NeuroNetV1: A Unified End-to-End Framework for Multi-Condition EEG Classification

Supplementary Document

I. Analysis and Discussion on Hyperparameter Tuning

1. Effect of varying Number of Epochs

As shown in Figure 1(a), the classification accuracy showed a clear upward trend as the number of epochs increased, starting from 65.83% at 5 epochs and reaching a peak of 98.75% at 40 epochs. Beyond this point, performance plateaued, with only a marginal improvement at 55 epochs (98.85%) before slightly declining at 60 epochs. The initial increase in accuracy suggests that the model gradually learns complex EEG representations over time, while the saturation beyond 40 epochs implies that further training does not introduce new discriminative information but instead increases the risk of overfitting. This behavior is expected in deep learning models, as excessive training allows the network to memorize training data rather than generalizing well to unseen EEG signals. Consequently, we selected 40 epochs as the optimal choice since it ensures a balance between sufficient training and avoiding unnecessary computational overhead.

2. Effect of varying Learning Rates

The influence of different learning rates on classification accuracy is depicted in Fig. 1(b). The impact of learning rate variation was significant, as it directly influenced the rate of convergence and model stability. Higher learning rates such as $1e^{-3}$ led to unstable learning and frequent fluctuations, which compromised model generalization. In contrast, excessively small values such as $1e^{-6}$ slowed down convergence, causing the model to get stuck in suboptimal minima. The best performance was observed at $1e^{-4}$, achieving an accuracy of 98.75%, as it allowed for fast yet stable convergence. This result aligns with the theoretical understanding that moderate learning rates ensure efficient weight updates without overshooting the loss landscape. Based on this, we adopted $1e^{-4}$ as the default learning rate across all EEG datasets, ensuring consistent and optimized training behavior.

3. Effect of varying Batch Size

The impact of varying batch sizes is shown in Fig. 1(c). Smaller batch sizes (8 and 16) led to high variance in accuracy, likely due to noisy gradient updates that introduced instability. Larger batch sizes (64 and 128) showed slightly lower accuracy, suggesting that reducing stochasticity in updates reduced the model's ability to generalize well. The best performance was observed at batch size 32, which achieved 98.75% accuracy, providing an ideal trade-off between stable weight updates and diverse training samples per batch.

These findings indicate that an intermediate batch size ensures robust feature extraction across multidomain EEG datasets, making it the most efficient choice for NeuroNetV1.

4. Effect of varying Optimizers

The performance of different optimizers is illustrated in Fig. 1(d). Among the tested optimizers, Adam consistently outperformed all other methods, achieving 98.75% accuracy. RMSProp followed closely with 97.97%, while AdaGrad (96.42%), L-BFGS (95.23%), and SGDM (94.92%) lagged behind. Adam's superiority is attributed to its adaptive learning rate strategy, which dynamically adjusts the step size for each parameter, preventing drastic fluctuations and ensuring smooth convergence. SGDM and L-BFGS, on the other hand, suffered from slower adaptation, making them less effective in handling the complex, non-stationary nature of EEG signals. The results confirm that Adam remains the most reliable choice for EEG classification tasks, balancing speed, stability, and convergence efficiency.

5. Effect of different Activation Functions in the Network

As observed in Fig. 1(e), the choice of activation function played a crucial role in determining the model's ability to capture non-linear EEG patterns. ELU yielded the highest accuracy (98.75%), followed by GELU (97.80%) and Leaky ReLU (97.10%). ReLU, while effective, performed slightly worse (96.30%) due to dead neuron issues. Traditional functions like Tanh (94.50%) and Sigmoid (92.10%) exhibited significantly lower performance, as they suffer from saturation problems, leading to vanishing gradients. The superior performance of ELU can be attributed to its ability to maintain a smooth gradient flow, especially for negative inputs, reducing the chances of dead neurons and allowing better feature representation. Given this, ELU was selected as the preferred activation function for NeuroNetV1.

6. Effect of different Loss Functions

The impact of different loss functions is presented in Fig. 1(f). MSE loss yielded the highest accuracy (98.75%), outperforming BCE (97.85%), KL Divergence (97.23%), and Huber Loss (96.87%). The effectiveness of MSE suggests that minimizing squared errors enhances the model's ability to distinguish EEG patterns across multiple domains. BCE, while often used in classification, was less effective due to its sensitivity to imbalanced data, whereas KL Divergence and Huber Loss showed slightly lower accuracy due to their weaker adaptation to multidomain EEG feature variations. Thus, MSE was adopted as the optimal loss function, ensuring stable and accurate classification.

7. Effect of varying Kernel Size

The role of kernel size in different convolutional layers is analyzed in Fig. 1(g). The effect of kernel size was analyzed across the various convolutional layers in NeuroNetV1, with specific focus on dilated convolution (Block 1), ConvAT (Block 2), and depth-wise convolution. In Block 1, which uses dilated convolutions, a kernel size of 8 yielded the best performance (98.75%). This can be attributed to the fact that smaller kernels allow the model to capture local temporal dependencies more efficiently, especially in time-series data like EEG, where fine-grained variations within short time windows are crucial for identifying event-related synchronization and desynchronization patterns. The dilation factor further increases the receptive field, allowing the model to analyze these short-term dependencies over a wider context without requiring larger kernels, thereby reducing the computational burden.

In Block 2, the ConvAT block, which combines convolution and attention mechanisms, performed optimally with a kernel size of 32. Larger kernels are essential here because ConvAT needs to capture long-range contextual dependencies across the entire signal. This kernel size allows the model to integrate information from broader temporal spans, enhancing the self-attention mechanism to focus on the most relevant parts of the signal, which are typically spread across larger windows. By using a larger kernel, the model can better capture global patterns while maintaining higher computational efficiency, crucial for handling the non-stationary nature of EEG signals.

Lastly, the depth-wise convolution (Block 2) showed the best results with a kernel size of 16. Depth-wise convolutions operate on each input channel independently, making it important to strike a balance between capturing local spatial features and retaining important inter-channel relationships. A kernel size of 16 optimally extracts spatially invariant features while preserving enough context to identify inter-frequency dependencies across the EEG bands. This size is large enough to capture meaningful patterns but not so large as to introduce unnecessary computational complexity, which could disrupt the model’s ability to generalize across domains.

