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Investigating Resting-State Functional Connectivity in Autism Spectrum Disorder: An EEG-Based Study

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***Abstract*— This study examines resting-state functional connectivity in ASD-i.e., autism spectrum disorder- using EEG across delta, theta, alpha, and beta frequency bands. The results reveal distinct connectivity patterns in ASD, with widespread hyperconnectivity in frontal-parietal and frontal-occipital networks in higher frequency bands (alpha, beta) and reduced coherence in lower bands (delta, theta). Delta band analysis indicates impaired inter-regional communication, affecting sensory and cognitive integration. Theta band findings show left-hemisphere hyperconnectivity in ASD, contrasting with widespread right-hemisphere coherence in controls. Alpha and beta bands exhibit pervasive hyperconnectivity in ASD, especially in frontal midline regions, suggesting compensatory mechanisms for sensory and executive function deficits. In contrast, controls show localized, efficient connectivity, particularly in posterior regions, supporting typical sensory integration and visuospatial processing. These findings highlight frequency-specific connectivity alterations in ASD, where hyperconnectivity may both compensate for and disrupt neural processing. EEG-based connectivity measures could serve as biomarkers for ASD's neurophysiological mechanisms, guiding future diagnostic and therapeutic approaches.**

***Keywords*— EEG, Coherence, RSFC, ASD, Neurotypical Controls**

I. INTRODUCTION

Autism spectrum disorder encompasses a group of neurodevelopmental conditions characterized by a broad range of symptoms affecting social interaction, communication, and behaviour. ASD exhibits significant heterogeneity in its presentation, with symptoms ranging from mild to severe, often accompanied by comorbidities such as intellectual impairments, seizures, and mood dysregulation [1]. Increasing evidence suggests that these diverse symptoms stem from atypical neural connectivity patterns within the brain, emphasizing the importance of studying functional connectivity to better understand ASD's neurobiological foundations [2-5].

Resting-State Functional Connectivity (RSFC), which captures the temporal synchronization of neural activity between brain regions during rest, offers critical insights into the intrinsic network abnormalities associated with ASD [6]. EEG, a non-invasive, cost-effective neuroimaging tool with excellent temporal resolution, is particularly suited for investigating RSFC in clinical and developmental populations. By analysing EEG signals across multiple frequency bands, RSFC studies have the potential to identify neural biomarkers that can facilitate early diagnosis and monitor the progression of ASD [7].

In this study, RSFC is measured using coherence, a technique that quantifies the linear relationship between EEG signals in different brain regions at specific frequencies. Higher coherence values indicate strong connectivity, whereas lower values suggest weaker synchronization. Previous studies have highlighted its utility in capturing both local and long-range connectivity patterns in EEG data, making it a valuable tool for examining connectivity deficits in ASD [8, 9].

Although prior research has documented altered coherence patterns in individuals with ASD—such as reduced long-range coherence in the delta, theta, and alpha bands [10-13] and variable findings in short-range coherence—these results remain inconsistent. [10, 13-15]. Such variability underscores the need for standardized methodologies and advanced analytical approaches to reliably characterize the connectivity deficits associated with ASD. Moreover, there is a growing need to explore how coherence-based RSFC measures can differentiate ASD subgroups and relate connectivity abnormalities to behavioural manifestations.

This study aims to address these gaps by investigating RSFC patterns in individuals with ASD through coherence analysis of EEG data. By leveraging coherence as a robust measure of connectivity, this study provides novel

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insights into the neurophysiological mechanisms underlying ASD. The findings hold promise for enhancing diagnostic precision and informing the development of targeted interventions tailored to individuals across the autism spectrum.

II. LITERATURE REVIEW

Resting-state functional connectivity in ASD shows both hyperconnectivity and hypoconnectivity across frequency bands, indicating disrupted neural communication. Wang et al. (2020) found increased alpha and beta coherence in ASD, correlating with symptom severity, while Ghanbari et al. (2015) reported increased short-range delta and long-range alpha connectivity, alongside reduced complexity, linking these patterns to cognitive and sensory deficits [16] [17].

