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Research paper

Brooding rumination as a mediator of the association between default mode and central executive network connectivity and general psychopathology: a resting state EEG study

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ABSTRACT

Background: Although the use of brain imaging techniques has greatly improved our knowledge of the psychophysiological underpinnings of rumination, the number of studies investigating brooding and reflective rumination as separate dimensions within the Triple Network (TN) perspective is still limited. The main purpose of this study was to examine the relationship between resting-state electroencephalography (EEG) TN functional connectivity, rumination, and psychopathology in a sample of young adults.
Method: One hundred and twenty-seven individuals (95 females; mean age: 21.62 ± 2.53 years) were administered self-report measures assessing rumination and psychopathology and underwent a resting-state EEG recording with eyes closed. All EEG analyses were performed using the exact low-resolution electromagnetic tomography software (eLORETA).
Results: Our results showed that higher brooding rumination, but not reflection, was associated with increased beta connectivity ($r = 0.308$; adjusted-$p = .043$) between default mode network (DMN) and central executive network (CEN). This connectivity pattern was also positively correlated with the general level of psychopathology ($rho = 0.254$; $p = .004$). Lastly, a mediational model revealed that brooding rumination plays a significant role in the relationship between DMN-CEN beta connectivity and psychopathology and fully mediates this relationship.
Limitations: The cross-sectional design of the study and the retrospective self-reported data should be considered.
Conclusion: Our findings may reflect the neurophysiological pattern underlying the difficulty and/or attempt to disengage from internal/self-related negative thoughts and highlight the role of maladaptive rumination in mediating the relationship between DMN-CEN connectivity and psychopathology.

1. Introduction

Maladaptive rumination (i.e., rigid, repetitive and negative self-focused thoughts in response to stressful life events or feelings) is considered a transdiagnostic process involved in the development and maintenance of psychopathology in both clinical and non-clinical individuals (Cano-López et al., 2022; Clancy et al., 2020; Ehring, 2021; Grierson et al., 2016; Luca, 2019; Rood et al., 2009; Snyder et al., 2019; Wong et al., 2023).

Empirical and theoretical studies on this construct have often distinguished two subtypes of rumination: ruminative reflection and brooding (Nolen-Hoeksema, 1991; Satyshur et al., 2018; Treynor et al., 2003). While reflection is conceptualized as the tendency to engage in contemplative and intentional problem solving to alleviate one's

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negative mood, brooding is viewed as passive and self-critical pondering on the stressful effects of a current situation and/or negative feelings without planning a constructive solution (Treynor et al., 2003).

Although brooding and reflective rumination share some characteristics (e.g., the repetitive, self-focused thinking style), these two forms of rumination are considered distinct constructs on both a psychopathological and neurophysiological level. From a clinical perspective, despite some controversial data (e.g., Junkins and Haeffel, 2017; Miranda and Nolen-Hoeksema, 2007), compared to reflection, brooding is generally considered a dysfunctional form of rumination that is more strongly and reliably associated with depressive symptoms (e.g., Farina et al., 2025; Junkins and Haeffel, 2017; Moretta and Messerotti Benvenuti, 2022; Rogers and Joiner, 2017) as well as with general psychopathology (Selby et al., 2016; Shaw et al., 2021; Wang et al., 2017). On a neurophysiological level, neuroscientific reports also seem to suggest different neural patterns associated with these two subtypes of rumination (Misir et al., 2023). In particular, a recent systematic review of functional magnetic resonance imaging (fMRI) connectivity data reports that, compared to reflection, brooding rumination appears to be linked to a diminished top-down modulation (Misir et al., 2023).

More specifically, neuroscientific studies have shown that the triple network (TN) model (Menon, 2011) is a valid framework for understanding rumination (Misir et al., 2023) according to the modern conceptualization of the brain as a highly interconnected and dynamic system. This approach focuses on the relationship between three main large-scale networks, namely the default mode network (DMN), the salience network (SN), and the central executive network (CEN). These neural systems are closely interconnected not only during various cognitive and emotional tasks, but also in the resting-state (RS), a condition that highlights the intrinsic organization of the brain (Anderson and Perone, 2018; Blanken et al., 2021; Menon, 2011). According to this model, the efficient interaction between these networks is responsible for efficient cognitive control and adaptive behavior. Instead, imbalanced communication within and/or between these neural circuits is responsible for various psychopathological manifestations, and for various mental disorders (Menon, 2019; Menon, 2011, 2018, 2020). Indeed, these networks are dynamically involved in numerous basic and higher-order cognitive and emotional processes, including arousal modulation, self-referential thoughts, and top-down control (Bressler and Menon, 2010; Menon and Uddin, 2010).

