# MSVTNet: Multi-Scale Vision Transformer Neural Network for EEG-Based Motor Imagery Decoding

Ke Liu, Tao Yang, Zhuliang Yu, *Member, IEEE*, Weibo Yi, Hong Yu, Guoyin Wang, Wei Wu*, *Senior Member, IEEE*

## I. Evaluation Metrics

The effectiveness of our proposed model is assessed using accuracy, standard deviation and kappa as evaluation metrics:

*1) Accuracy:*

$$Acc = \frac{1}{S}\sum_{s=1}^{S} SubAcc_s, \quad SubAcc = \frac{n_{true}}{n_{target}} \times 100\% \tag{1}$$

where $Acc$ and $SubAcc$ is the decoding accuracy for each subject and the overall model, respectively. $n_{target}$ represents the total number of trials in the test set, $n_{true}$ represents the number of correctly classified trials, and $S$ represents the total number of subjects in the dataset.

*2) Standard deviation:*

$$Std = \sqrt{\frac{1}{S}\sum_{s=1}^{S}(SubAcc_s - Acc)^2} \tag{2}$$

*3) Kappa:*

$$Kappa = \frac{Acc - p_e}{1 - p_e} \tag{3}$$

where $p_e$ is the hypothetical probability of chance agreement.

## II. Experiment Analysis

TABLE I
Trainable Parameters of Different Deep Learning Methods

| Dataset | Shallow ConvNet | EEGNet | FBCNet | EEG Conformer | Light ConvNet | IFNet | MSVTNet | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Subject-dependent | Subject-independent |
| BCICIV2A | 23,444 | 1,884 | 11,812 | 789,572 | 13,156 | 11,396 | 75,494 | 43.670 |
| BCICIV2B | 11,722 | 1,354 | 4,034 | 759,106 | 2,082 | 7,938 | 71,524 | 39,700 |
| OpenBMI | 12,402 | 1,626 | 8,930 | 786,306 | 11,874 | 10,114 | 72,748 | 40,924 |

TABLE II
Data Volumes for Different Experiments. The Numbers Indicate The Number of Trials in The Training and Test Sets for Each Subject

| Dataset | Subject-dependent | | Subject-independent |
|---|---|---|---|
| | Session-dependent | Session-independent | |
| BCICIV2A | 432 / 72 | 576 / 288 | 2304 / 288 |
| BCICIV2B | 180 / 30 | 800 / 320 | 5800 / 720 |
| OpenBMI | 300 / 50 | 400 / 200 | 21200 / 400 |

To clearly present the number of trainable parameters for all deep learning algorithms in the experimental settings, as well as the number of trials under different datasets and analyses, we provide statistics in Table I and Table II, respectively.

It is noteworthy that on the OpenBMI dataset, most deep learning-based algorithms exhibit better decoding performance in the subject-dependent analysis compared to the subject-independent analysis. This is consistent with [1], indicating that deep learning models benefit from more training data. To investigate the underlying reasons for the accuracy improvement, we categorize subjects based on a 70% decoding accuracy threshold [2] in session-dependent and session-independent analyses, and then calculate the average decoding accuracy of these subjects in the subject-independent analysis. As shown in Fig. 1, those subjects who originally have decoding accuracies greater than 70% in the session-dependent and session-independent

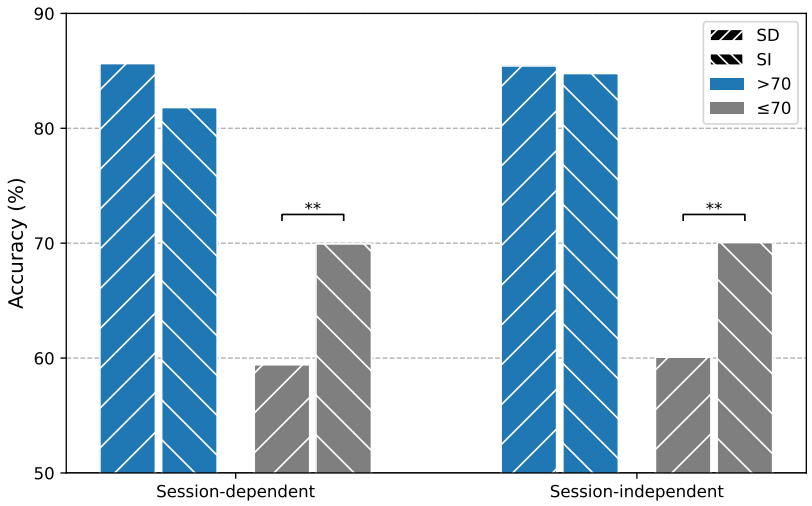


Fig. 1. Comparison of subject-independent decoding performance. SD and SI represent the performance of baseline subjects in the subject-dependent analysis and the corresponding subjects in the subject-independent analysis, respectively. ** indicates statistical significance with $p < 0.01$.

analyses show a slight performance decline in the subject-independent analysis. Conversely, the average accuracy of those subjects with original accuracies less than or equal to 70% increases by around 10% in the subject-independent analysis, with a statistically significant difference (p ¡ 0.01). This suggests that the large amount of training data from multiple subjects can significantly enhance the decoding performance of deep learning models for BCI illiterate users [3].

## III. Single Subject Classification Accuracies

For reproducibility and future comparisons, the single subject MI classification accuracies achieved by FBCSP-SVM [4], Shallow ConvNet [5], EEGNet [6], FBCNet [7], EEG Conformer [8], Ligth ConvNet [9], IFNet [10] and MSVTNet for subject-dependent (session-dependent and session-independent) and subject-independent analyses on BCI Competition IV 2a (BCIC-IV-2a) [11], BCI Competition IV 2b (BCIC-IV-2b) [12] and OpenBMI [13] datasets are presented in Table III, IV, V, VI and VII, respectively.