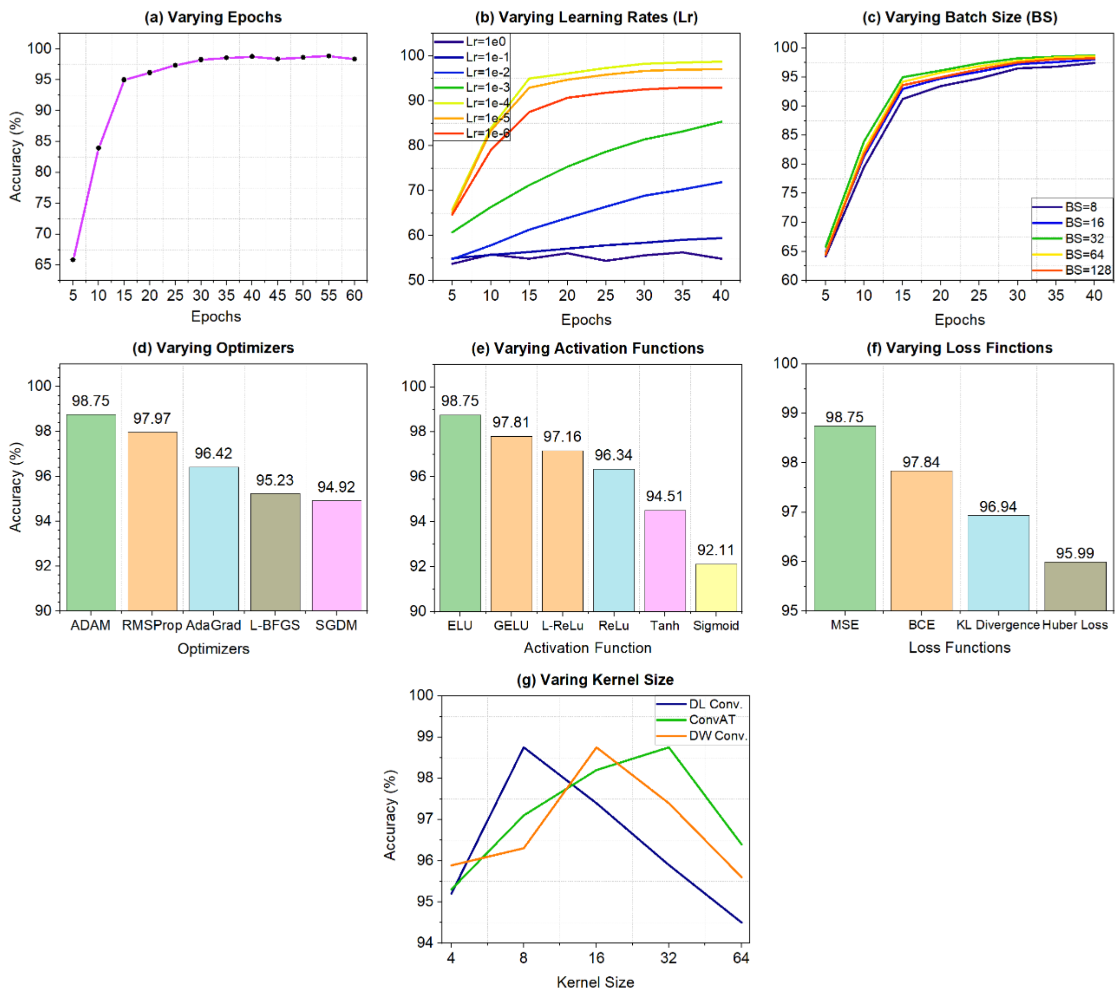

Figure 1: Hyperparameter tuning results for NeuroNetV1 on the MI-I dataset. (a) Number of epochs, (b) learning rate, (c) batch size, (d) optimizers, (e) activation functions, (f) loss functions, and (g) kernel size in different blocks.

II. Subject-wise 5-Fold Average Cross Validation Results for Individual Datasets using NeuroNetV1

This following tables offer a comprehensive analysis of the subject-wise results across all EEG datasets. The performance metrics included are accuracy, sensitivity, specificity, precision, $f1$-score, and Cohen's Kappa coefficient. These results are derived by averaging the 5-fold outcomes for each subject. The detailed results are presented as follows:

Table 1: Classification Performance of NeuroNetV1 on Motor Imagery EEG Dataset MI-I, Averaged Over 5 Folds for Each Subject

Subjects	Accuracy (%)	Sensitivity (%)	Specificity (%)	Precision (%)	F1-score (%)	Kappa (%)
1	98.80	98.80	98.88	98.82	98.80	97.59
2	99.11	99.11	99.11	99.11	99.11	98.21
3	97.62	97.62	97.62	97.73	97.62	95.24
4	98.21	98.21	98.45	98.28	98.22	96.42
5	100.00	100.00	100.00	100.00	100.00	100.00
Mean ± Std	98.75 ± 0.90	98.75 ± 0.90	98.81 ± 0.87	98.79 ± 0.86	98.75 ± 0.90	97.49 ± 1.81

Table 2: Classification Performance of NeuroNetV1 on Motor Imagery EEG Dataset MI-II, Averaged Over 5 Folds for Each Subject

Subjects	Accuracy (%)	Sensitivity (%)	Specificity (%)	Precision (%)	F1-score (%)	Kappa (%)
1	93.65	93.65	96.58	93.70	93.66	89.85
2	94.20	94.20	96.95	94.23	94.21	90.73
3	94.75	94.75	97.14	94.78	94.76	91.61
4	93.65	93.65	96.21	93.64	93.63	89.80
5	90.06	90.06	95.96	90.77	90.16	84.39
6	94.20	94.20	96.39	94.22	94.20	90.70
7	91.44	91.44	95.29	91.53	91.45	86.33
8	89.23	89.23	94.35	89.56	89.30	82.93
9	94.20	94.20	96.42	94.36	94.21	90.70
10	89.78	89.78	94.52	89.99	89.82	83.74
11	91.44	91.44	95.28	91.60	91.46	86.34
12	94.20	94.20	96.39	94.19	94.20	90.69
13	92.82	92.82	95.56	92.81	92.81	88.47
14	93.92	93.92	97.42	94.19	93.95	90.38
15	95.30	95.30	97.32	95.32	95.31	92.48
16	94.48	94.48	97.99	94.83	94.53	91.26
17	90.88	90.88	96.05	91.33	90.98	85.59
18	90.61	90.61	95.39	90.83	90.66	85.09
19	95.58	95.58	97.78	95.64	95.59	92.95
20	95.86	95.86	98.07	95.92	95.87	93.39

