A. SOTA in EEG Signal Processing An Annotated Bibliography

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References

1. Acharya, U.R., Oh, S.L., Hagiwara, Y., Tan, J.H., Adeli, H.: Deep convolutional neural network for the automated detection and diagnosis of seizure using eeg signals. Computers in Biology and Medicine **100**, 270–278 (2017). https://doi.org/10.1016/j.compbiomed.2017.09.017

   This paper introduces a 13-layer deep convolutional neural network (CNN) for analyzing electroencephalogram (EEG) signals to detect and classify normal, preictal, and seizure conditions. The authors demonstrate the efficacy of CNNs in EEG signal processing, achieving an accuracy, specificity, and sensitivity of 88.67%, 90.00%, and 95.00%, respectively. This study highlights the potential of deep learning techniques in enhancing the diagnostic processes for epilepsy, offering a significant step forward in the automated analysis of EEG signals for seizure detection and diagnosis.

2. Craik, A., He, Y., Contreras-Vidal, J.L.: Deep learning for electroencephalogram (eeg) classification tasks: a review. Journal of Neural Engineering **16**(3), 031001 (2019). https://doi.org/10.1088/1741-2552/ab0ab5

   This review provides a systematic overview of deep learning applications to EEG classification, addressing critical questions about which EEG classification tasks have been explored, input formulations for deep networks, and the suitability of specific deep learning network structures for various tasks. The paper presents a detailed analysis of 90 studies, categorizing them by task type, preprocessing methods, input type, and deep learning architecture, ultimately offering practical suggestions on architecture and input selection to guide future research. This comprehensive assessment highlights the evolution of deep learning in EEG analysis, emphasizing its potential in enhancing classification accuracy and paving the way for more practical applications in neuroscience and beyond.

3. Faust, O., Acharya, U.R., Adeli, H., Adeli, A.: Wavelet-based eeg processing for computer-aided seizure detection and epilepsy diagnosis. Seizure **26**, 56–64 (2015). https://doi.org/10.1016/j.seizure.2015.01.012

   This review paper presents an in-depth discussion of wavelet techniques for EEG signal processing aimed at seizure detection and epilepsy diagnosis. The authors emphasize research from the past decade, presenting a multi-paradigm approach that combines wavelets, nonlinear dynamics, chaos theory, and neural networks. This method, advanced by Adeli and associates, is highlighted as particularly effective for the automated EEG-based diagnosis of epilepsy. The paper summarizes significant advances in the field, offering insights into the potential of wavelet-based methods for improving the accuracy and efficiency of epilepsy diagnosis and seizure detection.

4. Kannathal, N., Choo, M.L., Acharya, U.R., Sadasivan, P.: Entropies for detection of epilepsy in eeg. Computer Methods and Programs in Biomedicine **80**(3), 187–194 (2005). https://doi.org/10.1016/j.cmpb.2005.06.012

   This work explores the application of different entropy estimators to EEG data for distinguishing between normal and epileptic signals. The authors comprehensively compare the effectiveness of various entropy measures in identifying epileptic EEG data, demonstrating that these measures can significantly differentiate between normal and epileptic conditions with over 95% confidence using a t-test. The study further assesses the classification capabilities of the entropy measures through an ANFIS classifier, achieving about 90% accuracy. This paper underscores the potential of entropy-based metrics as powerful discriminators for epilepsy detection in EEG signals, contributing to the diagnostic tools available for neurological conditions.

5. Michel, C.M., Murray, M.M., Lantz, G., Gonzalez, S.L., Spinelli, L., Grave de Peralta, R.: Eeg source imaging. Clinical Neurophysiology **115**(10), 2195–2222 (2004). https://doi.org/10.1016/j.clinph.2004.06.001

   This comprehensive review outlines the advancements and methodologies in EEG source imaging, a technique pivotal for localizing the sources of brain activity measured on the scalp. The paper discusses the challenges of solving the inverse problem, the importance of electrode placement, the variety of inverse solution models and algorithms, and the integration of EEG source estimations with MRI data. It highlights how modern EEG source imaging can detail both the temporal and spatial dimensions of brain activity, thereby serving as an essential tool in cognitive and clinical neuroscience for understanding the brain's functional architecture and dynamics.