TABLE III
Classification Accuracies in % for Each Subject on the BCIC-IV-2a Dataset

| Experiment | | Method | S01 | S02 | S03 | S04 | S05 | S06 | S07 | S08 | S09 | Avg | Std |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subject-dependent | Session-dependent | FBCSP-SVM | 79.17 | 65.28 | 88.89 | 62.50 | 70.83 | 43.06 | 93.06 | 84.72 | 63.89 | 72.38 | 14.84 |
| | | Shallow ConvNet | 74.17 | 63.33 | 90.56 | 60.56 | 65.56 | 66.94 | 80.56 | 80.00 | 78.33 | 73.33 | 9.33 |
| | | EEGNet | 75.28 | 52.50 | 88.33 | 69.72 | 69.72 | 67.50 | 79.44 | 85.00 | 88.61 | 75.12 | 11.06 |
| | | FBCNet | 78.06 | 56.94 | 95.28 | 68.33 | 79.17 | 50.28 | 84.44 | 87.50 | 78.89 | 75.43 | 13.66 |
| | | EEG Conformer | 72.50 | 61.39 | 87.22 | 64.72 | 62.22 | 58.61 | 79.17 | 87.22 | 57.78 | 70.09 | 11.18 |
| | | Light ConvNet | 84.17 | 62.78 | 91.11 | 73.61 | 80.28 | 61.94 | 92.50 | 89.72 | 79.17 | 79.48 | 10.82 |
| | | IFNet | 85.56 | 59.44 | 95.28 | 61.11 | 69.17 | 56.67 | 86.39 | 88.61 | 78.61 | 75.65 | 13.55 |
| | | MSVTNet | 81.67 | 64.17 | 93.61 | 77.78 | 80.56 | 78.61 | 90.56 | 87.50 | 88.61 | 82.56 | 8.36 |
| | Session-independent | FBCSP-SVM | 81.60 | 50.00 | 80.90 | 60.07 | 46.53 | 46.53 | 85.07 | 78.13 | 70.14 | 66.56 | 15.06 |
| | | Shallow ConvNet | 74.38 | 56.46 | 84.38 | 68.75 | 54.24 | 55.83 | 74.38 | 81.32 | 71.88 | 69.07 | 10.56 |
| | | EEGNet | 81.74 | 52.92 | 85.42 | 63.19 | 70.62 | 56.81 | 84.24 | 78.12 | 80.62 | 72.63 | 11.58 |
| | | FBCNet | 81.88 | 54.44 | 89.31 | 76.94 | 65.42 | 55.90 | 84.72 | 79.24 | 81.94 | 74.42 | 11.99 |
| | | EEG Conformer | 78.89 | 52.22 | 84.31 | 68.40 | 55.97 | 57.22 | 79.24 | 75.21 | 76.67 | 69.79 | 11.15 |
| | | Light ConvNet | 86.46 | 54.31 | 90.49 | 78.47 | 64.10 | 60.35 | 86.25 | 84.65 | 84.31 | 76.60 | 12.60 |
| | | IFNet | 83.68 | 51.74 | 90.83 | 76.25 | 67.85 | 57.50 | 88.75 | 82.15 | 84.17 | 75.88 | 13.09 |
| | | MSVTNet | 85.76 | 54.38 | 91.74 | 75.90 | 77.22 | 68.26 | 88.26 | 80.14 | 84.79 | 78.50 | 10.86 |
| Subject-independent | | FBCSP-SVM | 41.15 | 25.00 | 53.30 | 31.25 | 27.43 | 28.65 | 22.74 | 56.25 | 43.23 | 36.56 | 11.70 |
| | | Shallow ConvNet | 66.67 | 39.93 | 81.08 | 50.87 | 44.62 | 49.65 | 68.58 | 73.96 | 67.19 | 60.28 | 13.49 |
| | | EEGNet | 72.57 | 47.40 | 75.87 | 56.08 | 55.03 | 44.79 | 65.97 | 75.52 | 66.15 | 62.15 | 11.12 |
| | | FBCNet | 67.01 | 37.50 | 65.97 | 50.87 | 27.43 | 32.47 | 43.75 | 63.54 | 58.68 | 49.69 | 14.20 |
| | | EEG Conformer | 56.94 | 42.19 | 70.49 | 48.61 | 52.43 | 50.52 | 72.92 | 70.83 | 51.91 | 57.43 | 10.56 |
| | | Light ConvNet | 64.58 | 34.72 | 68.23 | 46.53 | 37.33 | 35.76 | 44.97 | 61.28 | 57.99 | 50.15 | 12.34 |
| | | IFNet | 60.76 | 30.73 | 77.95 | 45.83 | 29.51 | 34.72 | 40.10 | 62.85 | 65.45 | 49.77 | 16.47 |
| | | MSVTNet | 67.71 | 45.31 | 85.76 | 53.30 | 50.35 | 47.40 | 75.17 | 81.42 | 70.49 | 64.10 | 14.47 |