Several studies have shown that rumination is associated with various connectivity alterations of these neural systems at both inter- and intra-network levels (Misir et al., 2023). For example, despite some mixed results (e.g., Jacob et al., 2020), several fMRI and electroencephalogram (EEG) studies have found a positive association between increased DMN synchronization and rumination scores in patients with depression and healthy individuals (Benschop et al., 2021; Bocharov et al., 2021; Ho et al., 2024; Misir et al., 2023). At the inter-network level, investigations in patients with depression also showed that the total rumination score and the brooding severity were positively correlated, respectively, with DMN-CEN-SN functional connectivity (Bessette et al., 2018), and with the inverse correlation between the CEN and the DMN (Pisner et al., 2019). More recently, a functional near-infrared spectroscopy (fNIRS) study (Wei et al., 2024) found the association between increased DMN-CEN connectivity and reflective rumination scores in a sample of healthy participants.

Although the use of brain imaging techniques has greatly improved our knowledge of the psychophysiological underpinnings of rumination (Benschop et al., 2021), the number of studies investigating brooding and reflective rumination as separate dimensions within the TN perspective, especially in non-clinical samples, is still limited (Misir et al., 2023). Furthermore, while the relationship between altered TN connectivity and psychopathology has been extensively documented (Menon, 2019), the potential role of rumination in mediating this relationship remains relatively understudied (Ordaz et al., 2017).

Identifying the neural mechanisms underlying maladaptive rumination is crucial not only to understand the pathogenic processes related to the onset and development of several psychiatric disorders, but also to more effectively address this maladaptive thinking style in treatment (Hsu et al., 2015). Moreover, it is known that focusing on non-clinical individuals can provide valuable information about the potential etiological processes underlying psychopathology by shifting from a categorical to a dimensional perspective on mental disorders (Imperatori et al., 2025; Lawn et al., 2022; Maj, 2016; Marques et al., 2021).

Given these premises, the main purpose of this study was to investigate the complex relationship between RS-TN dynamics, brooding and reflective rumination, and their role in psychopathological symptoms in a non-clinical sample of young adults using EEG connectivity. This approach is not only a suitable method to evaluate and understand the neurophysiological features underlying rumination-related phenomena (Benschop et al., 2021; Bocharov et al., 2021), but also for to assess the specific electrophysiological signature that characterizes neural networks interactions (Liu et al., 2018; Mantini et al., 2007; Whitton et al., 2018).

Specifically, the current study aimed to (i) investigate the relationship between RS-TN connectivity and brooding and ruminative reflection, and (ii) test the mediating role of rumination in the relationship between TN connectivity and general psychopathology. In line with previous RS brain imaging studies (Benschop et al., 2021; Ho et al., 2024; Misir et al., 2023; Zhou et al., 2020), it was hypothesized that higher levels of brooding and ruminative reflection would be correlated with increased inter-network and intra-network TN connectivity, particularly in the alpha and beta frequency bands, and especially between DMN hubs. Furthermore, it was expected that brooding rumination, but not ruminative reflection, would mediate the association between TN connectivity and general psychopathology.

2. Method

2.1. Participants and procedure

The required sample size for this report was determined based on the correlation and the mediation analysis (i.e. the analyses required to achieve the study aims) using G*Power 3.1 software (Faul et al., 2009) and according to the guidelines for mediation studies (Fritz and Mackinnon, 2007). In relation to the correlation analysis, the G*Power 3.1 software showed that at a probability level of 0.05, a sample size of 91 is required to achieve acceptable statistical power ($1–\beta = 80$ %) to detect a medium effect size (i.e., $r = 0.285$[2]) in a two-tailed test. With regards to the mediational analysis, following the recommendation of Fritz and Mackinnon (2007), and assuming a small/moderate effect size for path "*a*" (i.e., TN connectivity on rumination) and, according to the literature (Rickerby et al., 2024), a medium effect size for path "*b*" (i.e., rumination on general psychopathology), a sample of 126 participants was required to achieve a statistical power of 0.80 using a mediational model performed with the percentile bootstrap procedure.

Participants were enrolled through an online survey distributed via web-based tools (e.g., social media) that assessed inclusion/exclusion study criteria, socio-demographic data (e.g., biological sex, chronological age, and educational attainment), and the main study variables (see Psychological measures section). Subjects responded by opening a QR code or the internet link to the survey form on their preferred device (e.g., smartphone, tablet or PC). All participants participated anonymously and voluntarily in the research (i.e., without any form of compensation) after giving written informed consent.

[2] This effect size was estimated following two recent RS-EEG studies (i.e., Benschop et al., 2021; Ho et al., 2024) reporting positive significant correlations between EEG connectivity data and rumination ranging from $r = 0.19$ to $r = 0.54$ (mean $r = 0.285$).

