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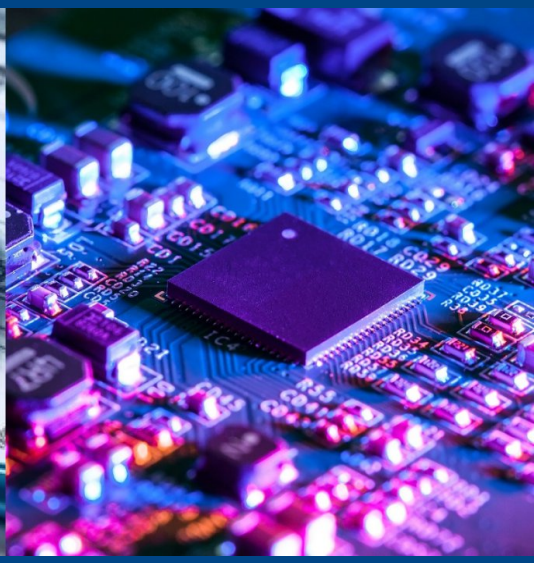

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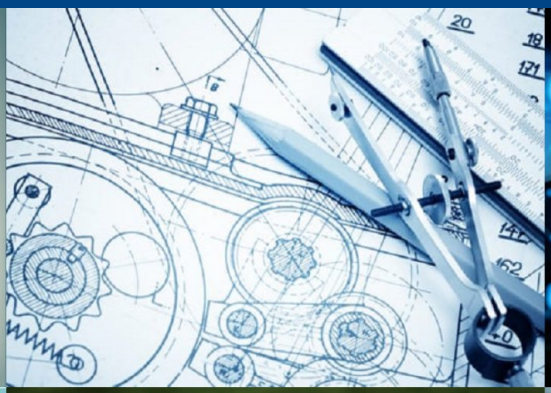

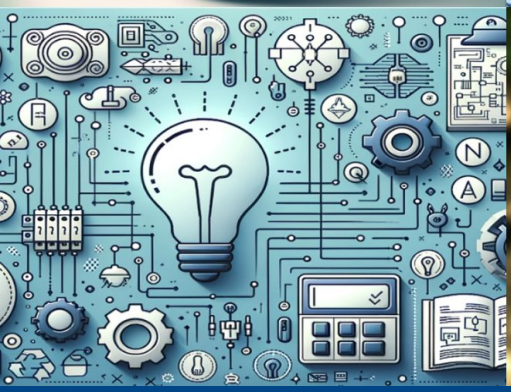

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Region-Wise Effect Size Analysis of EEG Stress Features under Short Temporal Windows

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ABSTRACT: EEG (Electroencephalography) used as a stress marker but the validity is still debatable especially when spatial reliability is taken into consideration. By using DEAP dataset, this study examines the geographically robustness of spectral entropy along with alpha and beta band power. Conventional pre-processing happens after which EEG dataset divided into 1 second non-overlapping frames. Then the characteristics are calculated in the region of central, frontal parietal and occipital areas. The Mann-Whitney U test was used to assess statistical differences between stress and non-stress circumstances, and Cohen's effect size was used to quantify these differences. Alpha and beta modulation in the central region is statistically significant of value $p<0.01$ as per result. The corresponding effect sizes were significant indicated by $|\mathbf{d}| < \mathbf{0.05}$ signifies less physiological distinction. There was no appreciable modulation neither in parietal nor in occipital region. But, trend level variation in the frontal region exists. The Mann-Whitney U test used to assess statistical differences between stress and non-stress circumstances. In order to quantify the differences Cohen's effect size is used. These results demonstrate difference between statistical significance and practical effect magnitude showing poor short window analysis under EEG geographical topology with weak consistency. Hence this work emphasize the necessity of reliability driven evaluation beyond p- value reporting in EEG based research in stress.

