., Abate, A., Marshall, K., Mouton-Odum, S., 2019. Pilot data supporting an attachment-based theory of adolescent social media use. Child Adolesc. Ment. Health 24 (3), 274–282. https://doi.org/10.1111/camh.12329.

Vijayakumar, N., Op De Macks, Z., Shirtcliff, E.A., Pfeifer, J.H., 2018. Puberty and the human brain: insights into adolescent development. Neurosci. Biobehav. Rev. 92, 417–436. https://doi.org/10.1016/j.neubiorev.2018.06.004.

Voytek, B., Kramer, M.A., Case, J., Lepage, K.Q., Tempesta, Z.R., Knight, R.T., Gazzaley, A., 2015. Age-related changes in 1/f neural electrophysiological noise. J. Neurosci. 35 (38), 13257–13265. https://doi.org/10.1523/JNEUROSCI.2332-14.2015.

Welch, P., 1967. The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. Article 2. IEEE Transactions on Audio and Electroacoustics. IEEE Trans. Audio Electro 15 (2). https://doi.org/10.1109/TAU.1967.1161901.

Wiesman, A.I., Heinrichs-Graham, E., Proskovec, A.L., McDermott, T.J., Wilson, T.W., 2017. Oscillations during observations: dynamic oscillatory networks serving visuospatial attention. Hum. Brain Mapp. 38 (10), 5128–5140. https://doi.org/10.1002/hbm.23720.

Wiesman, A.I., Murman, D.L., May, P.E., Schantell, M., Losh, R.A., Johnson, H.J., Willet, M.P., Eastman, J.A., Christopher-Hayes, N.J., Knott, N.L., Houseman, L.L., Wolfson, S.L., Losh, K.L., Johnson, C.M., Wilson, T.W., 2021. Spatio-spectral relationships between pathological neural dynamics and cognitive impairment along the Alzheimer's disease spectrum. Alzheimer Dement.: Diagn., Assess. Dis. Monit 13 (1). https://doi.org/10.1002/dad2.12200.

Wiesman, A.I., Wilson, T.W., 2020. Attention modulates the gating of primary somatosensory oscillations. Neuroimage 211, 116610.

Wilson, T.W., 2014. In: Xiong, In.H., Gendelman, H.E. (Eds.), Noninvasive Neurophysiological Imaging with Magnetoencephalography, *Current Laboratory Methods in Neuroscience Research*. Springer, pp. 293–311. https://doi.org/10.1007/978-1-4614-8794-4_21.

Wilson, T.W., Franzen, J.D., Heinrichs-Graham, E., White, M.L., Knott, N.L., Wetzel, M. W., 2011. Broadband neurophysiological abnormalities in the medial prefrontal region of the default-mode network in adults with ADHD (n/a-n/a). Hum. Brain Mapp.. https://doi.org/10.1002/hbm.21459.

Wilson, T.W., Heinrichs-Graham, E., Proskovec, A.L., McDermott, T.J., 2016. Neuroimaging with magnetoencephalography: a dynamic view of brain pathophysiology. Transl. Res.: J. Lab. Clin. Med. 175, 17–36. https://doi.org/10.1016/j.trsl.2016.01.007.

Zhou, Y., Lin, F.-C., Du, Y.-S., Qin, L., Zhao, Z.-M., Xu, J.-R., Lei, H., 2011. Gray matter abnormalities in Internet addiction: a voxel-based morphometry study. Eur. J. Radiol. 79 (1), 92–95. https://doi.org/10.1016/j.ejrad.2009.10.025.

Zimmer-Gembeck, M.J., 2002. The development of romantic relationships and adaptations in the system of peer relationships. J. Adolesc. Health 31 (6, ement), 216–225. https://doi.org/10.1016/S1054-139X(02)00504-9.

Zou, L., Wu, X., Tao, S., Yang, Y., Zhang, Q., Hong, X., Xie, Y., Li, T., Zheng, S., Tao, F., 2022. Functional connectivity between the parahippocampal gyrus and the middle temporal gyrus moderates the relationship between problematic mobile phone use and depressive symptoms: evidence from a longitudinal study. J. Behav. Addict. 11 (1), 40–48. https://doi.org/10.1556/2006.2021.00090.