Recruitment lasted from April 2024 to January 2025. Inclusion criteria were: age between 18 and 34 years [i.e., an age group vulnerable to the onset of various forms of psychopathology (Solmi et al., 2022)], both sexes, right-handedness (i.e., Laterality Quotient ≥50 (Oldfield, 1971)), native Italian speakers. The following exclusion criteria applied: i) current and/or past self-reported neuropsychiatric diagnoses; ii) self-declared consumption of psychoactive drugs and/or illicit substances in the 14 days prior to EEG recording.

One hundred and seventy respondents were assessed for eligibility. One hundred and twenty-seven individuals (95 females and 32 males; age range: 18–34 years; mean age: 21.62 ± 2.53 years) met the inclusion criteria and participated in the present study. The data were collected as part of a larger project investigating the endophenotypes and risk factors of depression (PRIN Project 20228P4H2K supported by the MUR of Italy). This study was approved by the Ethics Review Committee of the European University of Rome (Prot. n. 12/2023) in accordance with the principles of the Declaration of Helsinki.

2.2. Psychological measures

The psychological study variables (i.e., rumination and general psychopathology) were assessed with the short version of the Ruminative Responses Scale (RRS-10; Treynor et al., 2003) and the Brief Symptom Inventory (BSI; Derogatis and Melisaratos, 1983). Tobacco consumption and the frequency of alcohol consumption, which was determined using the first item of the Alcohol Use Disorders Identification Test (AUDIT#1; Babor et al., 2001), were also recorded.

The RRS-10 is a self-report questionnaire that separately (i.e., five items for each dimension) assesses ruminative reflection (RRS-10-R; e.g., "*Analyze recent events to try to understand why you are depressed*") and brooding rumination (RRS-10-B; e.g., "*What am I doing to deserve this*"). Each item is rated on a 4-point Likert scale (from 1 = "*never*" to 4 = "*always*"), with greater scores reflecting higher brooding and/or reflective tendencies. The RRS-10 showed satisfactory psychometric properties, including good reliability and validity (He et al., 2021; Lucena-Santos et al., 2018; Thanoi and Klainin-Yobas, 2015). In the present report, the Italian translation of the RRS-10 (Macchia et al., 2012) was used, with an internal consistency of 0.74 for both RRS-10-R and RRS-10-B subscales.

The BSI is a 53-item self-report questionnaire widely used to assess the general level of psychopathology (Derogatis, 2017). The scale is designed to investigate nine principal clinical dimensions: somatization, obsessive-compulsive tendencies, interpersonal sensitivity, depressive symptoms, hostility, paranoid ideation, psychoticism, anxiety and phobic anxiety. The global severity index (GSI), the most sensitive single quantitative indicator of general psychopathology (Derogatis, 2017), is also calculated as the mean of all items. Participants rate each item using a 5-point Likert scale (from 0= "not at all" to 4 = "*extremely*"), with greater scores reflecting higher psychopathological symptoms. Several studies showed that the BSI is characterized by adequate psychometric properties (Derogatis, 2017). In the current study, the Italian version (Adawi et al., 2019) of the scale was used, and Cronbach's alpha was excellent (i.e., 0.96) for the BSI total score.

2.3. EEG recordings, processing and analysis

In the week after enrolment, study participants were asked to perform a RS-EEG recording in an EEG laboratory with their eyes closed. They were asked to refrain from alcohol and/or caffeine for at least 4 h prior to the EEG recording. Each EEG recording lasted at least 5 min and was performed in a silent room using multi-channel amplifiers (BrainAmp, BrainProducts GmbH, Gilching Germany) with 64 passive electrodes located according to the international 10-10 system. Ground and reference electrode were respectively located at Fpz and FCz scalp sites. During the recordings impedances were kept below 20 kΩ. The online sampling frequency was 500 Hz.

A qualitative visual assessment of the EEG raw data revealed no significant mark of abnormal neurophysiological activity or signs of drowsiness during the recordings. Offline EEG processing was performed by means of EEGLAB toolbox for MATLAB (version 2022.1; Delorme and Makeig, 2004). The EEG raw data was down-sampled to 256 Hz. The band-pass filtered between 1 Hz and 40 Hz and average re-reference was also applied. After a preliminary visual examination and the removal of the main marked artifacts (e.g., muscle activity), the Independent Component Analysis (ICA) was run using the infomax decomposition algorithm in order to remove other artifacts. More specifically, in accordance with previous EEG connectivity studies (e.g., Assenza et al., 2024; Chang et al., 2024; Lanzone et al., 2022), components were first classified and ranked using the ICLabel algorithm (Pion-Tonachini et al., 2019; Pontifex et al., 2017), which evaluates their contribution to the overall variance and provides probabilistic labels (e.g., brain, muscle, eye, heart, line noise, channel noise, or other). Noisy components were then removed after careful visual inspection (qualitative spectral and topographical features), preserving as much physiological variance as possible for each individual.

