Evidence of Neuroplasticity Due to Acupuncture: An fNIRS Study

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Research

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Abstract

Background: Mild cognitive impairment (MCI) is a precursor to the critical disease known as Alzheimer's. It is imperative to develop a proper treatment for this neurological disease in the aging society. This study investigates the effects of acupuncture therapy (AT) on MCI patients.

Methods: Eleven healthy individuals and eleven MCI patients were recruited for this study. Oxy- and deoxy-hemoglobin signals in the prefrontal cortex during working-memory tasks were monitored using functional near-infrared spectroscopy. Before the AT, working-memory experiments were conducted for healthy control (HC) and MCI groups (MCI-0), followed by 24 sessions of AT for the MCI group. The AT sessions were initially carried out for six weeks (two sessions per week), after which experiments were performed again on the MCI group (MCI-1). This was followed by another set of AT sessions that also lasted for six weeks, after which the experiments were repeated again on the MCI group (MCI-2). Statistical analyses of the signals and classifications based on activation maps as well as temporal features were performed.

Results: The highest classification accuracies obtained using binary connectivity maps were 85.7% HC vs. MCI-0, 69.5% HC vs. MCI-1, and 61.69% HC vs. MCI-2. The classification accuracies using the temporal features mean (i.e., mean(5:28 s)) and maximum (i.e., max(5:28 s)) values were 60.6% HC vs. MCI-0, 56.9% HC vs. MCI-1, and 56.4% HC vs. MCI-2.

Conclusions: The results reveal that there was a change in the temporal characteristics of the hemodynamic response of MCI patients due to acupuncture. This was reflected by a reduction in the classification accuracy after the therapy, indicating that the patients' brain response improved and became comparable to those of healthy subjects. Similar trend was reflected in the classification using image feature. These results indicate that acupuncture can be used for the treatment of MCI patients.

Trial registration: Clinical research and information service (CRIS), KCT 0002451, Registered 05 September 2017, https://cris.nih.go.kr/cris/en/

1. Introduction

Neurological injuries and diseases are the major causes of the degradation of people's mental capabilities, and they can be treated via rehabilitation. One of the significant brain diseases is Alzheimer's disease (AD) [1]. AD starts with mild memory loss and eventually becomes severe, and it can develop into a neurodegenerative brain disease. According to a recent study, 70%–80% of dementia cases are caused by AD worldwide [2]. Mild cognitive impairment (MCI) is a neurological condition that occurs as a prior stage of AD. MCI is defined by a loss of vocabulary, thought, perception, and judgment-related memory [3-5]. It progresses more rapidly than other diseases associated with age and can lead to AD. Therefore, early diagnosis and treatment of MCI—involving either therapy or medication-based care—is necessary, as it can easily develop into advanced AD. Thus, it is necessary to examine the effects of therapy (acupuncture) on MCI patients and evaluate its effectiveness for treating MCI.

Acupuncture is a non-pharmacological procedure based on the placement of tiny needles at particular locations on the human body that are known as acupoints or acupuncture points [6]. The primary objective of this therapeutic approach is to enhance the safety and quality of life for the patient. Different diseases like colds, fevers, and cerebral pains have been treated using this traditional technique of acupuncture [7]. While the early phases of acupuncture are still being investigated, it has been recognized as part of traditional Korean medicine. Acupuncture has been part of traditional medication for more than 2000 years [8]. Acupuncture therapy also has neurological outcomes consistent with pain relief and anesthesia [9].

To investigate the brain conditions, several brain signal acquisition techniques are used. For acquiring the brain signal noninvasively, commonly used methods include electroencephalography [10, 11], functional near-infrared spectroscopy (fNIRS) [12-14], functional magnetic resonance imaging (fMRI) [15], and magnetoencephalography [16-17]. fNIRS is a brain imaging technique that utilizes near-infrared light to detect the cerebral blood flow in the brain. It uses light at two different wavelengths within the range of 650–1000 nm [18]. By utilizing an fNIRS-based brain imaging technique, two sensitive chromophores in blood, i.e., oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR), are detected [19].