6. Radüntz, T.: Signal quality evaluation of emerging eeg devices. Frontiers in Physiology **9**, 98 (2018). https://doi.org/10.3389/fphys.2018.00098

   This technology report by Radüntz evaluates the signal quality of various mobile and gel-free EEG devices in comparison to traditional gel-based systems. The study involved 24 subjects using six different EEG devices across tasks to assess artifact contamination and signal-to-noise ratios among other metrics. Findings indicated that while traditional gel-based EEG systems provided the highest signal quality, certain gel-free devices also offered promising results, making them suitable for field experiments and potential clinical use. The study provides a comprehensive overview of the capabilities and limitations of emerging EEG technologies, highlighting the importance of signal quality for accurate brain activity monitoring and the potential for these devices to be used outside laboratory settings.

7. Rampil, I.J.: A primer for eeg signal processing in anesthesia. Anesthesiology **89**(4), 980–1002 (1998). https://doi.org/10.1097/00000542-199810000-00023

   This foundational paper by Ira J. Rampil provides an extensive overview of EEG (electroencephalogram) signal processing within the context of anesthesia, highlighting its significance due to the renewed interest in using EEG as a clinical monitoring tool. The primer covers the technical and physiological foundations necessary for understanding EEG modulation and its implications for assessing anesthetic depth. Key topics include the genesis of EEG signals, signal acquisition and processing techniques, and the recognition of artifacts. Rampil's work emphasizes the complexity of extracting meaningful information from EEG signals, especially in the dynamic environment of anesthesia and sedation, and sets a framework for future advancements in anesthesia monitoring technologies.

8. Sanei, S., Chambers, J.A.: EEG Signal Processing. Wiley (2013)
This book by Sanei and Chambers offers an in-depth exploration of EEG signal processing, emphasizing digital signal processing techniques and algorithms. It provides comprehensive coverage of various tools and methods developed in the field, making it a valuable resource for researchers, practitioners, and students interested in EEG analysis. The book aims to bridge the gap between theoretical approaches and practical applications in EEG signal processing, covering topics from basic signal processing concepts to advanced analysis techniques.

9. Smith, S.: Eeg in the diagnosis, classification, and management of patients with epilepsy. Journal of Neurology, Neurosurgery, and Psychiatry **76** (2005). https://doi.org/10.1136/jnnp.2005.069245
This article reviews the central role of electroencephalography (EEG) in the diagnosis and management of epilepsy. Smith highlights the historical significance of EEG since its discovery by Hans Berger in 1929 and its evolution as a fundamental tool in neurology for demonstrating the physiological manifestations of abnormal cortical excitability underlying epilepsy. Despite the development of various diagnostic techniques over the last three decades, EEG remains a cornerstone due to its convenience and cost-effectiveness. However, the paper also discusses the limitations of EEG, including challenges in spatial and temporal sampling, the need for large areas of cortex to be activated synchronously to register potential changes, and the incomplete understanding of cortical generators for both normal and abnormal activities recorded. Smith emphasizes the importance of appropriate questioning and interpretation of EEG data to avoid diagnostic errors, underscoring the nuanced role of EEG in contemporary neurology.

10. Teplan, M.: Fundamentals of eeg measurement. Measurement Science Review **2**(2) (2002)
This review article provides a comprehensive introduction to EEG measurement, aiming to assist in understanding EEG's field and building foundational knowledge for conducting EEG recordings. The paper is divided into two main parts: the first part offers background information, a brief historical overview, and insights into EEG-related research areas. The second part details the EEG recording process, covering topics from electrode placement and the importance of signal amplification to the handling of artifacts and the implications of different recording techniques. By elucidating the technical and practical aspects of EEG measurement, Teplan contributes significantly to the accessibility of EEG technology for medical and research applications.

B. SOTA in EEG-Based Emotion Recognition An Annotated Bibliography

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References

1. Jenke, R., Peer, A., Buss, M.: Feature extraction and selection for emotion recognition from eeg. IEEE Transactions on Affective Computing **5**(3), 327–339 (2014). https://doi.org/10.1109/TAFFC.2014.2339834

   This paper addresses emotion recognition from EEG signals as a critical aspect of human-machine interaction, emphasizing the importance of understanding the user's inner state. The authors review 33 studies on feature extraction methods for emotion recognition from EEG and perform an experiment comparing these features using machine learning techniques for feature selection on a self-recorded dataset. The results highlight the performance of different feature selection methods, the advantages of advanced feature extraction techniques over traditional spectral power bands, and the significance of electrode locations over the parietal and centro-parietal lobes for emotion recognition. This study systematically compares features for emotion recognition from EEG, offering valuable insights for enhancing affective brain-computer interfaces.