21	91.99	91.99	96.00	92.23	92.03	87.27
22	93.09	93.09	96.02	93.12	93.10	88.96
23	90.33	90.33	95.67	90.76	90.41	84.74
24	93.92	93.92	96.85	94.08	93.94	90.32
25	93.65	93.65	96.77	93.76	93.67	89.88
26	95.30	95.30	97.32	95.33	95.31	92.49
27	91.99	91.99	95.66	92.09	92.02	87.20
28	92.27	92.27	96.12	92.41	92.30	87.69
29	90.61	90.61	95.39	90.89	90.66	85.12
30	95.03	95.03	97.43	95.12	95.05	92.07
31	89.50	89.50	94.65	89.72	89.54	83.34
32	89.23	89.23	95.32	89.85	89.34	83.05
33	92.82	92.82	96.70	93.04	92.86	88.61
34	95.03	95.03	97.04	95.03	95.02	92.02
35	95.58	95.58	98.35	95.77	95.61	92.97
36	94.48	94.48	97.04	94.54	94.49	91.19
37	95.86	95.86	98.07	95.96	95.88	93.40
38	94.20	94.20	96.94	94.23	94.21	90.70
39	95.86	95.86	98.07	95.89	95.87	93.37
40	95.03	95.03	97.97	95.19	95.06	92.10
41	90.06	90.06	95.02	90.35	90.10	84.27
42	94.20	94.20	96.76	94.27	94.21	90.75
43	95.03	95.03	97.79	95.22	95.04	92.12
44	95.03	95.03	96.66	95.02	95.01	91.99
45	95.30	95.30	98.07	95.44	95.34	92.53
46	93.92	93.92	97.80	94.37	93.96	90.43
47	91.99	91.99	95.86	92.11	92.02	87.24
48	90.61	90.61	95.39	90.83	90.66	85.06
49	94.48	94.48	97.05	94.52	94.49	91.17
50	90.33	90.33	94.94	90.50	90.38	84.61
51	89.50	89.50	95.02	89.90	89.57	83.41
52	95.03	95.03	97.60	95.06	95.04	92.04
53	92.54	92.54	96.02	92.70	92.55	88.12
54	92.82	92.82	97.06	93.14	92.87	88.64
55	90.88	90.88	95.11	91.02	90.92	85.46
56	94.75	94.75	97.13	94.80	94.77	91.61
57	91.44	91.44	95.63	91.72	91.49	86.38
58	90.06	90.06	95.01	90.14	90.09	84.10
59	91.16	91.16	95.76	91.50	91.24	85.98
60	94.20	94.20	96.95	94.27	94.22	90.75
61	93.65	93.65	96.95	93.83	93.67	89.92
62	91.44	91.44	96.04	91.77	91.49	86.45
63	89.50	89.50	94.84	89.88	89.58	83.37

64	95.30	95.30	97.51	95.37	95.31	92.52
65	92.54	92.54	95.84	92.64	92.55	88.11
66	95.03	95.03	97.42	95.04	95.03	92.04
67	92.82	92.82	96.49	92.95	92.84	88.56
68	95.58	95.58	97.60	95.60	95.59	92.93
69	91.44	91.44	95.85	91.63	91.49	86.39
70	91.71	91.71	95.19	91.75	91.72	86.76
71	91.44	91.44	95.10	91.58	91.45	86.36
72	95.03	95.03	97.23	95.06	95.03	92.06
73	93.65	93.65	96.96	93.73	93.66	89.87
74	90.06	90.06	94.65	90.19	90.07	84.14
75	91.16	91.16	95.80	91.50	91.24	86.00
76	93.92	93.92	96.49	93.92	93.92	90.25
77	93.65	93.65	97.55	93.98	93.72	89.94
78	90.06	90.06	95.58	90.64	90.14	84.35
79	89.23	89.23	94.19	89.39	89.27	82.86
80	90.33	90.33	94.93	90.56	90.36	84.67
81	94.20	94.20	96.59	94.20	94.20	90.69
82	92.82	92.82	96.50	92.96	92.85	88.57
83	93.92	93.92	97.41	94.21	93.98	90.36
84	89.78	89.78	95.86	90.48	89.90	83.93
85	89.78	89.78	94.74	89.99	89.82	83.76
86	92.82	92.82	95.76	92.93	92.79	88.47
87	95.03	95.03	97.77	95.19	95.06	92.09
88	91.97	91.97	96.29	92.27	92.03	87.28
89	95.77	95.77	98.21	95.92	95.80	93.27
90	91.16	91.16	96.15	91.63	91.24	86.05
91	94.20	94.20	96.40	94.24	94.20	90.71
92	94.04	94.04	97.32	94.19	94.08	90.52
93	91.44	91.44	94.89	91.54	91.39	86.23
94	90.33	90.33	94.74	90.54	90.36	84.64
95	94.48	94.48	97.61	94.59	94.51	91.20
96	92.27	92.27	96.13	92.44	92.31	87.69
97	93.37	93.37	96.86	93.53	93.40	89.46
98	91.44	91.44	95.11	91.62	91.47	86.38
99	93.09	93.09	96.40	93.18	93.12	88.99
100	90.91	90.91	95.30	91.09	90.94	85.53
101	94.48	94.48	97.24	94.57	94.49	91.19
102	95.03	95.03	97.22	95.09	95.05	92.04
103	91.16	91.16	95.00	91.15	91.15	85.82
104	94.13	94.13	96.73	94.19	94.15	90.64
105	93.65	93.65	97.33	94.00	93.67	89.97
106	91.79	91.79	95.69	91.91	91.83	86.89

107	92.54	92.54	96.22	92.65	92.56	88.12
108	92.27	92.27	96.32	92.52	92.29	87.75
109	95.03	95.03	97.61	95.16	95.03	92.11
Mean ± Std	92.84 ± 1.95	92.84 ± 1.95	96.37 ± 1.04	93.01 ± 1.87	92.87 ± 1.93	88.61 ± 3.08

Table 3: Classification Performance of NeuroNetV1 on Motor Imagery EEG Dataset MI-III, Averaged Over 5 Folds for Each Subject

Subjects	**Accuracy (%)**	**Sensitivity (%)**	**Specificity (%)**	**Precision (%)**	**F1-score (%)**	**Kappa (%)**
1	96.00	96.00	96.00	96.02	96.00	92.00
2	91.50	91.50	91.50	91.50	91.50	83.00
3	96.50	96.50	96.50	96.54	96.50	93.00
4	94.50	94.50	94.50	94.54	94.50	89.00
5	97.00	97.00	97.00	97.00	97.00	94.00
6	95.00	95.00	95.00	95.07	95.00	90.00
7	92.92	92.92	92.92	92.94	92.92	85.83
8	93.50	93.50	93.50	93.54	93.50	87.00
9	94.17	94.17	94.17	94.36	94.16	88.33
10	97.00	97.00	97.00	97.02	97.00	94.00
11	92.50	92.50	92.50	92.50	92.50	85.00
12	96.00	96.00	96.00	96.07	96.00	92.00
13	91.50	91.50	91.50	91.50	91.50	83.00
14	91.50	91.50	91.50	91.54	91.50	83.00
15	95.00	95.00	95.00	95.02	95.00	90.00
16	93.00	93.00	93.00	93.16	92.99	86.00
17	94.50	94.50	94.50	94.54	94.50	89.00
18	96.00	96.00	96.00	96.00	96.00	92.00
19	93.50	93.50	93.50	93.50	93.50	87.00
20	95.00	95.00	95.00	95.00	95.00	90.00
21	92.50	92.50	92.50	92.50	92.50	85.00
22	94.00	94.00	94.00	94.07	94.00	88.00
23	93.00	93.00	93.00	93.07	93.00	86.00
24	92.00	92.00	92.00	92.07	92.00	84.00
25	94.50	94.50	94.50	94.54	94.50	89.00
26	91.50	91.50	91.50	91.50	91.50	83.00
27	96.50	96.50	96.50	96.54	96.50	93.00
28	97.50	97.50	97.50	97.50	97.50	95.00
29	92.00	92.00	92.00	92.02	92.00	84.00
30	94.00	94.00	94.00	94.00	94.00	88.00
31	96.00	96.00	96.00	96.00	96.00	92.00
32	92.50	92.50	92.50	92.50	92.50	85.00
33	92.50	92.50	92.50	92.71	92.49	85.00
34	94.00	94.00	94.00	94.07	94.00	88.00
35	92.00	92.00	92.00	92.27	91.99	84.00