Artifacts-free EEG data were then analyzed by means of the Exact Low-Resolution Electromagnetic Tomography software (eLORETA; Pascual-Marqui et al., 2011). This software is a well-recognized device for localizing electrophysiological activity (Asadzadeh et al., 2020; Jatoi et al., 2014) as well as for the analysis of brain networks connectivity (Liu et al., 2018). In fact, despite its low spatial resolution, this software ensures an accurate reconstruction of the electrocortical activity, applying a three-dimensional (3D), linear, distributed non-inverse norm solution (Canuet et al., 2012).

According to previous eLORETA reports (Carbone et al., 2024; Carbone et al., 2022; Filosa et al., 2024; Imperatori et al., 2020; Massullo et al., 2022), EEG-TN connectivity was investigated identifying nine regions of interest (ROIs; Table 1). More specifically, ROIs were reconstructed selecting the "ROI-maker#1" option (i.e., using the Montreal Neurological Institute coordinates) in the eLORETA package. Furthermore, according with previous reports (e.g., Canuet et al., 2011; de la Salle et al., 2016; Kitaura et al., 2017), the "single nearest voxel" method was selected (i.e., each ROI made up of a single voxel, the nearest to each TN node).

Following the recommendation suggested by Miljevic et al. (2022), artifacts-free EEG data were divided into 4-seconds epochs (considering a minimum of 50 epochs for each participant). In the present research, the mean EEG epochs analyzed were 67.03 ± 6.57. Thus, the lagged phase synchronization (LPS) index (Pascual-Marqui et al., 2011) was applied to compute the functional connectivity in TN. Removing the instantaneous zero-lag contribution and minimizing the impact of non-physiological artifacts, this measure is one of the most used for the assessment of EEG connectivity (Hata et al., 2016; Olbrich et al., 2014).

Table 1
eLORETA reconstruction of the triple network according to MNI space coordinates (x, y, z)[a].

Salience network ROIs	Default monde network ROIs	Central executive network ROIs
dACC ($x = 0$, $y = 20$, $z = 35$)	MPFC ($x = 0$, $y = 55$, $z = 25$)	Left DLPFC ($x = -45$, $y = 20$, $z = 35$)
Left anterior insula ($x = -45$, $y = 15$, $z = -5$)	PCC ($x = 0$, $y = -55$, $z = 20$)	Right DLPFC ($x = 40$, $y = 25$, $z = 50$)
Right anterior insula ($x = 50$, $y = 15$, $z = -5$)		Left PPC ($x = -40$, $y = -70$, $z = 45$)
		Right PPC ($x = 50$, $y = -60$, $z = 40$)

Abbreviation: eLORETA = exact Low Resolution Electromagnetic Tomography software; MNI = Montreal Neurological Institute; ROI = Region of Interest; dACC = dorsal anterior cingulate cortex; MPFC = medial prefrontal cortex; PCC = DLPFC = dorsolateral prefrontal cortex; PPC = posterior parietal cortex.
[a] Coordinates referred to the ROI centroid.

By applying the normalized Fourier transform, this connectivity index estimates the similarity of EEG patterns in the frequency domain, with scores between 0 (i.e., no synchrony between two ROIs) to 1 (i.e., maximum synchrony between two ROIs). In the present report, the LPS was calculated in the following frequency: delta (1–4 Hz), theta (4.5–7.5 Hz), alpha (8–13 Hz), beta (13.5–30 Hz).

2.4. Statistical analysis

To investigate the relationship between the TN connectivity values and the RRS-10 scores, the eLORETA regression analysis option was used (i.e., the connectivity data between each TN hub at each frequency considered were correlated with the RRS-10-B and RRS-10-R total scores). The statistical non-parametric mapping approach (Nichols and Holmes, 2002) was used to perform this analysis. This procedure involves the calculation of 5000 randomizations with the aim of determining *r*-values and the equivalent statistically adjusted *p*-values (i.e., corrected for multiple comparisons among all connections, in each frequency band, without the need to rely on Gaussianity). This methodology is widely used in the eLORETA studies and is considered an effective approach for resolving the multiple testing problem (see Hata et al., 2016 for technical details).

As an exploratory analysis, the association between GSI and each significant TN connectivity pattern detected in the previous analysis was assessed by Spearman's *rho* correlation coefficient. Lastly, as specificity analysis, each significant association detected by the eLORETA software (i.e., between connectivity values and the RRS-10 scores) was also investigated using partial correlations (r_p), controlling for depressive symptoms (i.e., the BSI depression subscale).