TABLE IV
CLASSIFICATION ACCURACIES IN % FOR EACH SUBJECT ON THE BCIC-IV-2B DATASET

| Experiment | | Method | S01 | S02 | S03 | S04 | S05 | S06 | S07 | S08 | S09 | Avg | Std |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subject-dependent | Session-dependent | FBCSP-SVM | 56.67 | 50.00 | 66.67 | 80.00 | 88.57 | 70.00 | 60.00 | 63.33 | 36.67 | 63.54 | 14.58 |
| | | Shallow ConvNet | 56.00 | 57.33 | 43.33 | 86.29 | 83.43 | 78.67 | 65.33 | 74.00 | 44.00 | 65.38 | 15.31 |
| | | EEGNet | 65.33 | 62.67 | 50.67 | 87.43 | 69.71 | 91.33 | 78.67 | 62.67 | 54.00 | 69.16 | 13.28 |
| | | FBCNet | 58.00 | 55.33 | 55.33 | 93.14 | 90.86 | 85.33 | 52.67 | 64.00 | 46.00 | 66.74 | 16.99 |
| | | EEG Conformer | 74.67 | 56.67 | 56.67 | 85.14 | 93.14 | 68.00 | 66.00 | 65.33 | 49.33 | 68.33 | 13.27 |
| | | Light ConvNet | 64.00 | 62.00 | 51.33 | 92.57 | 88.00 | 76.67 | 66.00 | 65.33 | 46.67 | 68.06 | 14.43 |
| | | IFNet | 76.00 | 52.00 | 58.00 | 89.71 | 90.86 | 84.00 | 60.00 | 72.67 | 47.33 | 70.06 | 15.44 |
| | | MSVTNet | 60.67 | 67.33 | 58.00 | 90.86 | 81.14 | 82.00 | 78.67 | 62.67 | 51.33 | 70.30 | 12.55 |
| | Session-independent | FBCSP-SVM | 62.19 | 56.43 | 52.19 | 95.31 | 86.25 | 79.69 | 77.19 | 87.19 | 77.81 | 74.92 | 13.95 |
| | | Shallow ConvNet | 71.38 | 65.21 | 79.00 | 81.81 | 81.31 | 79.81 | 83.37 | 90.56 | 82.69 | 79.46 | 6.88 |
| | | EEGNet | 74.56 | 67.36 | 84.50 | 97.25 | 91.31 | 78.94 | 93.06 | 93.56 | 88.38 | 85.44 | 9.40 |
| | | FBCNet | 71.94 | 51.36 | 64.19 | 96.50 | 91.50 | 82.94 | 81.44 | 91.75 | 86.56 | 79.80 | 13.87 |
| | | EEG Conformer | 70.00 | 63.93 | 81.75 | 95.94 | 90.38 | 76.19 | 84.56 | 92.94 | 84.25 | 82.21 | 10.00 |
| | | Light ConvNet | 74.38 | 54.21 | 69.12 | 97.31 | 91.81 | 86.19 | 83.00 | 91.44 | 84.50 | 81.33 | 12.63 |
| | | IFNet | 73.25 | 54.71 | 59.06 | 97.50 | 86.19 | 84.62 | 83.19 | 92.81 | 90.19 | 80.17 | 14.01 |
| | | MSVTNet | 75.56 | 70.36 | 85.00 | 96.06 | 94.69 | 85.06 | 91.50 | 94.06 | 88.00 | 86.70 | 8.35 |
| Subject-independent | | FBCSP-SVM | 70.97 | 54.56 | 52.50 | 74.86 | 67.30 | 75.56 | 73.75 | 66.18 | 73.61 | 67.80 | 8.17 |
| | | Shallow ConvNet | 73.47 | 66.76 | 60.56 | 80.81 | 82.16 | 79.44 | 78.19 | 75.00 | 72.22 | 74.29 | 6.64 |
| | | EEGNet | 76.53 | 70.44 | 64.72 | 75.68 | 83.65 | 76.81 | 83.75 | 79.47 | 73.61 | 76.07 | 5.73 |
| | | FBCNet | 74.03 | 59.12 | 61.67 | 80.54 | 78.78 | 73.33 | 70.97 | 74.34 | 76.94 | 72.19 | 6.90 |
| | | EEG Conformer | 70.28 | 70.29 | 60.42 | 81.49 | 80.27 | 76.11 | 77.50 | 72.76 | 73.33 | 73.61 | 6.01 |
| | | Light ConvNet | 71.25 | 59.41 | 61.94 | 83.78 | 81.89 | 74.03 | 72.36 | 72.63 | 75.42 | 72.52 | 7.53 |
| | | IFNet | 72.78 | 60.29 | 56.11 | 80.81 | 75.14 | 80.83 | 73.47 | 72.50 | 80.00 | 72.44 | 8.30 |
| | | MSVTNet | 74.86 | 71.47 | 61.94 | 82.03 | 83.24 | 85.00 | 81.67 | 71.45 | 76.39 | 76.45 | 7.00 |

## IV. CONFUSION MATRIX FOR ALL EXPERIMENTS

To more comprehensively compare the performance of different decoding algorithms on the BCIC-IV-2a, 2b and OpenBMI datasets, the confusion matrices of all analysis experiments are displayed in Fig. 2, 3 and 4, respectively. Compared with the contrastive algorithms, MSVTNet achieved higher decoding accuracy for each MI class with smaller variance in all analysis experiments, demonstrating the reliability and generalization of the model decoding performance.

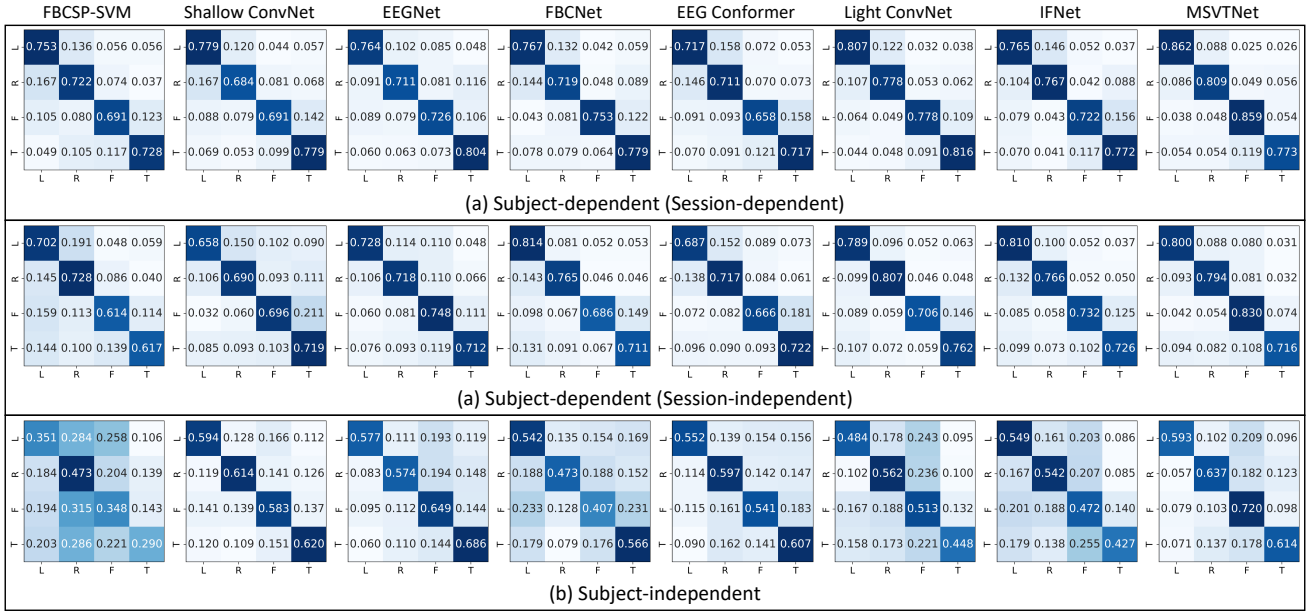


Fig. 2. Confusion matrices for different models on the BCIC-IV-2a dataset. Each column represents the true label and each row depicts the predicted label. L, R, F, and T refer to MI of left hand, right hand, feet and tongue, respectively.