36	93.00	93.00	93.00	93.00	93.00	86.00
37	93.50	93.50	93.50	93.61	93.50	87.00
38	96.50	96.50	96.50	96.62	96.50	93.00
39	96.00	96.00	96.00	96.02	96.00	92.00
40	91.50	91.50	91.50	91.60	91.49	83.00
41	91.50	91.50	91.50	91.50	91.50	83.00
42	93.00	93.00	93.00	93.02	93.00	86.00
43	92.50	92.50	92.50	92.50	92.50	85.00
44	93.00	93.00	93.00	93.02	93.00	86.00
45	92.00	92.00	92.00	92.02	92.00	84.00
46	92.92	92.92	92.92	93.16	92.91	85.83
47	96.50	96.50	96.50	96.50	96.50	93.00
48	97.50	97.50	97.50	97.50	97.50	95.00
49	95.50	95.50	95.50	95.50	95.50	91.00
50	92.00	92.00	92.00	92.00	92.00	84.00
51	92.50	92.50	92.50	92.50	92.50	85.00
52	97.50	97.50	97.50	97.50	97.50	95.00
Mean ± Std	94.00 ± 1.90	94.00 ± 1.90	94.00 ± 1.90	94.05 ± 1.89	94.00 ± 1.90	88.00 ± 3.81

Table 4: Classification Performance of NeuroNetV1 on Motor Imagery EEG Dataset MI-IV, Averaged Over 5 Folds for Each Subject

Subjects	**Accuracy (%)**	**Sensitivity (%)**	**Specificity (%)**	**Precision (%)**	**F1-score (%)**	**Kappa (%)**
1	94.79	94.79	98.26	94.81	94.78	93.06
2	94.44	94.44	98.15	94.46	94.43	92.59
3	94.10	94.10	98.03	94.18	94.11	92.13
4	97.92	97.92	99.31	97.93	97.92	97.22
5	98.26	98.26	99.42	98.30	98.27	97.69
6	94.44	94.44	98.15	94.47	94.45	92.59
7	97.57	97.57	99.19	97.60	97.57	96.76
8	98.26	98.26	99.42	98.29	98.26	97.69
9	99.31	99.31	99.77	99.31	99.31	99.07
Mean ± Std	96.57 ± 2.07	96.57 ± 2.07	98.86 ± 0.69	96.59 ± 2.06	96.57 ± 2.07	95.42 ± 2.76

Table 5: Classification Performance of NeuroNetV1 on Mental Imagery EEG Dataset MeI-V, Averaged Over 5 Folds for Each Subject

Subjects	**Accuracy (%)**	**Sensitivity (%)**	**Specificity (%)**	**Precision (%)**	**F1-score (%)**	**Kappa (%)**
1	98.60	98.60	99.37	98.63	98.61	97.89
2	97.76	97.76	98.94	97.78	97.76	96.61
3	98.17	98.17	99.08	98.18	98.17	97.26
Mean ± Std	98.18 ± 0.42	98.18 ± 0.42	99.13 ± 0.22	98.19 ± 0.43	98.18 ± 0.42	97.25 ± 0.64

Table 6: Classification Performance of NeuroNetV1 on P300 EEG Dataset P300-VI, Averaged Over 5 Folds for Each Subject

Subjects	Accuracy (%)	Sensitivity (%)	Specificity (%)	Precision (%)	F1-score (%)	Kappa (%)
1	95.88	95.88	96.62	96.05	95.91	91.12
2	95.29	95.29	95.79	96.91	95.77	71.75
3	96.18	96.18	94.18	96.85	96.38	80.55
4	96.76	96.76	97.50	96.90	96.79	92.88
5	97.35	97.35	97.09	97.36	97.35	94.63
6	96.76	96.76	96.78	96.77	96.77	93.52
7	95.29	95.29	95.25	95.35	95.31	89.95
8	97.94	97.94	97.84	97.95	97.94	95.63
9	96.47	96.47	95.61	96.47	96.47	92.08
10	96.76	96.76	96.37	96.89	96.80	91.13
11	95.59	95.59	95.90	95.76	95.63	89.80
12	95.29	95.29	99.58	97.01	95.76	75.29
13	97.06	97.06	96.36	97.66	97.23	82.28
14	97.06	97.06	96.09	97.05	97.05	93.51
15	96.18	96.18	97.24	96.42	96.22	91.07
16	97.35	97.35	97.06	97.43	97.35	94.67
Mean ± Std	96.45 ± 0.82	96.45 ± 0.82	96.58 ± 1.22	96.80 ± 0.68	96.54 ± 0.74	88.74 ± 7.25

Table 7: Classification Performance of NeuroNetV1 on Slow Cortical Potential EEG Dataset SCP-VII, Averaged Over 5 Folds for Each Subject

Subjects	Accuracy (%)	Sensitivity (%)	Specificity (%)	Precision (%)	F1-score (%)	Kappa (%)
1	95.90	95.90	95.87	95.96	95.89	91.79
2	92.50	92.50	92.50	92.50	92.50	85.00
Mean ± Std	94.20 ± 2.40	94.20 ± 2.40	94.18 ± 2.38	94.23 ± 2.44	94.20 ± 2.40	88.39 ± 4.80

Table 8: Classification Performance of NeuroNetV1 on Emotions EEG Dataset Emot-VIII, Averaged Over 5 Folds for Each Subject