Theta connectivity has been associated with ASD traits, with Hill et al. (2022) finding increased right anterior theta connectivity predicting higher autistic traits. Alotaibi and Maharatna (2021) demonstrated the diagnostic potential of EEG-based connectivity using machine learning [3,4]. Early excessive alpha-band connectivity in infants, as observed by Orekhova et al. (2014), suggests ASD-related network inefficiencies develop over time [5]. Interventions targeting connectivity abnormalities have shown promise. Coben et al. (2014) found that EEG biofeedback reduced hyperconnectivity in ASD, improving symptoms. Yang et al. (2023) demonstrated that rTMS enhanced long-range connectivity and reduced symptoms in ASD participants [18, 19].

Multimodal imaging studies highlight ASD's heterogeneous connectivity patterns. Mash et al. (2018) revealed both hyperconnectivity and hypoconnectivity using EEG, fMRI, and MEG. Wantzen et al. (2022) found reduced alpha- band connectivity in key resting-state networks, while Ronconi et al. (2020) reported beta-band hyperconnectivity in sensory regions, suggesting a compensatory mechanism [20-22]. Duffy and Als (2019) further identified distinct ASD subgroups based on EEG coherence, challenging traditional ASD classification [23].

Murray et al. (2024) linked increased alpha amplitude and suppression in ASD adults to sensory behaviors and brain structural differences, reinforcing the role of alpha activity in sensory dysfunction [24]. These findings suggest EEG-based connectivity measures as valuable biomarkers for ASD diagnosis and intervention, offering insights into its neurophysiological mechanisms.

III. METHODOLOGY

A. Participants and Experimental Design

The dataset was obtained from The University of Sheffield's open-source repository and included EEG recordings from 28 individuals with ASD and 28 neurotypical controls, aged 18–68. Ethical approval was granted by the Health Research Authority (IRAS ID: 212171). EEG recordings were collected during a 2.5-minute resting-state session with eyes closed using the Biosemi Active Two EEG system [25].

B. Dataset Pre-processing

To address inconsistencies in recordings, a data selection process was implemented, yielding a final sample of 16 participants (eight ASD, eight controls). The analysis utilized 26 EEG electrodes, including Fp1, Fp2, Fpz, AF3, AF4, Fz, F7, FC1, C4, C5, CPz, CP1, CP4, TP8, Pz, P1, P2, P9, P10, POz, PO3, PO4, Oz, O1, O2, and Iz. EEG pre-processing involved referencing, filtering, artifact removal, and segmentation. Signals were re-referenced to the mastoids, reducing the electrode count to 25 to minimize noise [26] [27]. A 1–30 Hz bandpass filter was applied to isolate delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), and beta (12–30 Hz) frequencies, which are critical for cognitive and sensory functions [26] [28]. The data were then segmented into 160 one-second epochs to facilitate analysis [29]. Independent Component Analysis (ICA) was performed to eliminate artifacts associated with muscle activity and eye blinks [30].

C. Coherence Calculation

Coherence is a frequency-domain measure used to evaluate functional connectivity by determining the consistency of phase relationships between two EEG signals over time. It provides essential information about the degree of synchronization between different brain regions. The coherence between two EEG signals at a specific frequency f is defined as:[31]:

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$$Coh_{xy}(f) = \frac{\left|\langle S_{xy}(f)\rangle_n\right|^2}{\langle S_{xx}(f)\rangle_n \langle S_{yy}(f)\rangle_n}, \qquad (1)$$

where:

- $S_{xy}(f)$ is the cross-spectrum between signals xx and yy
- $S_{xx}(f)$ and $S_{yy}(f)$ are the power spectral densities of signals xx and yy, respectively
- $\langle\cdot\rangle$ denotes averaging over multiple epochs.

The coherence value ranges from 0 to 1, where values approaching 1 signify high synchronization between signals, while values near 0 indicate weak or no synchronization.