Several studies have utilized fNIRS for examining the changes in the hemodynamic signals of MCI and AD patients while they perform cognitive tasks. A study focusing on right parietal region of brain found that the HbO concentration changes of MCI patients were significantly smaller as compared with healthy controls (HCs) [20]. A recent study indicated a significant loss of lateralization in MCI patients [21]. Another study indicated comparable task performance between MCI and HCs in behavior results. Significantly enhanced activation was not observed in MCI patients compared with HCs in a high-load working-memory task [22]. Furthermore, Uemura et al. reported a reduced activation pattern in the bilateral dorsolateral prefrontal cortex in a retrieval task [23]. Improved cortical activation was observed in a dual-task (walking and verbal frequency task), and reduced activation was observed during normal walking in MCI patients [24]. In a comparative study on HC, MCI, and AD patients, it was revealed that the time taken to achieve the activation level of HbO in the prefrontal cortex of an HC was shorter than those for MCI and AD patients [25]. They also observed a steeper slope of HbO for MCI patients compared with AD patients. Another study involving MCI patients revealed no activation changes with pre- and post-computer-based memory training; however, the behavioral performance was improved [26]. These results indicate the potential of fNIRS to be used as an imaging modality for the detection of diseases such as MCI and AD. However, the effects of pharmacological (medication) and non-pharmacological (i.e., acupuncture) intervention on MCI patients using fNIRS is still in the developing stage.

Regarding the acupuncture therapy, the initial study by our research group had investigated the longitudinal effects on the MCI patients: The analyses were primarily based on the Korean version of the Montreal Cognitive Assessment score (MoCA-K) and hemodynamic responses [27]. In this study, the functional connectivity and graph theory were analyzed. The results with and without acupuncture therapies were compared between the HC group and the MCI group. The improvement in mean MoCA-K test scores and averaged hemodynamics responses depicted that the cognitive function of the MCI group was enhanced upon acupuncture. After acupuncture therapy, the functional connectivity and graph theory parameters of the MCI group were comparable to those of the HC group. The increase in the MoCA-K score was positively correlated with fNIRS data that showed its capability as a feasible tool for the evaluation of cognitive functions in the clinical setting. Nevertheless, the conclusion on the averaged increase in fNIRS data and mean cognitive test scores were deduced on the basis of statistical analyses. In contrast, to further validate the impact of acupuncture, we aim to explore the changes at the trial-level (not averaged) temporal data, spatial activation patterns, and functional connectivity by employing advanced classification algorithms.

Therefore, in this study, we investigate the effects of acupuncture on MCI patients via classification. We aimed to determine whether acupuncture can improve the mental health of MCI patients in terms of brain activation. Additionally, we attempted to determine whether there are changes in the hemodynamic responses of the patients due to acupuncture with regard to the classification accuracies. In order to check our hypothesis, two different classification methods were adopted in the study, i.e. classification using temporal features and through a convolutional neural network (CNN).

2. Methods

2.1 Participants

For the experiment, 11 HC and 11 MCI patients were recruited. For consistency, the average age, sex, and number of years of education were identical between the groups. The demographic information for all the subjects has been summarized in Table 1. MCI patients were recruited at Dunsan Korean Medical Hospital. Newspapers were also used for advertisement. All the participants were informed that they could stop participating at any time. The medical history of the participants, along with demographic and drug-intake information, was obtained before the experiment. Additionally, on-spot assessments of the height, weight, and systolic blood pressure were performed. None of the participants had indulged in a brain signal acquisition experiment before this study. To evaluate the cognitive performance of the participants, MoCA-K test was performed. For the details of the test interested readers can refer to [27].

Table 1 Demographic information of the participants

	Healthy	MCI
Subjects	11	11
Age	55.92 7.65	61.58 6.55
Gender	Female	
p-value for group differences	0.0755	

(Note: Statistical significant value was set to *p* 0.01)

2.2 Optode placement and experimental paradigm

In the experiment, seven detectors and eight emitters were positioned over the region of interest. Figure 1 shows the optode configuration on the prefrontal cortex of the human brain. A total of 20 channels were formed using all the emitters and detectors. The optodes were placed by taking FpZ as a reference point. The reference points were set in accordance with the International 10-20 System of Electrode Placement. The separation between the emitter and detectors was ≤3 cm.

Fig. 1 Emitter–detector configuration on the prefrontal cortex: FpZ is taken as a reference point in accordance with the International 10-20 System [27].