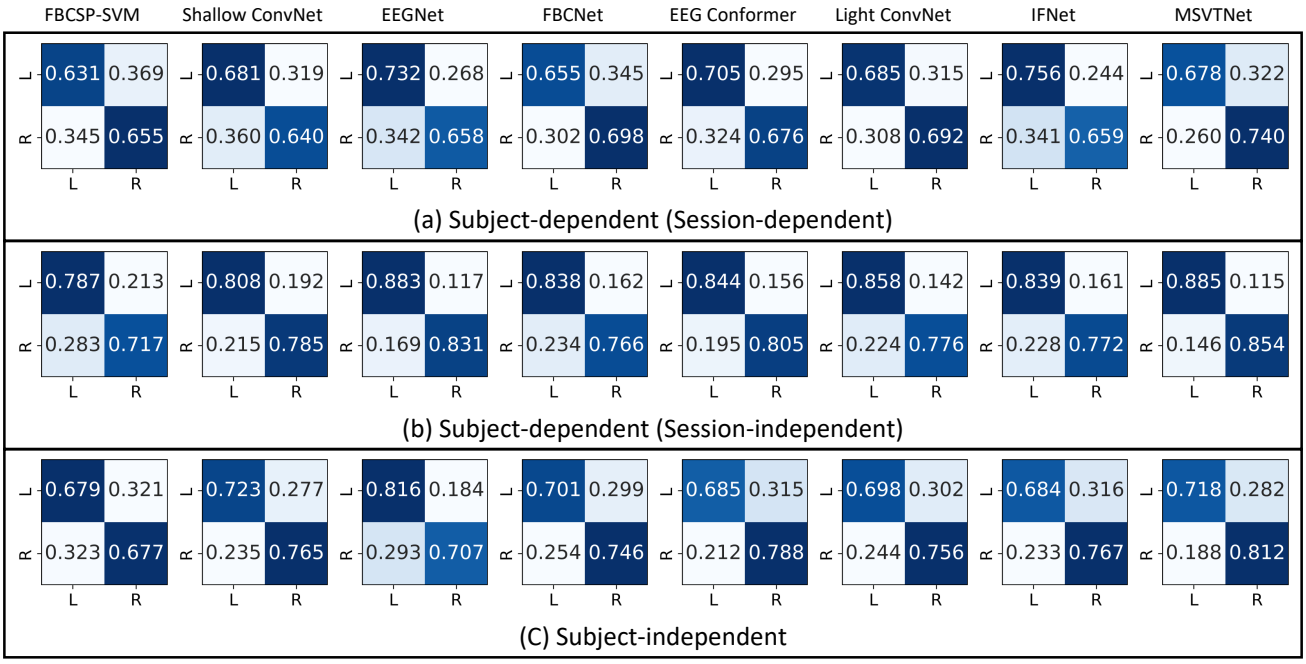


Fig. 3. Confusion matrices for different models on the BCIC-IV-2b dataset. Each column represents the true label and each row depicts the predicted label. L and R refer to MI of left hand and right hand, respectively.

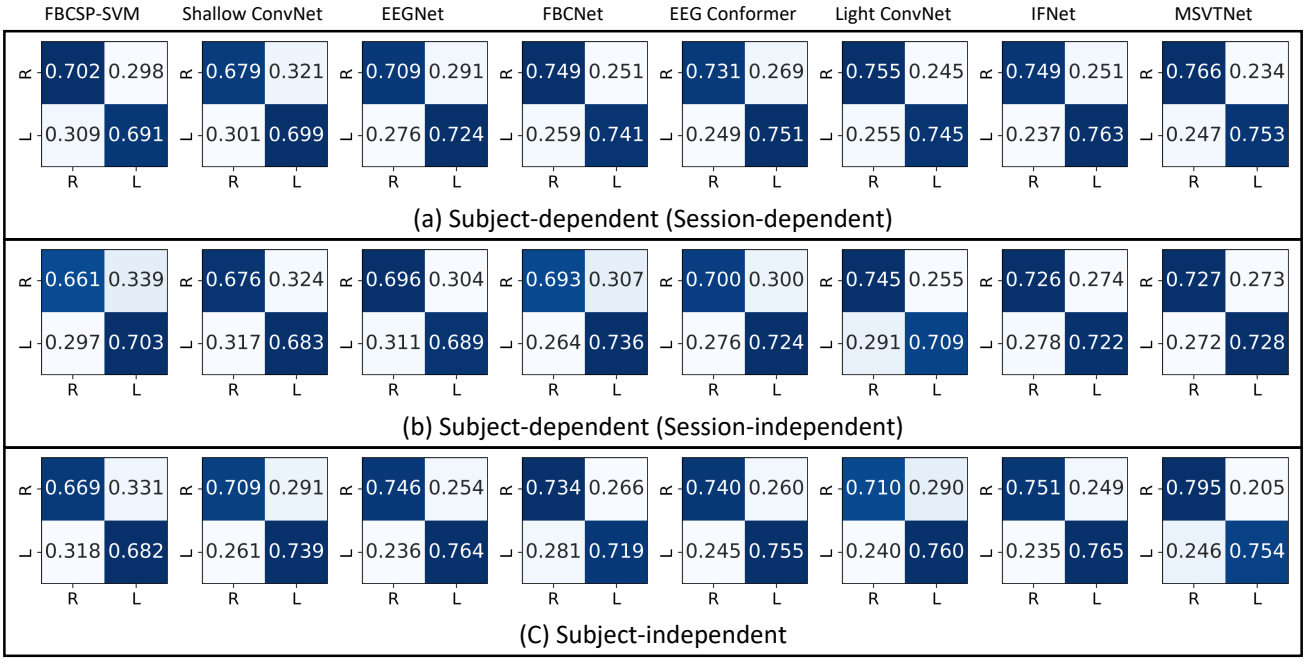


Fig. 4. Confusion matrices for different models on the OpenBMI dataset. Each column represents the true label and each row depicts the predicted label. L and R refer to MI of left hand and right hand, respectively.

TABLE V
CLASSIFICATION ACCURACIES IN % USING SUBJECT-DEPENDENT (SESSION-DEPENDENT) ANALYSIS FOR EACH SUBJECT ONT THE OPENBMI DATASET