Lastly, to investigate whether the association between TN connectivity and general psychopathology was mediated by rumination, a single mediation analysis was performed by means of the "Model 4" method of SPSS Macro Process v3.5 (Hayes, 2012) using 5000 bootstrap samples. Based on the previous analyses, each significant TN connectivity pattern detected with the eLORETA was set as the independent variable, GSI as the dependent variable, and rumination (i.e., RRS-10-B and/or RRS-10-R scores) as the mediator. Potential confounding variables (i.e., sex, age, education level, frequency of alcohol use, tobacco use, and RRS-10-B or RRS-10-R scores) were included as covariates due to their known relationship with rumination, GSI and/or EEG coherence data (Jausovec and Jausovec, 2010; Knott and Harr, 1997; Liu et al., 2022; Markman Geisner et al., 2004; Michel et al., 2024). Following Baron and Kenny (1986), three separate paths were reported: i) path *a* (i.e., the direct effect of TN connectivity on rumination), ii) path *c'* (i.e., the direct effect of TN connectivity on GSI), iii) path *c* (i.e., the total effect of TN on GSI, summing the direct and indirect effect). Path *b* (i.e., the association of rumination with GSI) and path *ab* (i.e., the indirect effect of TN connectivity on GSI through rumination) are also shown graphically.

Spearman's *rho* correlation, partial correlation and the mediation analysis were performed using the SPSS 20.0 software (IBM, Armonk, NY, USA).

3. Results

3.1. Rumination and general psychopathology

The descriptive statistics of the current sample are shown in Table 2. The RRS-10-B and RRS-10-R scores were significantly correlated with GSI scores (*rho* = 0.637, $p < .001$ and *rho* = 0.465, $p < .001$, respectively). Brooding scores were also positively correlated with ruminative reflection scores (*rho* = 0.504, $p < .001$).

3.2. EEG connectivity and rumination

The eLORETA detected a significant positive correlation between the RRS-10-B total score and DMN-CEN connectivity in the beta frequency band ($r = 0.308$; adjusted-$p = .043$). More specifically, higher levels of brooding rumination were correlated with increased beta LPS values between the medial prefrontal cortex (MPFC) and the right dorsolateral prefrontal cortex (DLPFC; Fig. 1). No other significant associations were detected by the eLORETA software. The correlation coefficients between the RRS-10 brooding total score and the connectivity values in all interconnected TN-ROIs, in all frequency bands, are reported in Supplementary Fig. 1. The eLORETA did not detect significant correlations between the RRS-10-R total score and TN the connectivity values. The strongest association was observed in the alpha frequency between the MPFC and the right anterior insula ($r = -0.247$; adjusted-$p = .351$). The

Table 2
Descriptive statistics of the sample ($N = 127$).

Age – M ± SD	21.62 ± 2.53
Females – N (%)	95 (74.8)
Students – N (%)	116 (91.3)
University degree or higher – N (%)	35 (27.6)
Tobacco use in the last 12 months – N (%)	44 (34.6)
AUDIT #1 – M ± SD	1.69 ± 0.78
RRS-10-Brooding – M ± SD	9.91 ± 2.85
RRS-10-Reflection – M ± SD	9.08 ± 3.15
BSI-GSI – M ± SD	0.83 ± 0.56
SOM – M ± SD	0.67 ± 0.66
O-C – M ± SD	1.13 ± 0.86
I-S – M ± SD	1.01 ± 0.95
DEP – M ± SD	0.99 ± 0.74
AXN – M ± SD	0.98 ± 0.73
HOST – M ± SD	0.70 ± 0.67
PHOB – M ± SD	0.37 ± 0.53
ID – M ± SD	0.87 ± 0.76
PSYC – M ± SD	0.67 ± 0.65

Abbreviation: mean; SD = standard deviation; AUDIT = Alcohol Use Disorders Identification Test; RRS-10 = 10-item version of the Ruminative Responses Scale; BSI = Brief Symptom Inventory; GSI = Global Severity Index; SOM = somatization; O-C = obsessive-compulsive symptoms; I-S = interpersonal sensitivity; DEP = depression; ANX = anxiety; HOS = hostility; PHOB = phobic anxiety; PAR = paranoid ideation; PSY = psychoticism.

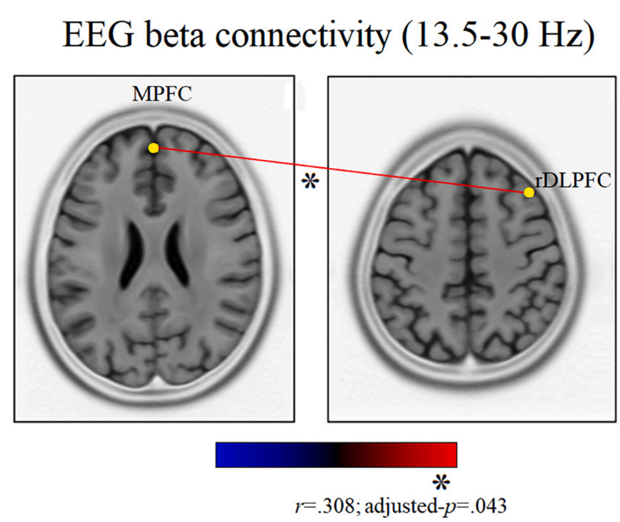

Fig. 1. Significant correlation between right DLPFC-MPFC connectivity and RRS-10-B total score in the beta frequency band. Red line indicates a positive correlation between the severity of brooding rumination and the strength of connections between two interconnected ROIs. Blue lines (not present) would indicate a negative correlation between the severity of anhedonia and the strength of connections between two interconnected ROIs.
Abbreviations: DLPFC = dorsolateral prefrontal cortex; MPFC = medial prefrontal cortex; ROIs = Regions of Interest. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