For the prefrontal cortex, a working-memory task was employed to detect neuronal activation. Nine trials were conducted during the experiment. Each trial consisted of a 24-s task period and a 14-s rest period. A "ready" cue of 2 s was given in each trial, before the start of the task period. This was done to alert the subject that a task was to be performed soon. During the task period, for the initial 8 s, 3–7 images randomly appeared on a screen placed in front of the subjects. After these 8 s, there was a period of 14 s during which the subjects were allowed to hold images that they selected (as per difficulty). This was followed by a probe period of 2 s in which the participants had to respond, indicating whether the image displayed was among the images shown previously. To respond, the subjects used two push buttons to reply "yes" or "no." Before the commencement of the experiment session, there was a pre-rest period of 4 min. Similarly, at the end of the experiment, there was a 30-s post-rest period. Figure 2 shows the experimental paradigm. A black screen was displayed during the rest period. Throughout the experiment, the subjects were advised to keep their eyes open.

Fig. 2 Experimental paradigm [27].

2.3 Intervention detail

The intervention details were presented in detail in a recently published work [27]. Briefly, the patients underwent several acupuncture sessions lasting 10 min each. A total of 24 sessions were conducted over twelve weeks (i.e., for brevity, before acupuncture: MCI-0, after 12 acupuncture sessions (6 weeks): MCI-1, and after 24 acupuncture sessions (12 weeks): MCI-2). During this time, the participants were instructed not to participate in any other acupuncture. The acupuncture was performed under the rules of Standards for Reporting Interventions in Clinical Trials of Acupuncture (STRICTA) [28]. Table 2 summarizes the intervention details.

Table 2. Intervention details [27]

Sr. No.	Elements	Description
1.	Acupuncture type	Traditional Korean medicine therapy
2.	Reason of treatment (literature support)	Acupoints based on the 12-meridian system used in clinical trials for AD and MCI [6]
3.	Number of needle insertion per subject and session	14 acupoints
4.	Location of acupoints	GV20, EX-HN1, CV12, (Shenmen HT7 bilateral), ST36 (bilateral), SP6 (bilateral), and Taixi (KI3 bilateral)
5.	Penetration of needle	Depending upon thickness of skin (approximately 5 – 10 mm)
6.	Stimulation on needle insertion	No
7.	Dimensions and material of needle	0.20 × 30 mm in size, made of stainless steel (Dongbang Medical Co., Korea)
8.	Total number of AT sessions	24
9.	Informed consent about acupuncture	Yes
10.	Qualification of acupuncturists	Medical doctor with clinical experience of more than 2 years

The study was performed in compliance with the Institutional Review Board of Dunsan Korean Medicine Hospital, Daejeon University [29]. Before the experiment, all the participants were given a complete description of the experimental procedure and provided written informed consent. For the MCI group, additional consent was obtained for the acupuncture. The entire study was in compliance with the latest Declaration of Helsinki [30].

2.4 Acquisition and preprocessing of fNIRS signals

In this study, the signals generated in the brain were sampled at a frequency of 7.81 Hz. A single-phase continuous wave fNIRS system NIRScout (NIRx Medical Technologies, USA) was used for the acquisition of fNIRS signals. Two different wavelengths were utilized by the system: 760 and 850 nm. The Modified Beer–Lambert's law was used to convert the raw intensities into changes in HbO (ΔHbO) and HbR (ΔHbR) [31]. This conversion was performed using the NIRSlab software.

After the data were converted into ΔHbO and ΔHbR, they were preprocessed to remove the effects of physiological noises. For this, a 4th-order Butterworth filter was utilized. A low-pass cutoff frequency of 0.15 Hz was used to remove cardiac, respiratory, and low-frequency drift signals [32, 33]. The cutoff frequency for the high-pass filter was selected according to the longest time period of a single trial (i.e., 38 s (1/38 s = 0.026 Hz)) [34, 35]. For analysis, the software MATLAB™ 17.0 was used (MathWorks, USA).

2.5 Data analysis

After the pre-processing, the next step was to classify the data. For the purpose of classification, two different methods were used: Classification based on temporal features and classification using images [36]. For classification based on temporal features, mean (i.e., mean(5:28 s) for brevity), maximum (i.e., max(5:28 s)), slope (i.e., slope(5:28 s)), skewness (i.e., skew(5:28 s)), kurtosis (i.e., kurt(5:28 s)), increasing slope (i.e., slope(2:12 s)), decreasing slope (i.e., slope(26:36 s)) and entire mean (i.e., mean(1:38 s)) were used as features. These features were classified using linear discriminant analysis (LDA) [37]. Fivefold cross-validation was performed for determining the classification accuracy.