2. Lin, Y.P., Wang, C.H., Jung, T.P., Wu, T.L., Jeng, S.K., Duann, J.R., Chen, J.H.: Eeg-based emotion recognition in music listening. IEEE Transactions on Biomedical Engineering **57**(7), 1798–1806 (2010). https://doi.org/10.1109/TBME.2010.2048568

   This study presents a novel approach for recognizing emotions from EEG signals during music listening. Utilizing machine learning algorithms, the research categorizes EEG dynamics according to subjects' self-reported emotional states, achieving an average classification accuracy of 82.29% across 26 subjects. The research framework optimizes emotion recognition by identifying emotion-specific EEG features and exploring classifier efficacy. Notably, the study highlights the significant role of the frontal and parietal lobes in emotional processing, aligning with existing literature. This contribution could pave the way for noninvasive emotional state assessments in practical and clinical applications.

3. Liu, Z.T., Xie, Q., Wu, M., Cao, W.H., Li, D.Y., Li, S.H.: Electroencephalogram emotion recognition based on empirical mode decomposition and optimal feature selection. IEEE Transactions on Cognitive and Developmental Systems **11**(4), 517–526 (2019). https://doi.org/10.1109/TCDS.2018.2868121

   This study introduces an innovative approach for EEG-based emotion recognition, employing empirical mode decomposition (EMD) for feature extraction combined with optimal feature selection through sequence backward selection (SBS). The method is evaluated using the DEAP dataset, aiming to classify emotional states along Valence and Arousal dimensions using K-nearest neighbor (KNN) and support vector machine (SVM). The findings demonstrate superior recognition accuracy, with the highest recorded at 86.46% for Valence and 84.90% for Arousal dimensions using a 1-second temporal window. These results outperform several state-of-the-art methods, showcasing the potential of the proposed approach for real-time emotion recognition in human-robot interaction systems.

4. Picard, R.W.: Affective Computing. MIT Press (2000)
   Part 1 of "Affective Computing" lays the intellectual groundwork for the field, exploring the theoretical and practical aspects of designing systems that can recognize, interpret, and process human emotions. Rosalind W. Picard, a pioneer in the field, introduces the concept of affective computing, explaining its importance and potential impact on human-computer interaction. The book discusses the challenges and opportunities in enabling computers to better understand the affective dimension of human experience, aiming to make technology more responsive to our emotional needs.
5. Picard, R.W.: Affective computing: challenges. International Journal of Human-Computer Studies **59**(1–2), 55–64 (2003). https://doi.org/10.1016/S1071-5819(03)00052-1
   In this pioneering work, Picard addresses several criticisms of affective computing and articulates research challenges, particularly in human-computer interaction. The paper discusses the broad modalities of emotion expression and recognition, the idiosyncratic nature of human emotional expression, challenges in affect modeling, and the ethical considerations of machines interacting with human emotions. Picard argues for the potential of affective computing to enhance human-computer interaction by recognizing, expressing, modeling, communicating, and responding to emotional information. This paper is foundational in the field, highlighting both the possibilities and the challenges inherent in integrating emotional intelligence into computing systems.
6. Poria, S., Cambria, E., Bajpai, R., Hussain, A.: A review of affective computing: From unimodal analysis to multimodal fusion. Information Fusion **37**, 98–125 (2017). https://doi.org/10.1016/j.inffus.2017.02.003
   This comprehensive review addresses the evolving field of affective computing, spanning from unimodal to multimodal analysis. The authors highlight the transition from traditional unimodal approaches to more complex multimodal fusion methods in analyzing online videos and other media for affective computing. The paper underscores the importance of integrating audio, visual, and textual modalities to enhance the accuracy and depth of emotion and sentiment analysis. By comparing state-of-the-art methods in both unimodal and multimodal affect analysis, this review serves as an educational foundation for new researchers and outlines future directions in this interdisciplinary field.
7. Suhaimi, N.S., Mountstephens, J., Teo, J.: Eeg-based emotion recognition: A state-of-the-art review of current trends and opportunities. Computational Intelligence and Neuroscience **2020** (2020). https://doi.org/10.1155/2020/8875426
   This review paper provides a comprehensive overview of recent advancements in EEG-based emotion recognition from 2016 to 2019, highlighting the crucial elements influencing this field such as emotion stimuli types,