I. INTRODUCTION

Present day surveys prioritize the stress identification and monitoring based on EEG. It combines signal processing method along with machine learning techniques for easy and automated analysis. EEG is popular due to its non-invasive nature and good temporal resolution and sensibly identifying the brain dynamics helps for cognitive analysis [1]. There is also real time assessment of stress in clinics and occupation with availability of low cost and wearable devices with EEG [2]. Recent research emphasizes on improving the classification accuracy with advancement in both deep learning and different hybrid architecture. Based on public dataset the CNN, RNN and different attention models analyses stress and well differentiate their performances [3][4]. Spectral optimization and features in time as well as frequency domain integrated with the help of SVM to get good results with higher accuracy by performing comparison [5][6]. Moreover, these works prime importance to predict and improve accuracy instead of evaluating the reliability and consistency of EEG bio-markers.It is found that the variations in methods across pre-processing pipelines and the procedures in feature extraction strategies is the main source of inconsistency in stress study using EEG [7]. The verification of computational and experimental procedures informs that slight changes in pre-processing can change the statistical outputs. Hence, this poses question marks to the transparency and reliability of biomarkers [8]. Few studies suggested that the event based and short window analysis are used for real time applications signifies that the short segments of EEG may capture and identify oscillatory modulations related to transient stress irrespective of spatial distribution of less investigation[9].Present day research combine cross frequency method of modelling with spatial distribution establishes relationship of neural signature related to stress that are dependent on region, they cannot be globally expressed[10]. This result motivates to make a shift of evaluation based on reliability and robustness than improving accuracy. Here approach is to identify the location of cortex where stress can not only be consistently identified but also can be observed regularly. Hence, this framework investigates the variations of EEG across different regions of cortex by taking DEAP dataset under short- window analysis. To satisfy robustness and reproducibility, non-parametric statistical verification and validation along with effect size estimation is used.

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II. METHODOLOGY

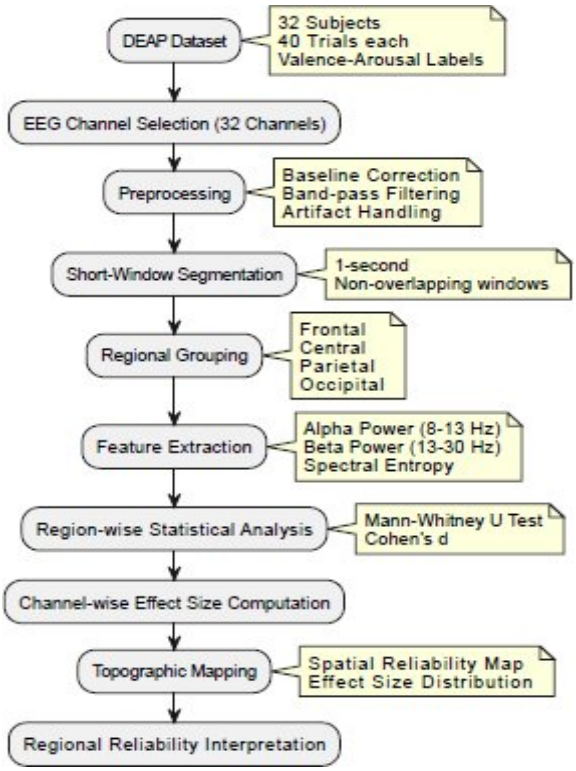

Figure 1 Proposed framework to determine the robustness in short window analyses

This proposed framework shown in figure1 uses DEAP dataset which consists of 32 subjects with 40 trials per subject. Labelling done for valence and arousal conditions. It consists of 32 electrodes of 10-20 standard system. To retain physiological integrity of EEG, pre-processing includes baseline correction, band pass filtering and conservative artefact. De-noising of EEG is spilt into 1-second non-overlapping windows to enable short-term temporal analysis. Channels grouped into frontal, central, parietal, and occipital regions to examine the spatial variability. From each region, alpha (8–12 Hz) and beta (13–30 Hz) band power are estimated using spectral analysis. Spectral entropy is extracted to quantify nonlinear signal complexity. Region-wise statistical comparison between stress and non-stress conditions is performed using the Mann–Whitney U test. Cohen's effect size is calculated to assess practical significance beyond p-values. Finally, channel-wise effect sizes are visualized through topographic mapping to interpret spatial reliability of EEG stress markers.