For analysis using images, the data for all the trials were first converted into pictorial form. Activation maps and connectivity maps were used as image features. For the representation of the activation maps, a *t*-test was performed. The *t*-values for all the channels were calculated using the built-in function robustfit of MATLAB®. In the test, the statistical significance level was set as 0.05. To obtain connectivity matrices, the Pearson correlation coefficients were calculated for the data of each channel. These connectivity matrices were then used to create connectivity maps. The obtained images were classified using CNN. In this study, the neural network consisted of two convolutional layers and two fully connected layers. Again, fivefold cross-validation was used. Additional details regarding the method were presented in a previous work [36]. For detecting cortical activation, the time-series signal for each trial was fitted to the desired hemodynamic response (dHRF) signal [38-40].

3. Results

3.1 Comparison of hemodynamic responses

The hemodynamic response function (HRF) is a typical response that is detected for healthy subjects and patients. To describe the shape of the HRF, the dHRF was used to identify the activation in each trial. After the active trials were extracted for all the subjects, the trials were averaged. The same procedure was followed for both the groups. Visual inspection revealed credible activation for both the patients and the healthy subjects. However, the responses of the MCI patients obtained before and after acupuncture sessions differed significantly. Figure 3 shows the maximum amount of activation observed for the MCI and HC groups, along with the standard deviation. For both groups, the amounts of activation were represented using bars, and the standard deviations were represented as dotted lines above them.

Fig. 3 Comparison of the maximum activations of HbO over all the subjects and their standard deviations: (a) HC, (b) MCI-0, (c) MCI-1, (d) MCI-2.

To evaluate the statistical difference between the MCI group and the healthy group, *t*-tests were performed. While comparing the average amount of activation between the healthy subjects and MCI patients, two independent sample t-tests were performed. Whereas paired t-tests were used for the comparison of the activation between the MCI patients before and after acupuncture sessions. A difference was considered to be statistically significant if the following two conditions were satisfied: i) t-value > critical t-value (t_{crt}) and ii) p-value < 0.05. The average amount of activation for healthy subjects was significantly higher as compared to MCI-0 (p-value < 0.001). Interestingly, after the first twelve acupuncture sessions, there was no longer a statistically significant difference in the responses between the HC and MCI-1 groups (p-value = 0.377). However, statistically significant differences were observed when the data of the MCI-0 were compared with MCI-1 (p-value < 0.001). The activation in case of MCI-2 was lower than HC group (p-value < 0.001).

Similarly, statistically significant results were obtained while comparing the MoCA-K scores of HC and MCI-0 (p-value < 0.001). Interestingly, no statistical significance was found while comparing the MoCA-K score of HC with MCI-1 and MCI-2 (p-value = 0.074 and p-value = 0.099, respectively). Figure 4 shows the obtained average MoCA-K scores for both HC and MCI. The standard deviations in the score are represented by lines in the figure.

Fig. 4 Comparison of the averaged MoCA-K scores along with standard deviations: (a) HC, (b) MCI-0, (c) MCI-1, (d) MCI-2.

3.2 Classification

For classification, all the features were extracted and then used in pairs. The classification accuracy obtained using each of these feature sets is shown in Figure 5. The maximum classification accuracy obtained using mean (i.e., mean(5:28 s)) and maximum (i.e., max(5:28 s)) values were 60.6% for HC vs. MCI-0, 55.9% for HC vs. MCI-1, and 56.4% for HC vs. MCI-2. According to the results, most of the feature combinations yielded a classification accuracy higher than the chance level (i.e., 50%). A decrease in the classification accuracies (after acupuncture sessions) can be seen in almost all of the feature combination. This shows that after acupuncture, the temporal characteristics of the hemodynamic response of MCI patients became similar to the healthy subjects.

Fig. 5 Comparison of classification accuracies for different feature sets: mean (i.e., mean(5:28 s) for brevity), maximum (i.e., max(5:28 s)), slope (i.e., slope(5:28 s)), skewness (i.e., skew(5:28 s)), kurtosis (i.e., kurt(5:28 s)), increasing slope (i.e., slope(2:12 s)), decreasing slope (i.e., slope(26:36 s)) and entire mean (i.e., mean(1:38 s)).

t-maps and connectivity maps are widely used in both fMRI and fNIRS for indicating the areas of activation. In this study, these maps were used for classification. Figure 6 shows the t-maps for each subject in HC and MCI groups.