| Subject No. | FBCSP-SVM | Shallow ConvNet | EEGNet | FBCNet | EEG Conformer | Light ConvNet | IFNet | MSVTNet |
|---|---|---|---|---|---|---|---|---|
| 1 | 78.00 | 74.80 | 80.80 | 81.20 | 74.80 | 74.00 | 85.60 | 82.40 |
| 2 | 100.00 | 98.40 | 100.00 | 100.00 | 98.80 | 98.80 | 100.00 | 100.00 |
| 3 | 90.00 | 93.20 | 97.20 | 94.40 | 89.20 | 87.20 | 96.80 | 97.60 |
| 4 | 58.00 | 62.80 | 65.20 | 66.40 | 60.80 | 60.40 | 73.20 | 63.60 |
| 5 | 98.00 | 85.60 | 98.00 | 91.20 | 91.60 | 96.80 | 97.60 | 98.80 |
| 6 | 78.00 | 70.00 | 79.60 | 76.80 | 82.80 | 80.00 | 77.20 | 81.20 |
| 7 | 60.00 | 53.60 | 49.60 | 56.80 | 72.00 | 57.60 | 68.00 | 66.80 |
| 8 | 40.00 | 55.20 | 69.20 | 78.40 | 65.60 | 69.60 | 70.00 | 67.20 |
| 9 | 78.00 | 76.80 | 85.20 | 79.60 | 78.00 | 83.20 | 81.20 | 80.00 |
| 10 | 64.00 | 69.20 | 71.20 | 76.00 | 69.20 | 70.40 | 72.40 | 74.40 |
| 11 | 42.00 | 50.00 | 46.00 | 52.80 | 64.00 | 60.40 | 48.00 | 58.80 |
| 12 | 56.00 | 63.60 | 73.20 | 66.00 | 69.60 | 73.60 | 66.00 | 75.20 |
| 13 | 54.00 | 44.80 | 52.40 | 56.80 | 62.80 | 61.60 | 56.80 | 70.80 |
| 14 | 68.00 | 58.80 | 57.60 | 74.40 | 64.40 | 70.00 | 63.60 | 70.40 |
| 15 | 50.00 | 63.20 | 72.40 | 76.80 | 66.40 | 71.20 | 66.00 | 76.80 |
| 16 | 42.00 | 61.20 | 58.80 | 58.40 | 56.80 | 53.20 | 57.20 | 54.40 |
| 17 | 78.00 | 75.60 | 79.60 | 82.40 | 86.00 | 83.20 | 80.80 | 88.40 |
| 18 | 90.00 | 84.00 | 94.00 | 86.00 | 89.20 | 91.20 | 90.80 | 90.80 |
| 19 | 76.00 | 84.40 | 83.60 | 88.00 | 82.80 | 80.80 | 89.60 | 83.60 |
| 20 | 52.00 | 52.80 | 56.40 | 60.40 | 65.20 | 70.40 | 66.00 | 57.60 |
| 21 | 98.00 | 96.00 | 98.40 | 98.40 | 99.60 | 99.60 | 100.00 | 100.00 |
| 22 | 90.00 | 76.40 | 90.40 | 90.80 | 84.40 | 89.60 | 92.00 | 89.60 |
| 23 | 68.00 | 64.80 | 69.20 | 67.20 | 62.00 | 65.20 | 70.80 | 73.20 |
| 24 | 52.00 | 56.80 | 47.20 | 47.60 | 58.80 | 66.00 | 55.20 | 63.60 |
| 25 | 52.00 | 60.80 | 55.60 | 68.80 | 57.20 | 64.40 | 61.60 | 62.40 |
| 26 | 52.00 | 58.00 | 49.20 | 55.60 | 56.00 | 52.40 | 56.00 | 53.20 |
| 27 | 52.00 | 57.60 | 50.40 | 66.80 | 63.60 | 63.20 | 62.40 | 57.20 |
| 28 | 98.00 | 89.60 | 92.80 | 94.00 | 96.40 | 94.40 | 95.60 | 94.40 |
| 29 | 94.00 | 84.00 | 86.80 | 90.80 | 88.00 | 92.00 | 89.60 | 86.80 |
| 30 | 82.00 | 63.60 | 69.20 | 74.80 | 73.60 | 74.80 | 82.40 | 75.60 |
| 31 | 76.00 | 70.00 | 76.40 | 74.40 | 80.80 | 76.40 | 95.60 | 85.60 |
| 32 | 78.00 | 84.80 | 79.20 | 88.40 | 82.40 | 83.20 | 82.00 | 85.20 |
| 33 | 100.00 | 94.00 | 99.60 | 100.00 | 100.00 | 98.40 | 100.00 | 100.00 |
| 34 | 42.00 | 55.20 | 59.20 | 67.20 | 60.40 | 59.60 | 68.80 | 60.40 |
| 35 | 64.00 | 83.60 | 86.80 | 85.20 | 78.40 | 88.80 | 84.00 | 89.60 |
| 36 | 96.00 | 92.00 | 96.00 | 92.40 | 95.20 | 94.40 | 98.00 | 96.40 |
| 37 | 98.00 | 90.80 | 95.60 | 96.00 | 95.20 | 94.80 | 96.80 | 98.00 |
| 38 | 46.00 | 60.80 | 49.20 | 61.60 | 63.60 | 56.40 | 55.20 | 57.20 |
| 39 | 92.00 | 84.00 | 88.00 | 84.80 | 87.60 | 89.20 | 94.40 | 95.20 |
| 40 | 58.00 | 50.00 | 60.40 | 54.00 | 54.80 | 54.00 | 53.60 | 60.80 |
| 41 | 66.00 | 59.60 | 55.20 | 66.00 | 62.00 | 65.60 | 68.80 | 71.60 |
| 42 | 46.00 | 50.00 | 50.00 | 57.20 | 56.00 | 58.40 | 56.00 | 54.00 |
| 43 | 86.00 | 71.20 | 77.20 | 77.20 | 82.80 | 82.80 | 91.60 | 82.00 |
| 44 | 98.00 | 88.80 | 97.20 | 94.00 | 90.40 | 97.20 | 96.80 | 98.80 |
| 45 | 92.00 | 87.60 | 88.80 | 90.00 | 89.60 | 92.40 | 97.20 | 92.00 |
| 46 | 56.00 | 58.40 | 48.80 | 58.00 | 61.20 | 70.00 | 51.20 | 60.80 |
| 47 | 48.00 | 52.40 | 46.00 | 51.20 | 56.40 | 59.60 | 55.20 | 50.40 |
| 48 | 56.00 | 70.00 | 64.00 | 75.20 | 70.40 | 83.20 | 74.40 | 74.40 |
| 49 | 70.00 | 63.60 | 73.20 | 75.60 | 77.20 | 74.40 | 73.20 | 76.00 |
| 50 | 50.00 | 51.20 | 57.20 | 55.60 | 61.20 | 62.80 | 58.40 | 59.20 |
| 51 | 58.00 | 52.40 | 64.00 | 69.20 | 72.00 | 66.80 | 67.60 | 68.80 |
| 52 | 78.00 | 63.20 | 72.80 | 72.40 | 78.40 | 73.20 | 79.60 | 76.80 |
| 53 | 52.00 | 51.60 | 55.20 | 63.20 | 60.00 | 62.80 | 64.00 | 58.00 |
| 54 | 66.00 | 50.80 | 50.40 | 55.60 | 57.20 | 51.60 | 47.60 | 54.00 |
| Avg | 69.67 | 68.92 | 71.66 | 74.48 | 74.13 | 75.02 | 75.60 | 75.93 |
| Std | 18.82 | 14.90 | 17.31 | 14.52 | 13.66 | 14.16 | 16.14 | 15.14 |