study size, EEG hardware, machine learning classifiers, and classification approaches. The authors identify the growing interest in integrating consumer-grade wearable EEG solutions for emotion recognition, emphasizing their affordability and ease of use. They propose future research directions, including the exploration of virtual reality (VR) as a novel method for presenting stimuli, addressing the gap in research for VR-based emotion recognition. The paper aims to guide and stimulate further research in the field of EEG-based emotion recognition, suggesting that the integration of VR could enhance emotional response elicitation and recognition accuracy.

8. Tao, W., Li, C., Song, R., Cheng, J., Liu, Y., Wan, F., Chen, X.: Eeg-based emotion recognition via channel-wise attention and self attention. IEEE Transactions on Affective Computing **14**(1), 382–393 (2023). https://doi.org/10.1109/TAFFC.2020.3025777

This paper introduces an attention-based convolutional recurrent neural network (ACRNN) for EEG-based emotion recognition, addressing the challenge of extracting discriminative features from EEG signals. The ACRNN employs a channel-wise attention mechanism to adaptively weight different EEG channels and uses a CNN to capture spatial information, followed by extended self-attention integrated into an RNN to leverage temporal information based on intrinsic signal similarities. Extensive testing on the DEAP and DREAMER databases shows the ACRNN's superior performance over existing methods, highlighting its potential to improve emotion recognition accuracy in brain-computer interfaces.

9. Zhang, J., Chen, M., Zhao, S., Hu, S., Shi, Z., Cao, Y.: Relieff-based eeg sensor selection methods for emotion recognition. Sensors **16**(10), 1558 (2016). https://doi.org/10.3390/s16101558

This study investigates the application of ReliefF-based methods for selecting EEG sensor channels to enhance emotion recognition accuracy. The authors explored three strategies for channel selection on the DEAP database, aiming to classify four emotional states: joy, fear, sadness, and relaxation. Utilizing support vector machine (SVM) as a classifier, they demonstrated that channel reduction could be achieved with minimal loss in classification accuracy. Their findings suggest that evaluating channels as units and adjusting their weights based on contribution to classification accuracy can effectively reduce computational complexity and improve user convenience in EEG-based emotion recognition systems. This work contributes to the development of more efficient and practical EEG-based emotion recognition systems.

10. Zhong, P., Wang, D., Miao, C.: Eeg-based emotion recognition using regularized graph neural networks. IEEE Transactions on Affective Computing **13**(3), 1290–1301 (2022). https://doi.org/10.1109/TAFFC.2020.2994159

This paper proposes a novel approach for EEG-based emotion recognition using a Regularized Graph Neural Network (RGNN) that leverages the biological topology among different brain regions to capture both local and global relationships among EEG channels. The methodology incorporates an adjacency matrix to model inter-channel relations, inspired by neuroscience theories of brain organization. To address cross-subject EEG variations and noisy labels, the study introduces two regularizers: node-wise domain adversarial training (NodeDAT) and emotion-aware distribution learning (EmotionDL). Extensive testing on SEED and SEED-IV datasets demonstrates the model's superior performance over existing state-of-the-art models in most scenarios. Ablation studies affirm the significant contributions of the adjacency matrix and both regularizers to the RGNN's effectiveness. Further analysis identifies key brain regions and inter-channel relations critical for emotion recognition, offering insights into the neural underpinnings of emotional processing.

C. SOTA in Clustering for EEG Signal Processing

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References

1. Gao, Z.K., Cai, Q., Yang, Y.X., Dong, N., Zhang, S.S.: Visibility graph from adaptive optimal kernel time-frequency representation for classification of epileptiform eeg. International Journal of Neural Systems **27**(04), 1750005 (2017). https://doi.org/10.1142/S0129065717500058

    This paper introduces a novel approach for detecting epileptic seizures from EEG signals by combining adaptive optimal kernel time-frequency representation with visibility graph techniques. The authors construct complex networks from EEG recordings to distinguish between healthy subjects and epilepsy patients, employing network measures such as clustering coefficient and average degree for topological analysis. Their method, tested across three different experiments, demonstrates high accuracy in classifying epileptiform EEG signals, offering a promising tool for epilepsy diagnosis and the study of brain dynamics.