Fig. 6 Activation maps of all participants: (a) HC, (b) MCI-0, (c) MCI-1, (d) MCI-2.

Figure 7 shows the connectivity maps whereas the corresponding binary matrices are shown in Figure 8. For converting the connectivity maps into binary matrices, a threshold value of 0.8 was used. The trend of the connectivity maps was similar to that of the *t*-maps. These results support the claim that the acupuncture made the patients more normal. To verify the results based on functional connectivity, independent sample and paired *t*-tests were performed. The values of correlation for both healthy and MCI group were converted from *r*-values to *z*-values. This was done using Fisher's *r*-to-*z* transform. Significant difference was found while comparing the HC with MCI-0 groups (p-value < 0.001). Same was the case for the comparison of functional connectivity maps of MCI-0 and MCI-1 (i.e., p-value < 0.001). CNN was used for the classification of the images. Figure 9 presents the classification accuracies obtained using *t*-maps. Whereas Figure 10 and Figure 11 shows the classification accuracies obtained using connectivity maps and corresponding binary maps, respectively. As shown, the classification accuracies were changed due to the acupuncture. After the therapy, the classification accuracy decreased, which is similar to trend of the temporal features. However, among the three different types of maps used in the CNN-based classification, the binary matrices yielded the highest classification accuracy i.e., 85.7% for HC vs MCI-0, 69.5% for HC vs MCI-1, and 61.69% for HC vs MCI-2.

Fig. 7 Connectivity maps of all participants: (a) HC, (b) MCI-0, (c) MCI-1, (d) MCI-2.

Fig. 8 Binary matrices of all participants with threshold of 0.8: (a) HC, (b) MCI-0, (c) MCI-1, (d) MCI-2.

Fig. 9 Comparison of CNN-based classification results obtained using *t*-maps: (a) HC vs. MCI-0, (b) HC vs. MCI-1, (c) HC vs. MCI-2.

Fig. 10 Comparison of CNN-based classification results obtained using connectivity maps: (a) HC vs. MCI-0, (b) HC vs. MCI-1, (c) HC vs. MCI-2.

Fig. 11 Comparison of CNN-based classification results obtained using binary maps: (a) HC vs. MCI-0, (b) HC vs. MCI-1, (c) HC vs. MCI-2.

4. Discussion

The objective of this study was to investigate the effects of acupuncture on MCI patients and to validate it as a method for improving their mental capabilities. It was hypothesized that acupuncture would change the hemodynamic response. Our second hypothesis was that the acupuncture would change the activated area, resulting in making the patients response like healthy subjects. To the best of the author's knowledge, this was the first study in the field of fNIRS to investigate the effects of acupuncture with regard to classification. We aimed to determine whether acupuncture can make patients normal, by using fNIRS as a brain imaging tool. Our findings are summarized below.

1. i) As a first step, the brain activation area of the MCI group was compared with that of the healthy group. This was done both before and after the acupuncture. The brain activation patterns for the working-memory task were compared using a *t*-test. Initially, there were significant differences

between the hemodynamic responses of the two groups (*p*-value < 0.001). After six weeks, over which 12 acupuncture sessions were conducted, interestingly, there was no significant difference between the hemodynamic responses of the MCI and healthy groups (*p*-value = 0.377). Thus, the statistical test validated our hypothesis, i.e., the acupuncture made the patients more normal.

2. ii) For classification using temporal features, a feature set consisting of eight features was extracted from the hemodynamic responses of both groups. These features were then used as pairs to classify the healthy and MCI groups. LDA was used for classification. The combination of mean(5:28 s) and max(5:28 s) features yielded the highest classification accuracies. According to the results, in most of the cases, the classification accuracy was higher before the acupuncture than after it. Validation based on temporal features was in accordance with our hypothesis and the results of the statistical test. The results obtained through classification are in line with MoCA-K scores. In a future study, advanced techniques can be utilized to further validate the hypothesis.

iii) The prefrontal cortex of the brain is the major contributor to most active-memory tasks, such as mental arithmetic, counting, and working-memory tasks, as it is sensitive to mental training [41, 42]. With age, this area becomes weak with regard to capabilities, giving rise to dangerous diseases such as AD [43]. Such changes in mental health can be monitored using brain activation maps and brain connectivity maps. Thus, the effects of the acupuncture were validated using connectivity maps and activation maps.