full correlation matrix between RRS-10-R scores and connectivity values in all interconnected TN-ROIs, in all frequency bands, is reported in Supplementary Fig. 2. An exploratory analysis (see Supplementary Table 1) showed that beta DMN-CEN connectivity values were positively and significantly correlated with GSI scores (*rho* = 0.254: p = .004) and with all BSI subscales (*rho* ≥ 0.183; p = .039) except somatization (*rho* = 0.093; p = .297). Lastly, a specificity analysis showed that the association between the RRS-10-B total score and DMN-CEN beta connectivity remained significant when depressive symptoms were controlled for (r_p = 0.256; p = .004).

3.3. EEG connectivity, brooding and psychopathology

The results of mediational model (i.e., DMN-CEN beta connectivity values as the independent variable, GSI scores as the dependent variable, and the RRS-10-B total score as the mediator) are shown graphically in Fig. 2 and fully reported in Supplementary Table 2. The statistical factor of tolerance and Variance Inflation Factor (VIF) showed that there were no interfering interactions between the variables (i.e., tolerance values >0.10 and VIF < 5). The total effect was positive and significant [B = 0.136, SE = 0.045 (95 % CI: 0.046; 0.226), p = .003], suggesting that higher DMN-CEN beta connectivity was associated with higher psychopathological symptoms. Moreover, the effect of DMN-CEN beta connectivity was positive and significant on brooding rumination [B = 0.647, SE = 0.222 (95 % CI: 0.208; 1.087), p = .004]. In turn, brooding rumination was positively associated with GSI scores [B = 0.093, SE = 0.017 (95 % CI: 0.060; 0.127), p < .001]. The direct effect of DMN-CEN beta connectivity on psychopathology was not significant [B = 0.075, SE = 0.042 (95 % CI: −0.008; 0.158), p = .076], while the indirect effect via the RSS-10-B total score was significant [B = 0.060, BootSE = 0.021 (95 % CI: 0.020; 0.103) p = .004]. This latter result suggests that the totality of the effect of DMN-CEN beta connectivity on general psychopathology was via brooding rumination.

4. Discussion

The main aim of this study was to investigate the complex relationship between RS-TN connectivity, brooding/reflective rumination, and psychopathology in a non-clinical sample of young adults. Our data indicated that higher brooding rumination, but not reflective rumination, was associated with increased DMN-CEN connectivity. Specifically, the RRS-10-B total score was positively correlated with increased EEG beta connectivity between the MPFC (i.e., a DMN hub) and the right DLPFC (i.e., a CEN hub). This connectivity pattern was also positively associated with the general level of psychopathology. Lastly, as hypothesized, the results of the mediational model showed that brooding rumination plays an important role in the relationship between DMN-CEN beta connectivity and psychopathology and fully mediates this relationship. Remarkably, this latter result was statistically significant even when controlling for potential confounding factors (i.e., sex, chronological age, educational attainment, frequency of alcohol and tobacco use, and RRS-10-R total score).

These findings are in line with previous studies reporting an association between altered connectivity between RS networks and both rumination and psychopathology (Menon, 2019; Misir et al., 2023). In particular, our data highlighted the role of increased RS synchronization between the DMN and CEN in brooding rumination. In fact, increased beta coherence has been theorized as a neurophysiological marker of hyperexcitability (Lee et al., 2021; Park et al., 2018), and previous studies have linked enhanced RS beta coherence to high-level mental processing (Basharpoor et al., 2021; Fleck et al., 2016) and to phenomena associated with rumination (Benschop et al., 2021; Ho et al., 2024).