A. Dataset Description

The proposed framework was using standard dataset available in online using 32 subjects. These dataset is recorded based on different emotions categorised in terms of valence and arousal lebel. Based on different valence and arousal values, subjects are identified as stressed or non-stressed based on specific threshold value usually adopted in affective computing of EEG research [11.The dataset are sampled at the rate of 128Hz and electrodes are placed according to the international 10-20 system. Only EEG channels were considered in this study to ensure consistent spatial analysis.

B. Pre-processing

Conservative pre-processing is adopted to retain the physiological activity by minimising the artefacts and noise present in highly oscillatory EEG. This process includes baseline correction to remove low frequency components and band pass filtering to eliminate high frequency noise components. To preserve spatial dynamics of oscillatory EEG, excessive artefact removal techniques are avoided. That's what standard pre-processing methods are adopted to maintain the reproducibility [12][13].

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C. Short-window Segmentation

Pre-processed EEG signals were spiltted into non-overlapping 1-second windows. In order to extract spectral feature, short window analysis is used. This method supports real time applications with precisely characterizing the temporal dynamics. Along with this it maintains enough frequency resolution. Earlier studies support this short temporal windows since it efficiently capture the transient oscillatory modulations 14].

D. Regional Grouping

Region wise anatomical analysis was done by grouping the electrodes in the frontal, parietal, occipital and central cortical area. With this arrangement, the investigation was easy & the local area spatial variability which may be hidden from global analysis was observed. Research shows the improvement average neural effect in local area compared to global and also the interpretation was simple [15].

E. Feature Extraction

Three important features were extracted are alpha band power, beta band power and spectral entropy. Welch's power spectral density is used to estimate alpha and beta band power of range 8-12 Hz and 13-30Hz respectively. Shannon entropy from welch PSD is used to quantify the signal complexity along with irregularity which is beyond the scope of measurement of band limited power. The purpose of selecting these three features is that, it is associated with cognitive load and stress related cortical activation.

F. Statistical Analysis and Topographic Mapping

To determine localized performance reliability and consistency statistical method of non-parametric testing was used. To differentiate between stress and non-stress condition Mann-Whitney U test and to compute the effect magnitude not dependent on sample size Cohen's *d* was employed. Topographic mapping was used to find out region wise and channel wise effect size with visualisation. Topographic mapping provides spatial distribution related to stress modulation. Practical physiological relevance and statistical validation further justified with topographical mapping.

III. RESULT

This section presents the outcomes in terms of plots and its interpretation in terms of topography, alpha band power, beta band power followed by Shannon entropy with statistical validation and effect size estimation.

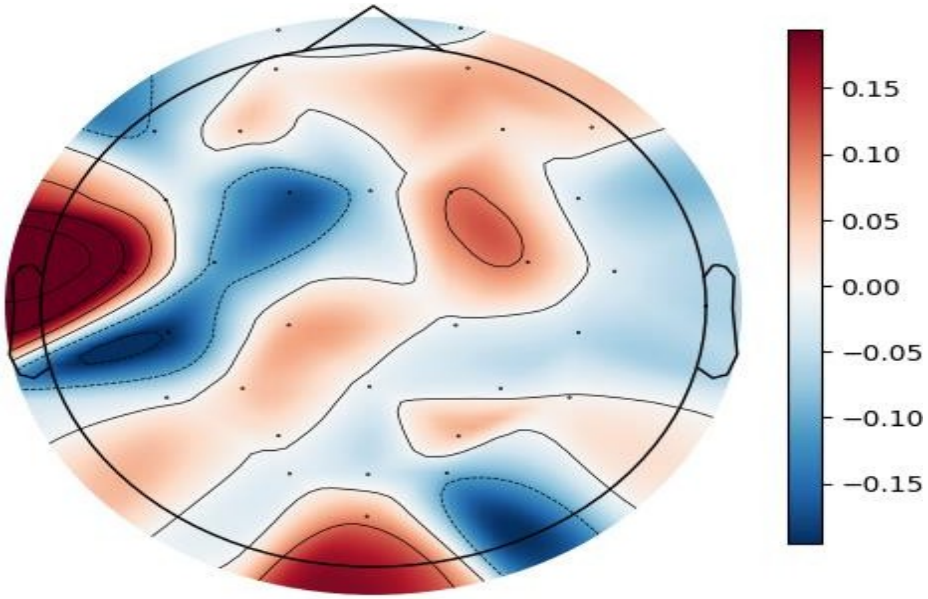

Figure 2 Topographic plot of spatial distribution

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The topographic map as shown in figure 2 illustrates spatial distribution of alpha-band effect sizes in the cortical regions. The red areas predominantly observed indicates localized positive effect size in the lateral frontal regions. Blue colour regions shows the negative modulation in central posterior area identifies the heterogeneous stress related activity. Anyway, the magnitude of the effect overall remains little signifies limited spectral stability of alpha band stress markers for short window analysis. Hence, these outcomes emphasize the region dependent variability over global stress response.