Subjects	Accuracy (%)	Sensitivity (%)	Specificity (%)	Precision (%)	F1-score (%)	Kappa (%)
1	97.99	97.99	99.00	97.99	97.99	96.98
2	94.31	94.31	97.16	94.31	94.31	91.45
3	93.72	93.72	96.89	93.79	93.72	90.57
4	96.81	96.81	98.39	96.81	96.81	95.21
5	97.35	97.35	98.67	97.35	97.35	96.02
6	98.09	98.09	99.04	98.09	98.09	97.13
7	95.14	95.14	97.58	95.14	95.14	92.71
8	93.86	93.86	96.90	93.89	93.86	90.79
9	92.73	92.73	96.36	92.73	92.73	89.10
10	93.27	93.27	96.65	93.28	93.28	89.91
11	94.55	94.55	97.25	94.56	94.55	91.82
12	95.24	95.24	97.62	95.25	95.24	92.85
13	93.47	93.47	96.74	93.47	93.47	90.20

14	98.23	98.23	99.11	98.24	98.23	97.35
15	98.87	98.87	99.44	98.88	98.87	98.31
Mean ± Std	95.58 ± 2.10	95.58 ± 2.10	97.79 ± 1.05	95.59 ± 2.10	95.58 ± 2.10	93.36 ± 3.15

Table 9: Classification Performance of NeuroNetV1 on Sleep Stage Dataset Sleep-IX, Averaged Over 5 Folds for Each Subject

Subjects	Accuracy (%)	Sensitivity (%)	Specificity (%)	Precision (%)	F1-score (%)	Kappa (%)
1	95.86	95.86	98.92	95.94	95.88	94.58
2	96.69	96.69	99.31	96.81	96.72	95.02
3	91.78	91.78	98.08	92.23	91.88	88.58
4	99.16	99.16	99.78	99.17	99.16	98.78
5	98.30	98.30	99.53	98.36	98.31	97.58
6	95.83	95.83	98.93	95.94	95.85	94.24
7	97.08	97.08	99.36	97.18	97.10	95.96
8	94.09	94.09	98.45	94.19	94.11	92.23
9	95.23	95.23	98.87	95.48	95.30	93.78
10	98.02	98.02	99.65	98.10	98.04	97.13
11	94.93	94.93	98.65	95.42	95.06	91.73
12	97.69	97.69	99.56	97.74	97.71	96.50
13	95.07	95.07	98.58	95.17	95.09	93.40
14	83.45	83.45	96.02	85.23	83.92	76.82
15	90.80	90.80	97.77	91.84	91.10	87.47
16	98.79	98.79	99.68	98.80	98.79	98.35
17	94.87	94.87	98.84	95.16	94.94	92.96
18	98.71	98.71	99.64	98.73	98.72	98.22
19	93.78	93.78	98.46	93.98	93.81	91.77
20	94.15	94.15	98.72	94.63	94.26	91.75
Mean ± Std	95.21 ± 3.59	95.21 ± 3.59	98.84 ± 0.87	95.51 ± 3.20	95.29 ± 3.49	93.34 ± 4.99

Table 10: Classification Performance of NeuroNetV1 on Schizophrenia EEG Dataset SZ-XI, Averaged Over 5 Folds for Each Subject. The data for all 81 subjects was combined to form the training and testing set. Here we present the classification accuracies for three different cases.

Cases	Accuracy (%)	Sensitivity (%)	Specificity (%)	Precision (%)	F1-score (%)	Kappa (%)
1	98.51	98.51	98.58	98.52	98.51	96.91
2	99.13	99.13	99.15	99.13	99.13	98.21
3	99.33	99.33	99.34	99.33	99.33	98.62
Mean ± Std	98.99 ± 0.43	98.99 ± 0.43	99.02 ± 0.40	98.99 ± 0.43	98.99 ± 0.43	97.91 ± 0.89

Table 11: Classification Performance of NeuroNetV1 on Alcoholism EEG Dataset AC-XI, Averaged Over 5 Folds for Each Subject. The data for all 122 subjects was combined to form the training and testing set.

Subjects	Accuracy (%)	Sensitivity (%)	Specificity (%)	Precision (%)	F1-score (%)	Kappa (%)

1-122 combined	98.29	98.29	98.27	98.30	98.29	96.34

Table 12: Classification Performance of NeuroNetV1 on Alzheimer EEG Dataset AD-XI, Averaged Over 5 Folds for Each Subject. The data for all 88 subjects was combined to form the training and testing set.

Subjects	**Accuracy (%)**	**Sensitivity (%)**	**Specificity (%)**	**Precision (%)**	**F1-score (%)**	**Kappa (%)**
1-88 combined	89.18	89.18	89.13	89.28	89.21	77.88

Table 13: Classification Performance of NeuroNetV1 on Epilepsy EEG Dataset EP-XI, Averaged Over 5 Folds for Each Subject

Subjects	**Accuracy (%)**	**Sensitivity (%)**	**Specificity (%)**	**Precision (%)**	**F1-score (%)**	**Kappa (%)**
1	98.82	98.82	98.82	98.82	98.82	97.63
2	98.72	98.72	98.72	98.72	98.72	97.43
3	99.15	99.15	99.15	99.15	99.15	98.30
4	98.78	98.78	98.78	98.78	98.78	97.57
5	99.38	99.38	99.38	99.38	99.38	98.77
Mean ± Std	98.97 ± 0.29	98.97 ± 0.29	98.97 ± 0.29	98.97 ± 0.29	98.97 ± 0.29	97.94 ± 0.57

III. Multiple Comparison Correction: Benjamini-Hochberg Results

Multiple hypothesis testing increases the risk of false-positive results, necessitating statistical correction techniques to control for inflated Type I errors. In this study, we applied the Benjamini-Hochberg (BH) correction to the Wilcoxon signed-rank test p-values to ensure that our statistical significance findings remain robust against multiple comparisons. The BH correction method is particularly suitable for our analysis, as it controls the false discovery rate (FDR) while maintaining higher statistical power compared to conservative approaches such as the Bonferroni correction. To assess the impact of multiple comparison correction, we computed the BH-adjusted p-values for all statistical comparisons conducted in the manuscript. The results are illustrated in Fig. 2, which provides a direct comparison between the original Wilcoxon p-values (blue bars) and the BH-corrected p-values (yellow bars) for all models analyzed in this study.