Previous neuroimaging reports have also recognized the link between DMN hyper-synchronization/hyper-activation and brooding (Benschop et al., 2021; Ho et al., 2024; Misir et al., 2023; Zhou et al., 2020). In particular, given their crucial role in self-referential

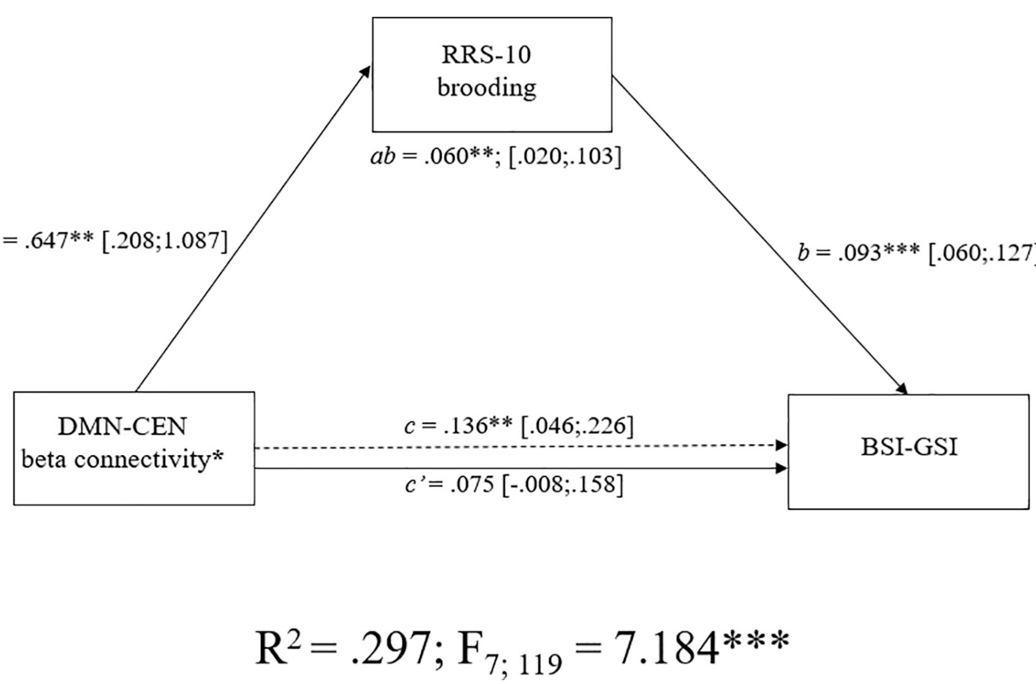

Fig. 2. Graphical representation of the mediational model.
Abbreviation: DMN = Default Mode Network; CEN = Central Executive Network; RRS-10 = The 10-item ruminative response scale; BSI-GSI = global severity index of the Brief Symptom Inventory.
Note: The reported estimates were obtained controlling for potentially competing factors (i.e., sex, age, educational level; frequency of alcohol use, tobacco use, and RRS-10 reflection total score).
* = connectivity data are expressed as standardized values.
** = p < 0.01; *** = p < 0.001.

processing, the midline hubs of the DMN, and especially the MPFC, are thought to be crucially involved in rumination by promoting the individual tendency "*to repetitively and passively recall personal past events, simulate assumed future events related to themselves and also introspect about personally relevant attributes and the related emotions*" (Zhou et al., 2020 page 6). Similarly, the involvement of the right DLPFC in rumination has been consistently documented (Ferdek et al., 2016; Int-Veen et al., 2023; Kuhn et al., 2014; Vanderhasselt et al., 2011; Vanderhasselt et al., 2017). For example, Vanderhasselt et al. (2011) reported that healthy individuals with high levels of brooding tendencies showed increased activity in this brain area during the disengagement from a series of negative stimuli.

The right DLPFC is a crucial node of the CEN that supports cognitive control processes involved in the allocation of top-down attentional resources (Fassbender et al., 2006; Pulopulos et al., 2022), especially during conflict-driven conditions (Vanderhasselt et al., 2009). According to the impaired disengagement model, abnormal recruitment of attentional control is considered critical in explaining maladaptive rumination (De Raedt and Koster, 2010; Koster et al., 2011). More specifically, according to this perspective, the persistent processing of self-referential negative thoughts is strongly related to the difficulty of successfully disengaging from negative thoughts and feelings (De Raedt and Koster, 2010; Koster et al., 2011). In this context, behavioral data have recently supported a bidirectional influence between impaired attentional control and maladaptive rumination (Sanchez-Lopez et al., 2019). On the one hand, impaired attentional disengagement from negative information increases brooding in response to stress. On the other hand, the habitual use of brooding increases the impairment of attentional disengagement from negative information in stressful situations (Sanchez-Lopez et al., 2019).

Given this background, the positive association between brooding rumination and the increased DMN-CEN beta connectivity reported in the present research may reflect the neurophysiological pattern underlying the difficulty and/or the attempt to disengage from internal/self-related negative thoughts. In other words, the RS DMN-CEN hyper-synchronization may reflect the tendency of individuals with high levels of maladaptive rumination to control and regulate their brooding responses. This interpretation also appears to be consistent with a recent fMRI study that found a link between increased DMN-CEN connectivity and maladaptive repetitive thinking in response to negative feelings (Lydon-Staley et al., 2019).