2. Geva, A.B.: Feature extraction and state identification in biomedical signals using hierarchical fuzzy clustering. Medical and Biological Engineering and Computing **36**, 608–614 (1998). https://doi.org/10.1007/BF02524432

    This paper addresses the challenge of state recognition and event prediction in biomedical signal processing, with applications ranging from tachycardia detection in ECG signals to epileptic seizure prediction in EEG signals. Geva proposes the use of hierarchical fuzzy clustering for grouping discontinuous related temporal patterns in continuously sampled measurements, overcoming the non-stationary nature of biomedical signals. An innovative recursive algorithm for hierarchical fuzzy partitioning is introduced, allowing patterns to have non-zero membership in multiple data subsets. This method's effectiveness is demonstrated through applications in heart rate signal analysis during recovery from exercise and in forecasting generalized epileptic seizures from EEG signals, showcasing its potential in enhancing diagnostic and predictive capabilities in biomedical signal processing.

3. Gunes, S., Polat, K., Yosunkaya, S.: Efficient sleep stage recognition system based on eeg signal using k-means clustering based feature weighting. Expert Systems with Applications **37**(12), 7922–7928 (2010). https://doi.org/10.1016/j.eswa.2010.04.043

    This study introduces a novel sleep stage recognition system employing EEG signals, aiming to aid sleep physicians in the sleep scoring process.

The proposed system combines k-means clustering based feature weighting (KMCFW) with k-NN (k-nearest neighbor) and decision tree classifiers to categorize sleep into six stages. Through the utilization of Welch spectral analysis for feature extraction and KMCFW for feature reduction and weighting, the system achieves a significant improvement in classification success rate, demonstrating an 82.15% accuracy with the k-NN classifier for a k value of 40. This approach not only simplifies the data preprocessing but also enhances classification ability, potentially serving as an online tool for automatic sleep stage scoring.

4. Gurudath, N., Riley, H.B.: Drowsy driving detection by eeg analysis using wavelet transform and k-means clustering. Procedia Computer Science **34**, 400–409 (2014). https://doi.org/10.1016/j.procs.2014.07.045, open access

This research focuses on developing a monitoring system to detect driver drowsiness by analyzing electroencephalographic (EEG) signals using a driving simulator. The study utilizes Discrete Wavelet Transform (DWT) for time-frequency analysis and K-means clustering for unsupervised learning, aiming to classify unknown signal classes effectively. By filtering and decomposing EEG signals into sub-bands and calculating statistical moments as features, this system provides a robust tool for real-time drowsiness detection. The proposed method, tested on the Physionet sleep-EDF database, demonstrates the potential for enhancing driving safety through advanced EEG signal analysis.

5. Mammone, N., Ieracitano, C., Adeli, H., Bramanti, A., Morabito, F.C.: Permutation jaccard distance-based hierarchical clustering to estimate eeg network density modifications in mci subjects. IEEE Transactions on Neural Networks and Learning Systems **29**(10), 5122–5135 (Oct 2018). https://doi.org/10.1109/TNNLS.2018.2791644

This paper introduces a novel EEG-based methodology for quantifying brain-electrical connectivity changes in subjects with mild cognitive impairment (MCI). By constructing a dissimilarity matrix and applying hierarchical clustering, the study evaluates the coupling strength between EEG signals to estimate connectivity density changes. This method, leveraging permutation Jaccard distance (PJD) and wavelet coherence (WC), was tested on MCI patients over a follow-up period. The findings reveal significant connectivity and network density modifications in patients converting to Alzheimer's Disease (AD), particularly in delta and theta bands. The study demonstrates the potential of this nonlinear analysis and machine learning approach in detecting early signs of MCI-AD conversion through noninvasive EEG analysis.