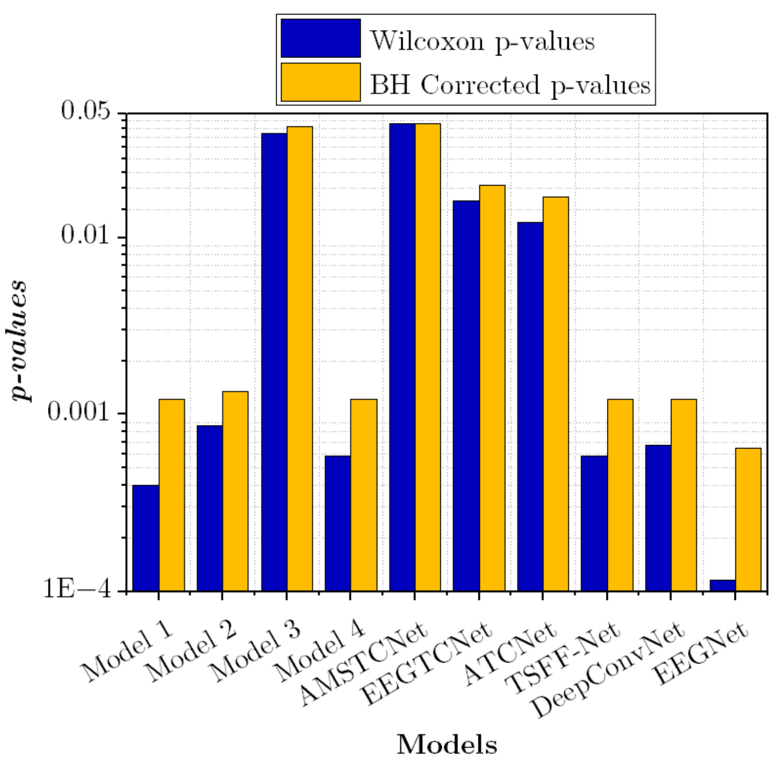

Figure 2: Comparison of Wilcoxon signed-rank test p-values (blue) and Benjamini-Hochberg (BH) corrected p-values between NeuroNetV1 and different models.

After applying the BH correction, the p-values slightly increased across all models compared to their original Wilcoxon values. However, all corrected p-values remained below the 0.05 threshold, confirming that the reported statistical significance of NeuroNetV1's performance is not an artifact of multiple comparisons. This result reinforces the validity of our findings and suggests that the improvements demonstrated by NeuroNetV1 are statistically robust. The extent of correction varied across models, with Model 3 and AMSTCNet exhibiting a more noticeable increase in p-values post-correction. This variation is expected, as the BH procedure ranks p-values and applies corrections based on their relative significance levels. Despite the adjustments, all models retained statistically significant differences, further confirming the reliability of our comparative analysis. Conversely, models such as DeepConvNet, EEGNet, and TSFF-Net showed only minor increases in p-values, indicating that their statistical significance was already strong and less affected by FDR correction. This approach ensures that our statistical analysis remains both rigorous and interpretable while avoiding unnecessary modifications to the main manuscript.

IV. Difference Between ConvAT, Conformer and ATCNet

Figure 2 below illustrates convolutional attention mechanisms across three scenarios: ***a)*** Mimicking the *ConFormer architecture*, where features are first extracted from the EEG signals and then passed to the attention network to compute attention weights for different features. ***b)*** Mimicking the *ATCnet architecture*, where the attention mechanism is applied to the EEG features first, and then convolutional kernels are used to extract temporal features. ***c)*** Our *ConvAT mechanism*, where convolution is integrated directly within the attention process, enabling the model to extract both local and global contextually aware features.

From these architectures, we can identify two major differences in how the mechanisms function:

i. *Traditional Attention in ConFormer and ATCnet:* These models use a conventional attention mechanism that relies on separate weight matrices for queries, keys, and values (denoted as W_q, W_k, W_v). The dimensions of these matrices are $W_q = d \times d_q$, $W_k = d \times d_k$, $W_v = d \times d_v$, accordingly, where d is the embedding size, and d_q, d_k is and d_v represent the query, key, and value dimensions, respectively.

ii. *ConvAT Block:* In contrast, the ConvAT block modifies the traditional attention mechanism by replacing the weight matrices with convolutional kernels. The kernel sizes in ConvAT are designed to match the 1-dimensional time sequence of the input ($T_s \times 1$), allowing the model to focus on local and global dependencies directly in the attention process.

Below, we outline the specific innovations that set ConvAT apart from prior convolution-attention designs:

i. ***Reduction in Weight Matrix Complexity:*** The replacement of traditional attention weight matrices (W_q, W_k, W_v) with convolution kernels simplifies the model architecture, potentially reducing the computational burden and improving efficiency. The number of trainable parameters in traditional attention model are $3d(d_q + d_k + d_v)$ (combining the weight matrices of query, key and value). Whereas, the number of trainable parameters in ConvAT are $3T_s$. This drastically reduces the number of parameters while keeping the soul of attention process intact. A more comprehensive comparison for model parameters and computational efficiency is given in ***Section 4.5 of the manuscript***.

ii. ***Improved Temporal Contextualization:*** Weight matrix multiplication in ConFormer and ATCNet applies a uniform transformation across all time steps, treating each segment equally in terms of attention. It does not allow for nuanced, dynamic focus on short-term vs long-term temporal patterns. In contrast, ConvAT uses convolutional kernels, which are inherently more sensitive to local features and can prioritize temporal patterns at different scales. This results in more effective temporal contextualization, especially for EEG signals with both short-term and long-range dependencies.

iii. ***Flexibility in Temporal Representation:*** The convolutional operation in ConvAT enables the model to learn dynamic time-specific features. The local context captured by convolutions is crucial for accurately understanding time-sensitive phenomena in EEG signals, such as event-related potentials (ERPs), rhythmic brain oscillations and disorder-oriented signals. This is not as naturally possible with fixed weight matrices in traditional attention mechanisms, where long-range dependencies are emphasized more than the short-term local features that are often the most relevant in EEG classification.