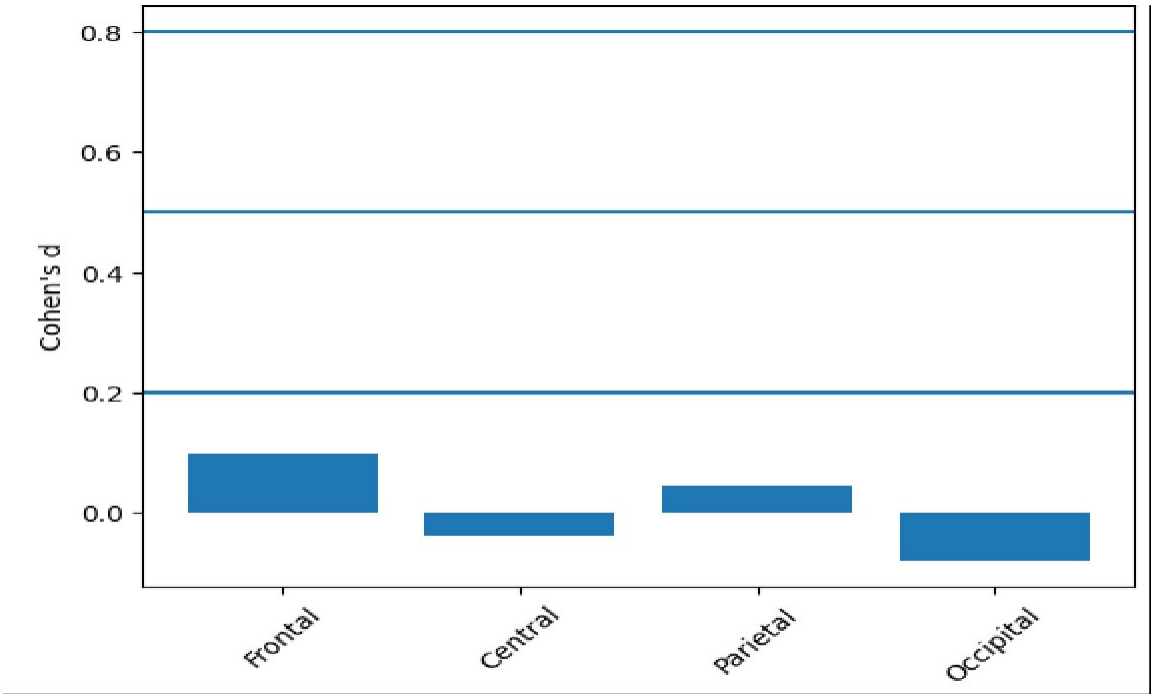

Figure3 Alpha band size effect across different region of brain

The alpha-band effect size shown in figure3 indicates very weak stress related modulation as the value of effect size is below 0.2 of threshold for all regions. Little positive effects shown by parietal and frontal region in comparison to slight negative modulation in occipital and central region by shifting below zero reference. Therefore, the alpha modulation magnitude is negligible signifies slight regional reliability in short window analysis. These results indicate strong spatial consistency is not possible by alpha power alone with this DEAP dataset.