TABLE VI
CLASSIFICATION ACCURACIES IN % USING SUBJECT-DEPENDENT (SESSION-INDEPENDENT) ANALYSIS FOR EACH SUBJECT ON THE OPENBMI DATASET

| Subject No. | FBCSP-SVM | Shallow ConvNet | EEGNet | FBCNet | EEG Conformer | Light ConvNet | IFNet | MSVTNet |
|---|---|---|---|---|---|---|---|---|
| 1 | 81.00 | 80.50 | 88.50 | 87.70 | 81.10 | 87.40 | 88.90 | 86.40 |
| 2 | 63.00 | 72.50 | 72.40 | 64.90 | 60.20 | 61.00 | 70.40 | 68.30 |
| 3 | 96.00 | 94.40 | 96.30 | 96.20 | 91.60 | 95.50 | 97.90 | 96.80 |
| 4 | 68.00 | 61.50 | 63.90 | 76.70 | 68.10 | 78.40 | 67.70 | 74.50 |
| 5 | 89.50 | 83.80 | 84.60 | 87.60 | 93.70 | 89.60 | 86.20 | 91.00 |
| 6 | 84.50 | 75.00 | 84.30 | 82.20 | 80.40 | 83.10 | 86.60 | 84.80 |
| 7 | 71.50 | 54.30 | 57.70 | 65.90 | 68.40 | 73.00 | 67.20 | 75.10 |
| 8 | 57.50 | 61.40 | 65.80 | 65.20 | 61.60 | 62.60 | 64.40 | 63.20 |
| 9 | 71.00 | 72.80 | 81.60 | 79.90 | 80.90 | 81.90 | 81.00 | 81.90 |
| 10 | 53.00 | 58.90 | 60.30 | 62.70 | 67.20 | 66.20 | 63.00 | 61.10 |
| 11 | 50.00 | 53.60 | 51.60 | 52.10 | 59.00 | 54.50 | 54.10 | 58.30 |
| 12 | 61.00 | 65.60 | 62.30 | 69.90 | 65.80 | 67.50 | 71.30 | 71.20 |
| 13 | 59.50 | 56.70 | 56.80 | 54.70 | 55.10 | 57.30 | 60.10 | 58.50 |
| 14 | 54.00 | 56.40 | 54.40 | 59.00 | 61.10 | 59.80 | 61.60 | 62.90 |
| 15 | 47.50 | 60.60 | 59.40 | 59.60 | 50.70 | 57.40 | 55.00 | 55.00 |
| 16 | 55.50 | 50.10 | 50.30 | 57.40 | 63.30 | 60.10 | 56.20 | 57.90 |
| 17 | 49.50 | 66.10 | 52.70 | 58.00 | 60.60 | 52.60 | 56.70 | 62.10 |
| 18 | 72.50 | 82.50 | 88.70 | 87.00 | 87.70 | 91.00 | 91.80 | 87.90 |
| 19 | 73.00 | 75.70 | 75.80 | 69.30 | 79.20 | 77.10 | 78.90 | 71.20 |
| 20 | 64.50 | 60.40 | 59.40 | 71.90 | 73.60 | 74.20 | 70.90 | 78.40 |
| 21 | 99.50 | 96.60 | 99.70 | 99.20 | 98.30 | 99.60 | 100.00 | 98.60 |
| 22 | 52.00 | 66.50 | 74.90 | 67.70 | 77.70 | 73.40 | 76.00 | 77.20 |
| 23 | 66.00 | 66.30 | 60.30 | 66.10 | 68.70 | 68.90 | 68.60 | 67.90 |
| 24 | 49.00 | 50.70 | 51.10 | 52.00 | 54.70 | 53.90 | 51.00 | 57.30 |
| 25 | 59.00 | 68.30 | 62.50 | 66.70 | 63.90 | 65.70 | 70.00 | 64.50 |
| 26 | 61.00 | 53.30 | 49.60 | 54.50 | 55.50 | 53.60 | 50.30 | 55.20 |
| 27 | 57.50 | 54.30 | 54.10 | 55.90 | 61.70 | 58.90 | 51.80 | 54.40 |
| 28 | 95.00 | 88.10 | 91.50 | 95.70 | 95.30 | 97.90 | 97.70 | 95.00 |
| 29 | 97.00 | 93.30 | 94.60 | 93.50 | 89.90 | 95.00 | 94.40 | 90.40 |
| 30 | 65.00 | 61.90 | 65.00 | 68.80 | 71.60 | 71.20 | 75.20 | 72.90 |
| 31 | 71.00 | 59.20 | 59.80 | 67.20 | 62.10 | 71.00 | 77.30 | 68.70 |
| 32 | 92.50 | 87.00 | 87.50 | 90.10 | 80.10 | 85.70 | 92.20 | 92.70 |
| 33 | 93.00 | 95.30 | 96.00 | 97.20 | 94.00 | 97.40 | 98.40 | 96.30 |
| 34 | 52.50 | 52.40 | 51.20 | 55.30 | 57.00 | 58.00 | 56.20 | 54.60 |
| 35 | 58.00 | 70.80 | 68.80 | 73.60 | 73.10 | 70.20 | 76.70 | 79.60 |
| 36 | 98.50 | 96.60 | 97.50 | 97.00 | 98.50 | 98.40 | 97.60 | 97.70 |
| 37 | 93.50 | 92.50 | 96.60 | 95.20 | 95.50 | 94.10 | 96.20 | 95.40 |
| 38 | 61.00 | 49.50 | 53.00 | 57.40 | 59.80 | 61.90 | 54.60 | 58.30 |
| 39 | 77.00 | 79.20 | 84.00 | 83.00 | 80.30 | 84.20 | 88.20 | 85.20 |
| 40 | 58.50 | 56.90 | 57.00 | 58.00 | 56.30 | 58.20 | 60.40 | 63.60 |
| 41 | 60.50 | 49.40 | 54.20 | 57.90 | 58.40 | 59.50 | 58.20 | 58.90 |
| 42 | 64.00 | 54.70 | 55.30 | 65.30 | 60.90 | 66.00 | 61.60 | 64.40 |
| 43 | 62.00 | 69.00 | 77.40 | 76.40 | 83.60 | 81.60 | 83.70 | 85.90 |
| 44 | 98.00 | 96.10 | 98.80 | 97.90 | 97.60 | 97.50 | 98.10 | 97.20 |
| 45 | 94.50 | 90.10 | 93.70 | 91.80 | 90.10 | 93.80 | 95.80 | 95.60 |
| 46 | 62.00 | 61.20 | 61.10 | 74.60 | 63.50 | 70.00 | 65.50 | 64.70 |
| 47 | 49.00 | 56.70 | 53.70 | 60.50 | 56.90 | 64.20 | 53.80 | 56.80 |
| 48 | 51.50 | 57.90 | 60.00 | 62.40 | 58.10 | 63.30 | 60.20 | 64.90 |
| 49 | 58.50 | 67.20 | 69.10 | 63.60 | 68.60 | 70.50 | 68.20 | 71.50 |
| 50 | 49.00 | 51.70 | 52.30 | 55.60 | 51.90 | 55.70 | 55.80 | 53.40 |
| 51 | 58.50 | 58.50 | 53.40 | 58.80 | 54.30 | 59.80 | 57.90 | 54.70 |
| 52 | 80.00 | 67.10 | 79.90 | 76.70 | 76.60 | 78.50 | 79.60 | 76.20 |
| 53 | 60.00 | 53.70 | 55.50 | 54.90 | 60.20 | 58.20 | 50.40 | 56.10 |
| 54 | 57.00 | 53.20 | 54.80 | 58.60 | 61.60 | 57.60 | 56.20 | 56.40 |
| Avg | 68.20 | 67.93 | 69.27 | 71.43 | 71.21 | 72.66 | 72.36 | 72.75 |
| Std | 15.95 | 14.68 | 16.21 | 14.58 | 14.13 | 14.48 | 15.82 | 14.66 |