1) *Coherence Matrix and Connectivity Analysis:* For each participant, a 25 × 25 coherence matrix was generated, representing pairwise connectivity between all electrode locations. Given the matrix's symmetry, only the upper triangular portion was analysed, with diagonal elements excluded since coherence between an electrode and itself is always 1. To compare ASD and control groups, individual coherence matrices were averaged within each frequency band (delta, theta, alpha, beta). The difference in connectivity patterns was assessed by subtracting the ASD group's averaged coherence matrix from that of the control group.
2) *Statistical Thresholding and Smoothing:* To ensure meaningful differences, a statistical threshold was applied based on the number of epochs and frequency intervals (Table 1) used in coherence estimation [32]. The coherence deviation parameter was computed as:

$$\sigma = \frac{1}{\sqrt{(\text{number of epochs}) * (\text{number of frequencies})}} \qquad (2)$$

TABLE 1 PRESENTS THE COMPUTED THRESHOLDS FOR DIFFERENT FREQUENCY BANDS

Frequency Band	**Delta**	**Theta**	**Alpha**	**Beta**
Threshold (σ)	0.**002**	0.002	0.001	0.0004

Since raw coherence differences were difficult to interpret due to the large number of electrode pairs, the threshold was adjusted to 0.1 across all frequency bands to highlight significant connectivity variations. This structured approach ensures reliable EEG connectivity analysis, allowing for an in-depth investigation of functional connectivity differences between ASD and control participants.

IV. RESULTS AND DISCUSSION

The results reveal significant differences in functional connectivity between ASD and control participants across all frequency bands. Topographical figures illustrate these connectivity variations (red lines representing greater coherence in ASD participants and green lines indicating enhanced coherence in control participants), with ASD participants exhibiting widespread hyperconnectivity, particularly in the alpha and beta bands, while controls demonstrate more localized and efficient neural integration.

Delta band analysis as in Fig. 1 (a) shows robust inter-regional coherence in controls, particularly in frontal, parietal, and occipital regions, supporting sensory and cognitive processes. This contrasts with ASD participants, who display weaker or absent connectivity in these regions, suggesting disruptions in low-frequency network communication crucial for sensory integration. These findings align with Wang et al. (2020) and Ghanbari et al. (2015), who reported stronger delta connectivity in neurotypical individuals, facilitating higher-order cognitive functions [16] [17].

Theta band connectivity as shown in Fig. 1 (b) reveals hemispheric differences, with ASD participants exhibiting localized left-hemisphere hyperconnectivity in frontal-parietal and frontal-central connections, while controls display widespread right-hemisphere coherence. This pattern, consistent with Chan et al. (2024) and Hill et al. (2022), suggests that theta hyperconnectivity in ASD may reflect compensatory mechanisms for sensory processing deficits, whereas controls maintain more integrated network dynamics [33].

Fig. 1 (c) and (d) show dense alpha and beta band connectivity differences between ASD and controls. Due to high connection density, coherence increases were clarified by dividing the data into separate topographical figures as presented in Figure 2.

Alpha band Fig. 2 (a and b) show pervasive hyperconnectivity in ASD, particularly in frontal-parietal and frontal-occipital networks. ASD participants exhibit heightened alpha coherence in prefrontal and posterior regions, linked to atypical executive functioning and sensory integration. This aligns with Orekhova et al. (2014) and Coben

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et al. (2014), who associated increased alpha-range connectivity with restricted and repetitive behaviors [34] [18]. Similarly, beta band Fig. 2 (c and d) analysis highlights excessive long-range connectivity in ASD, with connections originating from frontal midline regions and extending to parietal and occipital areas. This hyperconnectivity, reported by Wang et al. (2020) and Ronconi et al. (2020), may represent compensatory activity supporting detail-oriented visual processing but also reflect neural inefficiencies [16] [22].

Control participants, in contrast, display localized and efficient connectivity, particularly in posterior regions associated with visual-spatial processing. This pattern, noted by Mash et al. (2018) and Duffy et al. (2019), suggests that neurotypical individuals maintain structured and task-specific neural coordination, facilitating stable perceptual and cognitive functions [20] [23].

These findings emphasize the dual role of hyperconnectivity in ASD, where increased synchronization may compensate for deficits but also contribute to inefficient information processing. The results support previous studies, such as Yang et al. (2023) and Murray et al. (2024), which suggest that interventions targeting connectivity abnormalities, including repetitive transcranial magnetic stimulation (rTMS), may help reorganize dysfunctional networks and improve ASD symptoms[19] [24]. Future research should explore how frequency-specific connectivity alterations correlate with behavioral phenotypes to refine ASD diagnostics and therapeutic approaches.