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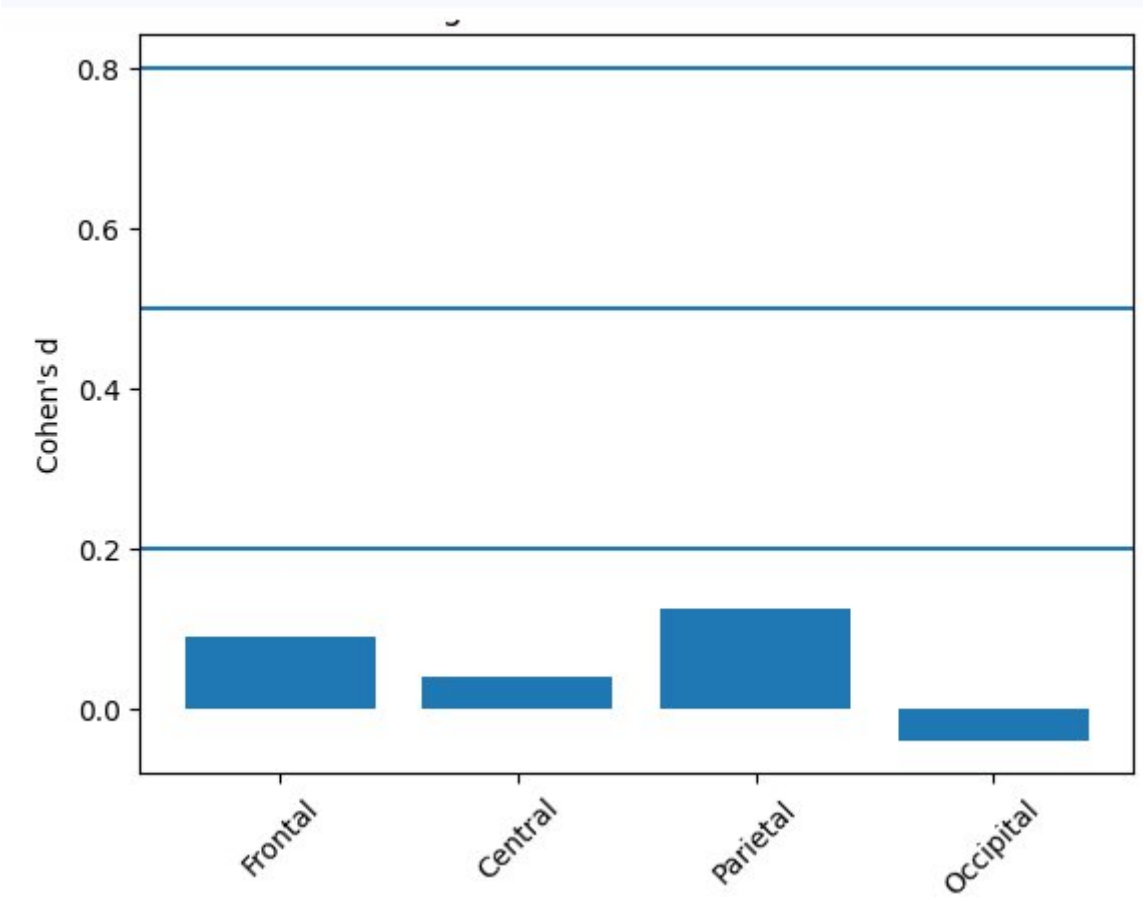

Figure 4 Beta band power effect across different brain regions

Figure 4 shows the beta band power effect size. All the regions reflect the values below threshold of d=0.2 signifies weak stress related modulation. Among all, the parietal region shows the highest positive effect and slight negative impact shown by occipital region with reference to zero. Among stress and non-stress condition minimal differences displayed by central and frontal region. Overall, beta power exhibit consistency compared to alpha power band but still not strong enough reliable for robust analysis under short window.