TABLE VII
CLASSIFICATION ACCURACIES IN % USING SUBJECT-INDEPENDENT ANALYSIS FOR EACH SUBJECT ON THE OPENBMI DATASET

| Subject No. | FBCSP-SVM | Shallow ConvNet | EEGNet | FBCNet | EEG Conformer | Light ConvNet | IFNet | MSVTNet |
|---|---|---|---|---|---|---|---|---|
| 1 | 79.50 | 66.17 | 84.00 | 82.25 | 83.00 | 79.75 | 82.75 | 85.25 |
| 2 | 55.00 | 86.50 | 81.00 | 74.75 | 87.00 | 80.25 | 85.00 | 86.50 |
| 3 | 87.75 | 97.67 | 95.50 | 93.00 | 92.25 | 94.50 | 96.00 | 97.75 |
| 4 | 61.25 | 73.67 | 55.75 | 51.50 | 73.00 | 71.25 | 69.00 | 74.75 |
| 5 | 74.50 | 90.17 | 95.75 | 89.00 | 94.25 | 92.25 | 95.00 | 92.50 |
| 6 | 80.25 | 83.00 | 89.00 | 81.00 | 85.25 | 84.00 | 87.25 | 88.75 |
| 7 | 52.75 | 60.17 | 66.50 | 63.00 | 63.25 | 65.75 | 70.00 | 73.50 |
| 8 | 67.25 | 68.17 | 76.00 | 71.75 | 72.75 | 69.00 | 73.50 | 76.50 |
| 9 | 80.25 | 82.50 | 85.25 | 81.75 | 82.75 | 83.50 | 83.75 | 82.50 |
| 10 | 53.25 | 66.00 | 60.75 | 59.75 | 63.25 | 62.25 | 60.75 | 60.50 |
| 11 | 50.25 | 60.00 | 62.00 | 56.00 | 63.75 | 59.25 | 61.00 | 65.75 |
| 12 | 58.50 | 69.00 | 73.75 | 72.00 | 75.25 | 72.25 | 72.75 | 78.00 |
| 13 | 56.75 | 57.83 | 67.25 | 61.50 | 59.75 | 54.00 | 62.50 | 65.25 |
| 14 | 58.50 | 75.00 | 81.25 | 73.75 | 77.75 | 75.25 | 78.75 | 80.25 |
| 15 | 54.50 | 54.00 | 62.25 | 56.25 | 60.50 | 56.75 | 62.25 | 62.50 |
| 16 | 65.00 | 70.50 | 71.25 | 70.75 | 71.75 | 70.25 | 70.75 | 68.00 |
| 17 | 64.25 | 68.50 | 78.25 | 75.00 | 80.25 | 74.25 | 79.50 | 83.25 |
| 18 | 75.50 | 84.67 | 91.75 | 83.75 | 85.25 | 83.50 | 89.25 | 89.75 |
| 19 | 69.50 | 83.67 | 83.25 | 77.75 | 81.25 | 77.50 | 80.75 | 82.00 |
| 20 | 72.00 | 74.17 | 80.25 | 75.50 | 78.50 | 76.75 | 80.75 | 81.25 |
| 21 | 83.75 | 79.00 | 92.00 | 87.00 | 90.25 | 86.50 | 95.50 | 92.50 |
| 22 | 78.00 | 74.67 | 84.50 | 77.50 | 81.00 | 84.00 | 87.25 | 85.50 |
| 23 | 67.00 | 79.67 | 70.50 | 71.00 | 72.25 | 69.75 | 65.00 | 73.50 |
| 24 | 49.75 | 55.00 | 54.00 | 55.25 | 52.75 | 54.75 | 58.25 | 58.00 |
| 25 | 59.75 | 68.67 | 68.75 | 73.25 | 67.50 | 63.75 | 76.75 | 79.00 |
| 26 | 56.25 | 61.33 | 67.25 | 64.75 | 64.25 | 64.00 | 63.50 | 68.00 |
| 27 | 59.25 | 58.67 | 66.25 | 61.75 | 66.75 | 62.00 | 68.50 | 70.75 |
| 28 | 91.50 | 94.17 | 98.75 | 96.00 | 97.25 | 97.25 | 99.00 | 97.00 |
| 29 | 85.25 | 49.50 | 66.50 | 57.50 | 46.00 | 57.75 | 54.50 | 56.25 |
| 30 | 72.50 | 71.00 | 75.75 | 74.75 | 71.00 | 70.75 | 72.25 | 80.75 |
| 31 | 73.00 | 60.83 | 75.25 | 76.00 | 75.75 | 76.25 | 78.75 | 78.50 |
| 32 | 84.50 | 86.50 | 85.25 | 81.75 | 86.75 | 86.00 | 87.00 | 87.75 |
| 33 | 93.75 | 98.33 | 98.00 | 96.00 | 98.25 | 97.75 | 98.25 | 97.00 |
| 34 | 50.00 | 49.50 | 54.25 | 54.00 | 52.50 | 53.50 | 51.75 | 57.50 |
| 35 | 48.00 | 69.67 | 58.50 | 60.75 | 62.00 | 65.00 | 66.25 | 68.75 |
| 36 | 84.50 | 99.00 | 95.25 | 94.50 | 98.75 | 90.00 | 97.00 | 96.50 |
| 37 | 94.75 | 96.83 | 97.00 | 95.25 | 94.75 | 96.50 | 96.00 | 95.50 |
| 38 | 59.25 | 61.50 | 64.50 | 56.50 | 65.50 | 64.25 | 67.25 | 66.50 |
| 39 | 85.00 | 86.83 | 90.25 | 87.50 | 89.75 | 86.00 | 88.50 | 88.25 |
| 40 | 60.00 | 70.83 | 68.25 | 64.00 | 72.75 | 64.75 | 74.75 | 74.50 |
| 41 | 51.50 | 59.00 | 56.25 | 55.00 | 58.50 | 66.50 | 59.25 | 67.75 |
| 42 | 65.50 | 73.33 | 77.50 | 72.00 | 71.25 | 69.75 | 72.75 | 75.75 |
| 43 | 68.50 | 88.17 | 86.25 | 86.25 | 87.25 | 85.50 | 88.50 | 85.25 |
| 44 | 89.25 | 93.33 | 94.25 | 91.75 | 93.25 | 92.75 | 93.50 | 95.25 |
| 45 | 80.00 | 84.50 | 88.75 | 86.50 | 89.75 | 91.00 | 90.00 | 85.75 |
| 46 | 69.50 | 64.50 | 77.75 | 75.50 | 70.75 | 70.00 | 73.50 | 77.25 |
| 47 | 65.00 | 64.67 | 73.75 | 73.00 | 68.50 | 72.00 | 73.00 | 73.50 |
| 48 | 52.25 | 62.17 | 53.50 | 61.50 | 54.75 | 59.50 | 65.00 | 64.25 |
| 49 | 61.50 | 55.17 | 67.50 | 69.50 | 67.00 | 69.75 | 64.00 | 70.50 |
| 50 | 52.00 | 53.67 | 53.50 | 55.00 | 53.25 | 52.25 | 54.50 | 58.75 |
| 51 | 60.25 | 64.17 | 67.50 | 64.75 | 69.00 | 68.00 | 67.00 | 67.50 |
| 52 | 69.00 | 81.17 | 82.75 | 77.00 | 82.75 | 76.00 | 82.50 | 80.25 |
| 53 | 57.75 | 60.50 | 65.25 | 58.00 | 67.75 | 60.25 | 63.00 | 70.75 |
| 54 | 53.25 | 62.33 | 62.75 | 60.50 | 66.50 | 64.00 | 58.75 | 61.25 |
| Avg | 67.55 | 72.40 | 75.53 | 72.62 | 74.75 | 73.52 | 75.79 | 77.41 |
| Std | 13.03 | 13.48 | 13.19 | 12.62 | 13.12 | 12.39 | 12.98 | 11.53 |