6. Orhan, U., Hekim, M., Ozer, M.: Eeg signals classification using the k-means clustering and a multilayer perceptron neural network model. Expert Systems with Applications **38**, 13475–13481 (2011). https://doi.org/10.1016/j.eswa.2011.04.149

This study introduces a diagnostic decision support mechanism for epilepsy treatment using a multilayer perceptron neural network (MLPNN) model. EEG signals are decomposed into frequency sub-bands using discrete wavelet transform (DWT), and wavelet coefficients are clustered using the K-means algorithm. Probability distributions of these clusters serve as inputs for the MLPNN, leading to satisfactory classification accuracy rates across different EEG segment mixtures. The proposed model's effectiveness in classifying healthy, epileptic seizure-free, and

epileptic seizure segments demonstrates its potential in enhancing epilepsy diagnosis and treatment strategies.

7. Siuly, Li, Y., Wen, P.P.: Clustering technique-based least square support vector machine for eeg signal classification. Computer Methods and Programs in Biomedicine **104**(3), 358–372 (2011). https://doi.org/10.1016/j.cmpb.2010.11.014

   This paper introduces a novel approach, clustering technique-based least square support vector machine (CT-LS-SVM), for EEG signal classification. The method employs a two-stage decision-making process: first, using clustering techniques to extract representative features from EEG data; second, applying LS-SVM to these features for classifying two-class EEG signals. The approach demonstrates superior performance with higher sensitivity, specificity, and classification accuracy across multiple publicly available benchmark databases, including those for epileptic, mental imagery, and motor imagery EEG data. The proposed CT-LS-SVM method not only outperforms previous methods in terms of classification rates but also reduces execution time significantly, showcasing its efficiency and effectiveness for EEG signal classification.

8. Taran, S., Bajaj, V.: Clustering variational mode decomposition for identification of focal eeg signals. IEEE Sensors Letters **2**(4), 7001304 (2018). https://doi.org/10.1109/LSENS.2018.2872415

   This article introduces a novel method named clustering variational mode decomposition (CVMD) for the identification of focal EEG signals, which are crucial for diagnosing epilepsy. CVMD addresses the limitations of traditional variational mode decomposition (VMD) in handling nonhomogeneous EEG signals by implementing an optimum allocation sampling to analyze signals into homogeneous clusters before decomposition. Spectral moment-based features extracted from CVMD modes are used with an extreme learning machine classifier to identify focal EEG signals. The method demonstrates high performance with an accuracy of 96%, sensitivity of 94.69%, and specificity of 97.39%, offering a promising approach for identifying epileptogenic areas in patients with focal epilepsy.

9. Wilson, S.B., Turner, C.A., Emerson, R.G., Scheuer, M.L.: Spike detection ii: automatic, perception-based detection and clustering. Clinical Neurophysiology **110**, 404–411 (1999). https://doi.org/10.1016/S1388-2457(98)00023-6

   This paper develops and evaluates a novel, perception-based spike detection and clustering algorithm using a multiple monotonic neural network (MMNN). Tested on EEG databases containing 2400 spikes from 50 epilepsy patients and 10 control subjects, the MMNN algorithm closely matches the performance of human experts in spike detection, without suffering from overtraining issues. Additionally, the paper introduces a hierarchical clustering method for automatic grouping of detected spikes, showing striking similarity to expert manual grouping. This work represents a significant advancement in the automatic analysis of EEG signals for epilepsy, providing a clinically useful tool for identifying spike generators and artifacts.

10. Zhang, Y., Zhou, T., Wu, W., Xie, H., Zhu, H., Zhou, G., Cichocki, A.: Improving eeg decoding via clustering-based multitask feature learning. IEEE Transactions on Neural Networks and Learning Systems **33**(8), 3587–3597 (2022). https://doi.org/10.1109/TNNLS.2021.3053576

This paper presents a novel approach for enhancing EEG decoding accuracy for brain-computer interface (BCI) applications through a clustering-based multitask feature learning algorithm. The authors propose a method to uncover the intrinsic distribution structure of EEG data by performing affinity propagation-based clustering to identify subclasses within the EEG signals. These subclasses are then utilized to develop a multitask learning algorithm, optimizing EEG pattern features and significantly improving the decoding accuracy across multiple datasets. This research contributes to the BCI field by offering a method that effectively leverages the underlying data structure for better EEG pattern decoding, demonstrating its superiority over existing algorithms.