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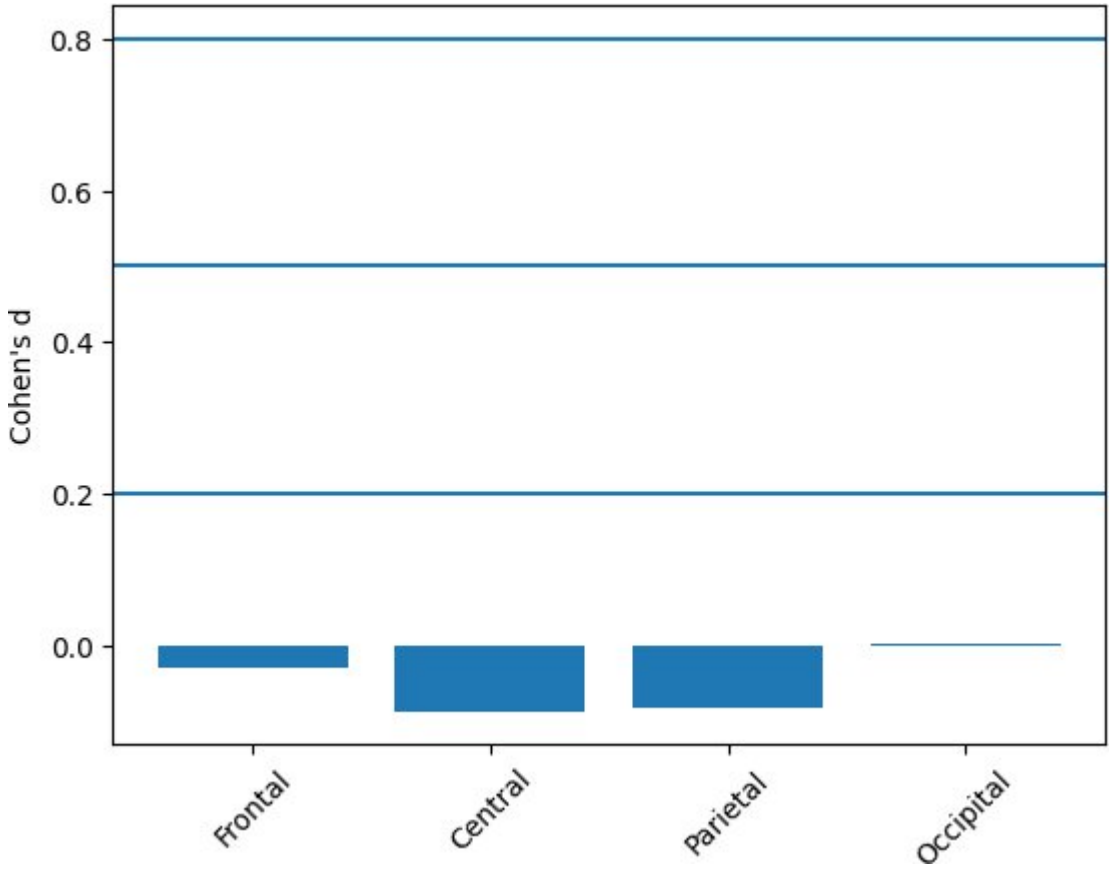

Figure 5 entropy effect size across various region of brain

The entropy effect sizes shown in figure 5 are close to zero across all regions, well below the small-effect threshold (d = 0.2). Central and parietal regions show more negative values, indicating reduction in complexity under stress, while frontal and occipital regions exhibit negligible differences. The overall magnitude suggests, spectral entropy does not reliably differentiate between stress and non-stress states in short-window analysis. These outcomes also suggest limited spatial sensitivity of entropy as a stress biomarker in the DEAP dataset.

Table 1 Regional band power and entropy related to stress analysis

Sl.no	Region	Feature	p-value	Cohen's d	significance	Effect size interpretation
1	Frontal	Alpha	0.087	+0.098	Trend level	Very small
		Beta	0.056	+0.089	Near significant	Very small
		Entropy	0.847	- 0.029	Not significant	negligible
2	Central	Alpha	0.007	- 0.039	significant	Very small
		Beta	0.008	+0.039	significant	Very small
		Entropy	0.418	- 0.085	Not significant	Very small
3	Parietal	Alpha	0.318	+0.047	Not significant	Very small
		Beta	0.639	+0.127	Not significant	small
		Entropy	0.349	-0.080	Not significant	Very small
4	Occipital	Alpha	0.655	-0.079	Not significant	Very small
		Beta	0.961	-0.038	Not significant	negligible
		Entropy	0.954	+0.003	Not significant	negligible

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Table1 shows the trends of borderline statistics and extremely small effect size < 0.1 which signifies weak and unstable stress.