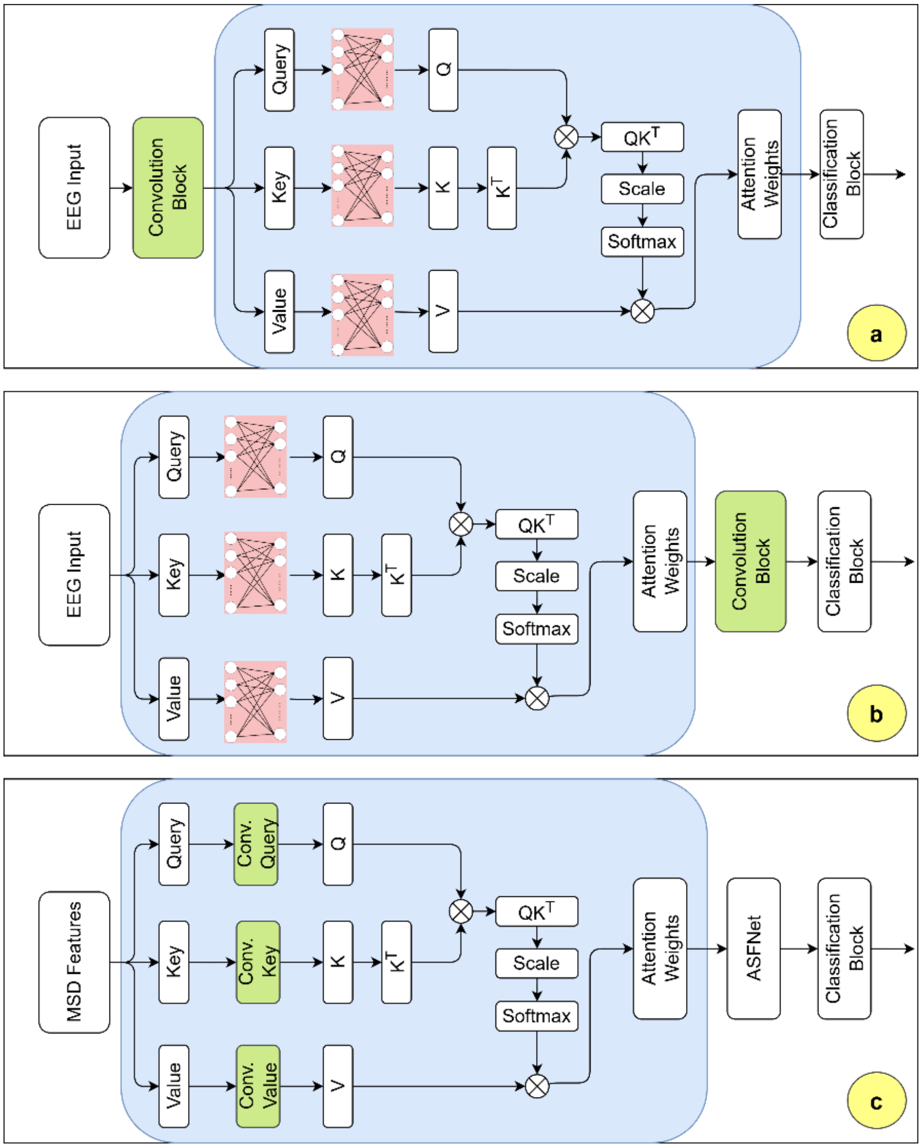

Figure 3: Coupling patterns between convolution and self-attention in EEG models. a) ConFormer-style (Conv→Attn); b) ATCNet-style (Attn→Conv); c) Proposed ConvAT (Conv ⊂ Attn). The Green region indicates convolution operations (either stand-alone blocks or kernels inserted in attention), red denotes fully connected projection weight matrices used in conventional attention, and lastly, blue region showcases self-attention workspace.

V. Extended Comparisons of NeuroNetV1 for Individual Datasets

Table 14: Extended Performance Evaluation of NeuroNetV1 Against Other Classification Methods on the MI-I Dataset.

Sr. #	Authored By	Publication Year	Methodology Name	Average Accuracy (%)
1	Shalu et.al [1]	2019	DCNN	99.35
2	**Our Study**	**2025**	**NeuroNetV1**	**98.75**
3	Sadiq et al [2]	2019	MEWT	97
4	Taheri et.al [3]	2020	CT+ Fourier EEMD+ CSP+DCNN	96.34
5	Wijaya et al. [4]	2021	LRFS+TSD	95.21
6	Xianglong et.al [5]	2025	Multi-Domain Feature Rotation and Stacking Ensemble	92.92
7	Yu et.al [6]	2015	SFBCSP	92.05
8	Ming et.al [7]	2024	STGAT-CS	91.50
9	Liang et.al [8]	2023	PCC+GCN	89.14
10	Miao et.al [9]	2020	Adaptive Multi-Domain Feature Optimization	87.80
11	Miao et.al [10]	2021	SFT-3D CNN	86.60

Table 15: Extended Performance Evaluation of NeuroNetV1 Against Other Classification Methods on the MI-II Dataset.

Sr. #	Authored By	Publication Year	Methodology Name	Average Accuracy (%)
1	Hamidi et.al [11]	2025	Transformer+ GCN	97.43
2	Hou et al. [12]	2022	Attention-based BiLSTM-GCN	95.48
3	Huang et.al [13]	2023	RP-BCNNs	94.07
4	Hou et al. [14]	2022	GCNs-net	93
5	**Our Study**	**2025**	**NeuroNetV1**	**92.84**
6	Huang et al. [15]	2023	Convolutional Sliding window Attention Network (CSANet)	92.36
7	Fan et.al [16]	2023	3D-convolutional neural networks	89.86
8	Dose et.al [17]	2018	CNNs	87.98
9	Chowdhury et.al [18]	2023	EEGNet Fusion V2	87.80
10	Moaveninejad et al. [19]	2024	Using Fractal Dimension as a discriminative feature + machine learning	86
11	Lin et al. [20]	2024	NGC-STCSA SaSFS	84.49

Table 16: Extended Performance Evaluation of NeuroNetV1 Against Other Classification Methods on the MI-III Dataset.

Sr. #	Authored By	Publication Year	Methodology Name	Average Accuracy (%)
1	Wu et.al [21]	2023	Compact CNN	96.75
2	**Our Study**	**2025**	**NeuroNetV1**	**94**
3	Grear et al. [22]	2021	DR+ICA+SVM	93
4	Fan et.al [16]	2023	Compact 3D-CNN	91.91
5	Huang et al. [23]	2022	EFD-CNN	89.97
6	Chowdhury et.al [24]	2024	AIDC-CN	89.47
7	Zhang et.al [25]	2024	GPL	84.22
8	Yu et.al [26]	2021	IEFD	83.84
9	Kumar et.al [27]	2019	LSTM_CSP	82.22
10	Park et.al [28]	2023	3D-EEGNet	81.31
11	Zheng et.al [29]	2021	Adaptive layer+ fully connected layer	76

Table 17: Extended Performance Evaluation of NeuroNetV1 Against Other Classification Methods on the MI-IV Dataset.

Sr. #	Authored By	Publication Year	Methodology Name	Average Accuracy (%)
1	Phadikar et.al [100]	2023	Transforming EEG signal into a new domain, weight vector of autoencoder, unsupervised neural network	97
2	**Our Study**	**2025**	**NeuroNetV1**	**96.57**
3	Wang et.al [30]	2024	ERDFIS-2DSCG	89.89
4	Cai et.al [31]	2024	MT-MBCNN	89.30
5	Zhang et.al [32]	2023	CLRNet	89
6	Yang et.al [33]	2024	MSFCNNet	87.16
7	Lian et.al [34]	2024	An end-to-end deep neural network	85.10
8	Song et.al [35]	2023	FBCSP+ Transformer	84.16
9	Gu et.al [36]	2025	LSTM+ Transformer	83.02
10	Zhao et.al [37]	2024	CTNet	83
11	Zheng et.al [29]	2021	Adaptive layer+ fully connected layer	82
12	Zhao et.al [38]	2025	Multi-branch temporal convolutional network	81.47

Table 18: Extended Performance Evaluation of NeuroNetV1 Against Other Classification Methods on the MeI-V Dataset.