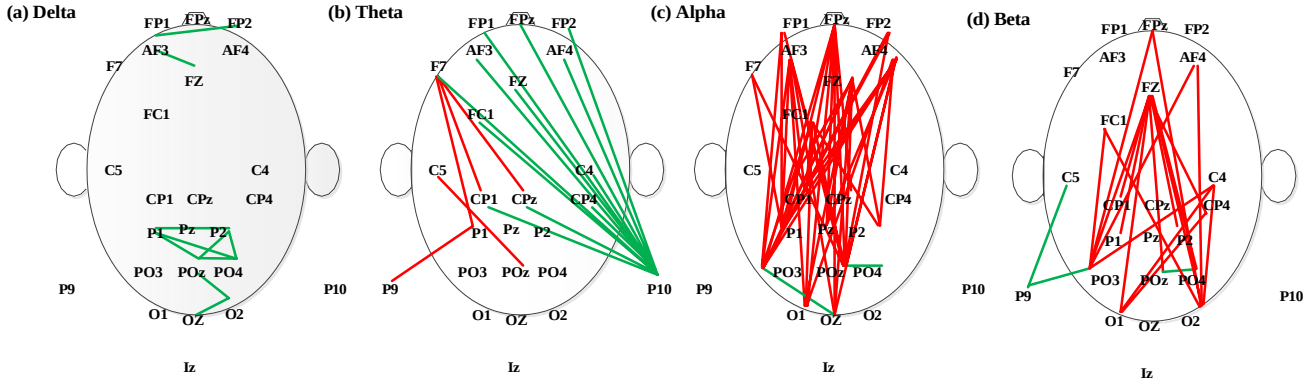

Fig. 1 Topographic maps of coherence differences between ASD and controls in (a) delta, (b) theta, (c) alpha, and (d) beta bands.

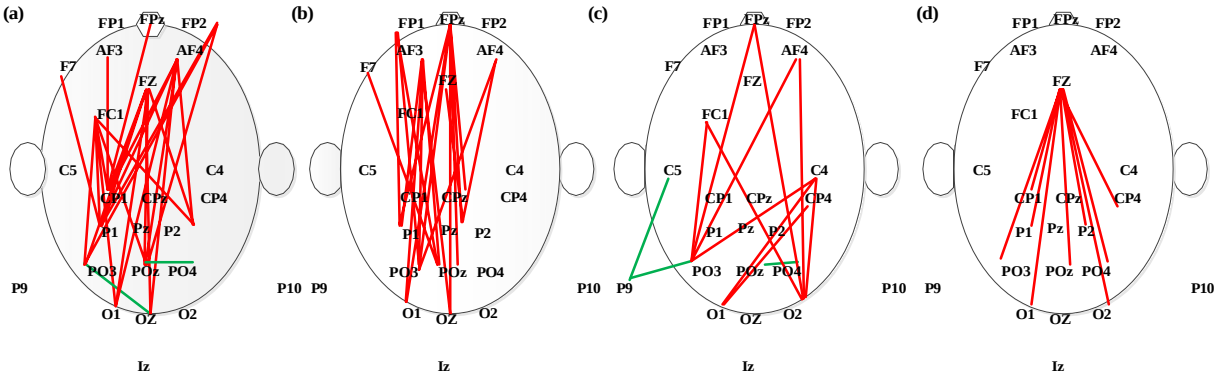

Fig. 2 Topographic maps of coherence differences between ASD and controls in (a and b) alpha, (c and d) beta bands.

V. CONCLUSIONS

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This study identified significant differences in resting-state EEG functional connectivity between ASD and neurotypical individuals. ASD participants exhibited widespread hyperconnectivity in alpha and beta bands, alongside disrupted delta and theta coherence, suggesting both compensatory mechanisms and network inefficiencies affecting sensory and cognitive processing. In contrast, controls displayed structured and efficient connectivity, particularly in posterior regions, supporting typical neural integration. These findings reinforce EEG-based functional connectivity as a potential biomarker for ASD and underscore the role of network dysregulation in the condition's characteristic cognitive and behavioral challenges.

The results also highlight the potential of interventions such as rTMS and EEG biofeedback in modulating atypical connectivity patterns and improving ASD symptoms. Future research should further investigate the developmental trajectory of these connectivity alterations, their relationship with behavioral phenotypes, and the effectiveness of targeted neuromodulation strategies. Advancing EEG-based biomarkers may enhance early diagnosis and personalized treatment approaches for ASD, improving long-term outcomes for affected individuals.

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