In a healthy brain, the DMN and the CEN dynamically alternate their synchronization in an anti-correlated and organized manner that support efficient cognitive control and adaptive behavior (Fox et al., 2005). Conversely, increased connectivity between the DMN and CEN during RS as well as during tasks is thought to interfere with higher-order cognitive processes involving both networks, mainly hampering goal-directed behavior and promoting a cognitive style characterized by internal, self-referential negative thoughts (Whitton et al., 2018). Interestingly, the hyper-synchronization between the DMN and the CEN has also been found to be associated with psychopathology, at the transdiagnostic level (Dotterer et al., 2020; Hu et al., 2017; Jones et al., 2023; Young et al., 2023). This latter data, as well as the evidence for maladaptive rumination in the development and/or maintenance of various mental disorders (Ehring, 2021; Grierson et al., 2016; Luca, 2019; Snyder et al., 2019; Wong et al., 2023) appear to support the result of our mediational model, which suggests a pathway leading from DMN-CEN beta hyper-connectivity via brooding rumination to psychopathological vulnerability.

Our findings could have several important clinical and therapeutic implications, including therapeutic ones. Investigating the relationship between DMN-CEN connectivity, rumination and psychopathology in non-clinical populations can provide valuable information about the neurophysio-pathogenic processes involved in the onset and development of several psychiatric disorders by moving from a categorical to a dimensional perspective on mental disorders (Imperatori et al., 2025; Lawn et al., 2022; Maj, 2016; Marques et al., 2021). This approach also has important therapeutic implications, including the use of neuromodulation techniques for those clinical pictures characterized by high levels of maladaptive ruminations. More specifically, DMN and CEN hubs could serve as target areas for the application of non-invasive brain stimulation methods such as transcranial Direct Current Stimulation (tDCS) and repetitive Transcranial Magnetic Stimulation (rTMS) for rumination. Similarly, EEG and/or real-time fMRI neurofeedback training may be used to reduce the hyperconnectivity pattern between RS networks. In this regard, our findings are consistent with previous studies indicating the usefulness of these techniques in reducing maladaptive rumination through neuromodulation of the main DMN and CEN nodes (Hoebeke et al., 2021; Kazemi et al., 2022; Taylor et al., 2022; Tsuchiyagaito et al., 2023).

Of note, in the current report, we did not find significant associations between brooding tendencies and SN nodes and between ruminative reflection score and TN hubs that have been previously reported (e.g., Ordaz et al., 2017; Wei et al., 2024). The discrepancies between these previous studies and the current research may be explained by various differences in study designs (e.g., young adults vs early pubertal youth) and/or methods (e.g., EEG connectivity vs fNIRS connectivity).

Although our results may be of interest, some limits should be noted. First, as a cross-sectional study, it is not possible to establish the cause-effect relationship between the study variables, which should be investigated in future longitudinal reports. Second, although participants with self-reported past and/or current psychiatric diagnoses were excluded from the current study, a full structured clinical interview was not conducted. Similarly, psychopathology and rumination have been assessed only via self-report measures, which may be subject to various biases (e.g., social desirability). Third, the current sample consisted mainly of university students and female participants, which limits the generalizability of our results. Furthermore, although the eLORETA is a suitable tool for the assessment of large-scale brain networks (Liu et al., 2018) and for localizing paralimbic/limbic areas (e.g., insula) (Mulert et al., 2004), it has an intrinsic low spatial resolution limit in detecting subcortical structures (e.g., the ventral striatum) that are known to be involved in rumination-related processes (Erdman et al., 2020). For this reason, the simultaneous combination of EEG and fMRI data could provide a better understanding of the spatiotemporal network dynamics of rumination-related phenomena. Finally, the present investigation is focused on the trait rumination and on the RS condition. Thus, TN connectivity patterns were not examined in relation to the state rumination and during the induction of negative feelings, so our findings are specific to the eyes-closed RS condition. Given these limitations, future studies should extend our data by examining both the trait and the state rumination, combining multimodal brain imaging techniques, and investigating TN synchronization also during rumination-related tasks.

Notwithstanding the limitations of the study, our data lend more specificity to this research area as we investigated the relationship between psychopathology, brooding and reflective rumination from the TN perspective in a non-clinical sample of young adults. Overall, our results suggest that high levels of maladaptive rumination are related with increased DMN-CEN beta synchronization and that the relationship between this connectivity pattern and psychopathology is mediated by trait brooding tendencies.

CRediT authorship contribution statement

Claudio Imperatori: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Elena De Rossi:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giorgia Allegrini:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Giuseppe Alessio Carbone:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Simone Messerotti Benvenuti:**

Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Mauro Adenzato:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Carola Dell'Acqua:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Aurelia Lo Presti:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Rita B. Ardito:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Benedetto Farina:** Writing – original draft, Supervision, Methodology, Conceptualization.

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Declaration of competing interest

The authors declare no conflicts of interest.

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None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jad.2025.120535.

Data availability

Data are available from the first author upon request.

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