## REFERENCE


[1] P. Autthasan, R. Chaisaen, T. Sudhawiyangkul, P. Rangpong, S. Kiatthaveephong, N. Dilokthanakul, G. Bhakdisongkhram, H. Phan, C. Guan, and T. Wilaiprasitporn, "MIN2Net: End-to-end multi-task learning for subject-independent motor imagery EEG classification," *IEEE Transactions on Biomedical Engineering*, vol. 69, no. 6, pp. 2105–2118, 2021.

[2] X. Shu, S. Chen, L. Yao, X. Sheng, D. Zhang, N. Jiang, J. Jia, and X. Zhu, "Fast recognition of bci-inefficient users using physiological features from eeg signals: A screening study of stroke patients," *Frontiers in neuroscience*, vol. 12, p. 93, 2018.

[3] M.-H. Lee, O.-Y. Kwon, Y.-J. Kim, H.-K. Kim, Y.-E. Lee, J. Williamson, S. Fazli, and S.-W. Lee, "Eeg dataset and openbmi toolbox for three bci paradigms: An investigation into bci illiteracy," *GigaScience*, vol. 8, no. 5, p. giz002, 2019.

[4] K. K. Ang, Z. Y. Chin, H. Zhang, and C. Guan, "Filter bank common spatial pattern (fbcsp) in brain-computer interface," in *2008 IEEE international joint conference on neural networks (IEEE world congress on computational intelligence)*, pp. 2390–2397, IEEE, 2008.

[5] R. T. Schirrmeister, J. T. Springenberg, L. D. J. Fiederer, M. Glasstetter, K. Eggensperger, M. Tangermann, F. Hutter, W. Burgard, and T. Ball, "Deep learning with convolutional neural networks for EEG decoding and visualization," *Human Brain Mapping*, vol. 38, no. 11, pp. 5391–5420, 2017.

[6] V. J. Lawhern, A. J. Solon, N. R. Waytowich, S. M. Gordon, C. P. Hung, and B. J. Lance, "EEGNet: a compact convolutional neural network for EEG-based brain–computer interfaces," *Journal of Neural Engineering*, vol. 15, no. 5, p. 056013, 2018.

[7] R. Mane, E. Chew, K. Chua, K. K. Ang, N. Robinson, A. P. Vinod, S.-W. Lee, and C. Guan, "FBCNet: A multi-view convolutional neural network for brain-computer interface," *arXiv preprint arXiv:2104.01233*, 2021.

[8] Y. Song, Q. Zheng, B. Liu, and X. Gao, "EEG conformer: Convolutional transformer for EEG decoding and visualization," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 31, pp. 710–719, 2022.

[9] X. Ma, W. Chen, Z. Pei, J. Liu, B. Huang, and J. Chen, "A temporal dependency learning CNN with attention mechanism for MI-EEG decoding," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2023.

[10] J. Wang, L. Yao, and Y. Wang, "IFNet: An Interactive Frequency Convolutional Neural Network for Enhancing Motor Imagery Decoding From EEG," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 31, pp. 1900–1911, 2023.

[11] C. Brunner, R. Leeb, G. Müller-Putz, A. Schlögl, and G. Pfurtscheller, "BCI Competition 2008–Graz data set A," *Institute for Knowledge Discovery (Laboratory of Brain-Computer Interfaces), Graz University of Technology*, vol. 16, pp. 1–6, 2008.

[12] R. Leeb, C. Brunner, G. Müller-Putz, A. Schlögl, and G. Pfurtscheller, "BCI Competition 2008–Graz data set B," *Graz University of Technology, Austria*, vol. 16, pp. 1–6, 2008.

[13] M.-H. Lee, O.-Y. Kwon, Y.-J. Kim, H.-K. Kim, Y.-E. Lee, J. Williamson, S. Fazli, and S.-W. Lee, "EEG dataset and OpenBMI toolbox for three BCI paradigms: An investigation into BCI illiteracy," *GigaScience*, vol. 8, no. 5, p. giz002, 2019.