Central region shows statistically significance indicates stress related modulation but the effect size is extremely small.This indicates that large sample size shows least statistical significance of physiological difference , hence it is not a strong bio-marker. Parietal region shows no meaningful stress related information under short window analysis. Occipital region is insignificant completely due to negligible effect size, therefore not sensitive to stress. Overall, specific region analysis reveals alpha and beta modulation significant in the central region with p value less than 0.01 with negligible effect size ($|d| < 0.05$) summarizes that short window global EEG markers lag in spatial robustness and shows limited reliability. This discrepancy between statistical significance and the effect magnitude emphasize the necessity for reliability driven evaluation than only reliance on p-values alone.

IV. DISCUSSION

The current stress analysis based over region reveals an important distinction in characterization of stress between statistical significance and practical reliability. Though alpha and beta power in the central region has statistical significance where both alpha ($p = 0.007$) and beta ($p = 0.008$) band powers demonstrated significant differences with ($p < 0.01$) but the corresponding effect sizes were negligible ($|d| < 0.1$). This indicates minimal physiological differentiation between stress and non-stress conditions. Hence this discrepancy suggests that large sample sizes may inflate statistical significance without meaningful physiological neural modulation. Similar concerns regarding over-reliance on p-values in EEG research have been raised in recent methodological research [16].The frontal region exhibited trend-level modulation in alpha and beta bands, shows weak effect of magnitude. Frontal alpha suppression has frequently been associated with cognitive load and stress-related cortical activation [17] but our present findings reflects that such modulation may not be spatially robust under short-window analysis segmentation. This observation matches with recent evidence suggesting that temporary transient emotional responses in DEAP standard dataset may produce little subtle oscillatory shift than strong localized biomarkers [18]. In this experimental context, the parietal and occipital regions demonstrated negligible effect sizes across all features, indicating limited posterior involvement in stress differentiation. Earlier studies shows that posterior alpha activity more strongly linked to visual processing and attentional mechanisms than stress-specific modulation [19], but weak spatial reliability observed here. These findings emphasize that not all classical EEG frequency bands exhibit consistent spatial sensitivity for stress characterization. Entropy-based analysis same way revealed minimal regional differentiation. Nonlinear complexity measures proposed as sensitive markers of cognitive and affective states [20], but their robustness appears dependent on task structure, window length, and signal quality. Under short-window analyses condition, entropy may lack sufficient temporal resolution to capture the changes in stress-induced neural organization.

Collectively, these results highlight the importance of reliability-driven evaluation frameworks in EEG stress research. Rather than focusing solely on classification accuracy, assessing effect magnitude and spatial consistency provides a more physiologically meaningful interpretation of stress-related neural dynamics. The observed regional heterogeneity suggests that globally averaged EEG features may hide some subtle localized effects, while short-window analysis may further attenuate detectable modulation. Future stress detection frameworks should therefore incorporate spatially adaptive feature modelling and subject-level variability analysis to improve robustness and translational applicability.

V. CONCLUSION

This study systematically examined regional EEG oscillatory and entropy based bio-markers associated with stress, revealing spatially selective neurophysiological modulation. The most consistent statistical effects were observed in the central region, where both alpha ($p = 0.007$) and beta ($p = 0.008$) band powers demonstrated significant differences. These findings suggest that central cortical dynamics play a measurable major role in stress-related neural processing. But, the corresponding effect sizes were very small ($|d| < 0.04$), indicating that modulation is statistically reliable where as its magnitude remains very subtle.Frontal oscillatory activity shows trend-level alterations in alpha and near significant changes in beta power , that matched with observed evidence that frontal networks are involved in stress regulation and cognitive-emotional control. In contrast, parietal and occipital regions did not demonstrate significant changes, suggesting limited posterior cortical involvement under examined stress condition. Entropy measures showed no significant regional differences, signifying global signal complexity,that remains relatively stable despite oscillatory modulations. This difference between spectral power changes and entropy stability suggests that stress may influence

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rhythmic synchronization more prominently than nonlinear signal irregularity. Overall, the results emphasizes that stress-related EEG alterations are spatially localized and basically reflected in central oscillatory dynamics rather than widespread cortical reorganization. Though the observed effects are very subtle, their regional specificity provides valuable insight into stress-sensitive neural responses. Future investigations incorporating multivariate modelling with cross-frequency interactions may further elucidate the functional relevance and practical utility of these markers for robust stress detection systems.

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