Sr. #	Authored By	Publication Year	Methodology Name	Average Accuracy (%)
1	Sadiq et. al [44]	2020	SDI feature extraction	99.33
2	**Our Study**	**2025**	**NeuroNetV1**	**98.18**
3	Li et.al [39]	2023	MABLES	94.87
4	Yu et.al [40]	2022	CABLES	94
5	Huang et al. [41]	2022	EFD-CNN	93.81
6	Manoharan et.al [42]	2022	DWT+SVM+ANN	92
7	Sadiq et.al [43]	2020	Matrix determinant feature extraction	91.80
8	Yu et.al [45]	2021	IEFD+ Welch PSD+FFNN	88.08
9	Siuly et al. [46]	2017	PCA based RF Model	83.27
10	Tiwari et.al [47]	2022	MIDNN	82.48
11	Hashim et.al [48]	2021	LS-SVM	81.67

Table 19: Extended Performance Evaluation of NeuroNetV1 Against Other Classification Methods on the P300-VI Dataset.

Sr. #	Authored By	Publication Year	Methodology Name	Average Accuracy (%)
1	**Our Study**	**2025**	**NeuroNetV1**	**96.45**
2	Rabeya et.al [49]	2024	SVM	80.48
3	Bhattacharyya et.al [50]	2017	An online transferable BCI system	74
4	Tong et.al [51]	2016	A new approach of fusing multiple-channel features from temporal, spectral, and spatial domains through two times of dimensionality reduction based on neural network	78.18
5	Sowndhararajan et.al [52]	2018	xDAWN	78

Table 20: Extended Performance Evaluation of NeuroNetV1 Against Other Classification Methods on the SCP-VII Dataset.

Sr. #	Authored By	Publication Year	Methodology Name	Average Accuracy (%)

1	Nazila et.al [53]	2023	FAM+SVM	99.83
2	Annaby et. al [54]	2019	Digraph Fourier transforms	96.58
3	Paranjape et.al [55]	2019	SVM+KNN	95
4	Hou et. al [56]	2018	V-SVM	94.50
5	**Our Study**	**2025**	**NeuroNetV1**	**94.20**
6	L. Duan et.al [57]	2016	PCA+LDA	94.20
7	Meena et.al [58]	2018	A preprocessing block for signal denoising of slow cortical potential (SCP)	94.10
8	Göksu et.al [59]	2018	Log Energy Entropy of wavelet packet analysis	92.80
9	Hou et. al [60]	2019	Concave convex feature	92.50
10	Duan et.al [61]	2017	KHELM	92
11	Yazici et.al [62]	2015	Time domain features + Nonlinear classifier	91.10

Table 21: Extended Performance Evaluation of NeuroNetV1 Against Other Classification Methods on the Emot-VIII Dataset.

Sr. #	Authored By	Publication Year	Methodology Name	Average Accuracy (%)
1	Zhang et.al [63]	2021	SparseDGCNN	98.53
2	Pusarla et.al [64]	2022	LMD	98.00
3	Hou et. al [65]	2024	MECAM	98
4	Gu et.al [66]	2023	DGGN	97.28
5	Li et al. [67]	2023	GMSS	96.48
6	**Our Study**	**2025**	**NeuroNetV1**	**95.58**
7	Zhong et.al [68]	2022	RGNN	94.24
8	Li et al. [69]	2021	BiHDM	93.12
9	Li et al. [70]	2018	BiDANN	92.38
10	Wang et.al [71]	2020	DGCNN	92.27
11	Li et.al [72]	2022	Reduced channel + PSD feature	89.63
12	Zhang et.al [73]	2019	STRNN	89.50
13	Zheng et.al [74]	2015	DBN	86.08
14	Zheng et.al [75]	2017	GSCCA	82.96

Table 22: Extended Performance Evaluation of NeuroNetV1 Against Other Classification Methods on the Sleep-IX Dataset.

Sr. #	Authored By	Publication Year	Methodology Name	Average Accuracy (%)
1	Liu et.al [76]	2024	GCN+ Transfomer	97.10
2	Xiao et.al [77]	2024	SPTESleepNet	96.60
3	**Our Study**	**2025**	**NeuroNetV1**	**95.21**
4	Duan et.al [78]	2025	MMS-SleepNet	92.90
5	Mao et.al [79]	2024	MVFSleepNet	90
6	Phan et.al [80]	2023	L-SeqSleepnet	88.60
7	Cong et.al [81]	2024	BiTS-SleepNet	88.50
8	Tsoi et.al [82]	2024	Positive-only approach	87.10
9	She et.al [83]	2024	CBLSNet	86.40
10	Shen et.al [84]	2023	LGSleepNet	86.00
11	Singh et.al [85]	2024	Efficient AttnSleep	85.80

Table 23: Extended Performance Evaluation of NeuroNetV1 Against Other Classification Methods on the SZ-X Dataset.

Sr. #	Authored By	Publication Year	Methodology Name	Average Accuracy (%)
1	Siuly et. al [101]	2023	DeepResNet	99.23
2	**Our Study**	**2025**	**NeuroNetV1**	**98.99**
3	Li et.al [39]	2023	MABLES	95.28
4	Yu et.al [86]	2022	CABLES	92
5	Siuly et.al [87]	2020	EMD+IMF	89.59
6	Bose et.al [88]	2017	A modified odd ball-paradigms	88.50
7	Faizal et. al [89]	2023	CNN	86.93

Table 24: Extended Performance Evaluation of NeuroNetV1 Against Other Classification Methods on the EP-XIII Dataset.

Sr. #	Authored By	Publication Year	Methodology Name	Average Accuracy (%)
1	Parija et.al [90]	2024	CWCA-OVMD-CSAE-KELM	99
2	**Our Study**	**2025**	**NeuroNetV1**	**98.97**
3	Kumar et. al [91]	2017	Approximate Entropy, Reiny Entropy, Sample Entropy, Non-nested generalized exemplars classifier	98
4	Sharma et. al [92]	2017	TQWT, Entropy, LS-SVM	95
5	Gupta et. al [93]	2017	FAWT, entropy, LS-SVM	94.41
6	Sharma et. al [94]	2017	WFB, Entropy, LS-SVM	94.2
7	Sriraam et. al [95]	2017	statistical, frequency based, entropy, FD, SVM	92.1
8	Das et. al [96]	2016	EMD–DWT, entropy, KNN	89.40
9	Acharya et. a. [97]	2019	bi-spectrum, DFA, entropies, FD, Hjorth parameters, Hurst exponent Kolmogorov complexity, LLE, LZC, LS-SVM	87.93
10	Sharma et.al [98]	2015	Average of Entropies over IMF + LS-SVM	87
11	Bhattacharyya et. al [99]	2017	TQWT, entropy, LS-SVM	84.67

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