Connectivity maps and activation maps were created for each trial. Using these maps, CNN-based classification was performed. For the MCI group, the acupuncture increased the activated area and enhanced the connectivity in the prefrontal cortex. The results indicated that with the acupuncture, the activation areas and connectivity maps of the MCI patients became more similar to those of the healthy subjects. Additionally, the classification accuracy decreased, supporting the aforementioned hypothesis. These results indicate improvements in the patients and are in accordance with the literature [27, 44].

The foregoing results support our hypothesis that acupuncture makes MCI patients more normal with regard to brain health. The enhancement of the patients' mental state due to acupuncture is clearly reflected by the ΔHbO signal, which is increased after acupuncture [25, 45]. Although there is a decrease in the maximum value after MCI-2, but the activation is higher as compared to MCI-0. Also, the improvement in the cognitive abilities of the MCI patients is reflected in the MoCA-K test scores. The results obtained through classification are in line with the predecessor of the current study [27]. Also, from the results of classification, there is a notable difference between the classification accuracies obtained from temporal features and from image features. By using images of brain activation and connectivity higher classification accuracies were obtained. These results are in line with a recently published work by [36]. Overall, the results indicate that acupuncture is useful for enhancing the mental state of patients.

Owing to the small number of fNIRS channels available, the study was limited to the prefrontal cortex of the brain. In future research, a larger number of channels can be used, for investigating other brain areas [46]. Additionally, hybrid neuroimaging modalities can be used for brain signal acquisition [47]. This would be useful for verifying the hypothesis of the present study for the entire brain. Furthermore, it would allow observation of the activation and connectivity of the entire brain. To make the activation maps more precise, bundled optodes placement can be utilized to increase the spatial resolution [48]. Another limitation of this study was the number of subjects. Although the number of subjects was similar to those for previous studies, the study can be extended to a larger number of subjects. Moreover, only female participants participated in the study, representing another limitation, as the sex-based variability cannot be evaluated. In the future, identical research can be performed on male subjects, and the results can be compared with those of the present study.

5. Conclusion

This study represents a step toward analyzing the treatment of MCI for making the brain of patients more active. It was found that the traditional method of acupuncture can improve the mental health of patients, which was confirmed using classification methods. The results revealed that the acupuncture improved the hemodynamic responses of the patients. This claim is in line with the cognitive performance of the participants monitored through MoCA-K test scores. Additionally, the results indicated that the activated area of the MCI patients, as well as the connectivity, increased with the acupuncture. These changes in the brain have been proven statistically. Finally, the decrease in the classification accuracies indicated that the brain activation of the MCI patients became somewhat similar to those of the HC group due to acupuncture therapy.

Abbreviations

MCI: Mild cognitive impairment; fNIRS: Functional-near infrared spectroscopy; AD: Alzheimer’s disease; fMRI: Functional magnetic resonance imaging; HbO: Oxy-hemoglobin; HbR: Deoxy-hemoglobin; HC: Healthy controls; MCI-0: MCI patients before acupuncture; MCI-1: MCI patients after 12 acupuncture sessions (6 weeks); MCI-2: after 24 acupuncture sessions (12 weeks); MoCA-K: Korean version of the Montreal Cognitive Assessment score; CNN: Convolutional neural network; STRICTA: Standards for Reporting Interventions in Clinical Trials of Acupuncture; ΔHbO: Changes in HbO; ΔHbR: Changes in HbR; LDA: Linear discriminant analysis; dHRF: Desired hemodynamic response; HRF: Hemodynamic response function;

Declarations

Ethics approval and consent to participate

The study was performed in compliance with the Institutional Review Board of Dunsan Korean Medicine Hospital, Daejeon University (DJDSKH-17-BM-13). Before the experiment, all the participants were given a complete description of the experimental procedure and provided written informed consent. For the MCI group, additional consent was obtained for the acupuncture. The entire study was in compliance with the latest Declaration of Helsinki.

Consent for publication

Not applicable

Availability of data and materials

The fNIRS data used to support the findings of this study are open and available from the corresponding author upon request.

Competing interests

The authors declare that they have no conflicts of interest. This research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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Authors' contributions

MNAK wrote the first draft of the manuscript and participated in the data processing. UG carried out the data processing. HRY managed the process related to experimentation and interventions. KSH has suggested the theoretical aspects of the study, corrected the manuscript, and supervised all the process from the beginning. All the authors have approved the final manuscript.

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Figures

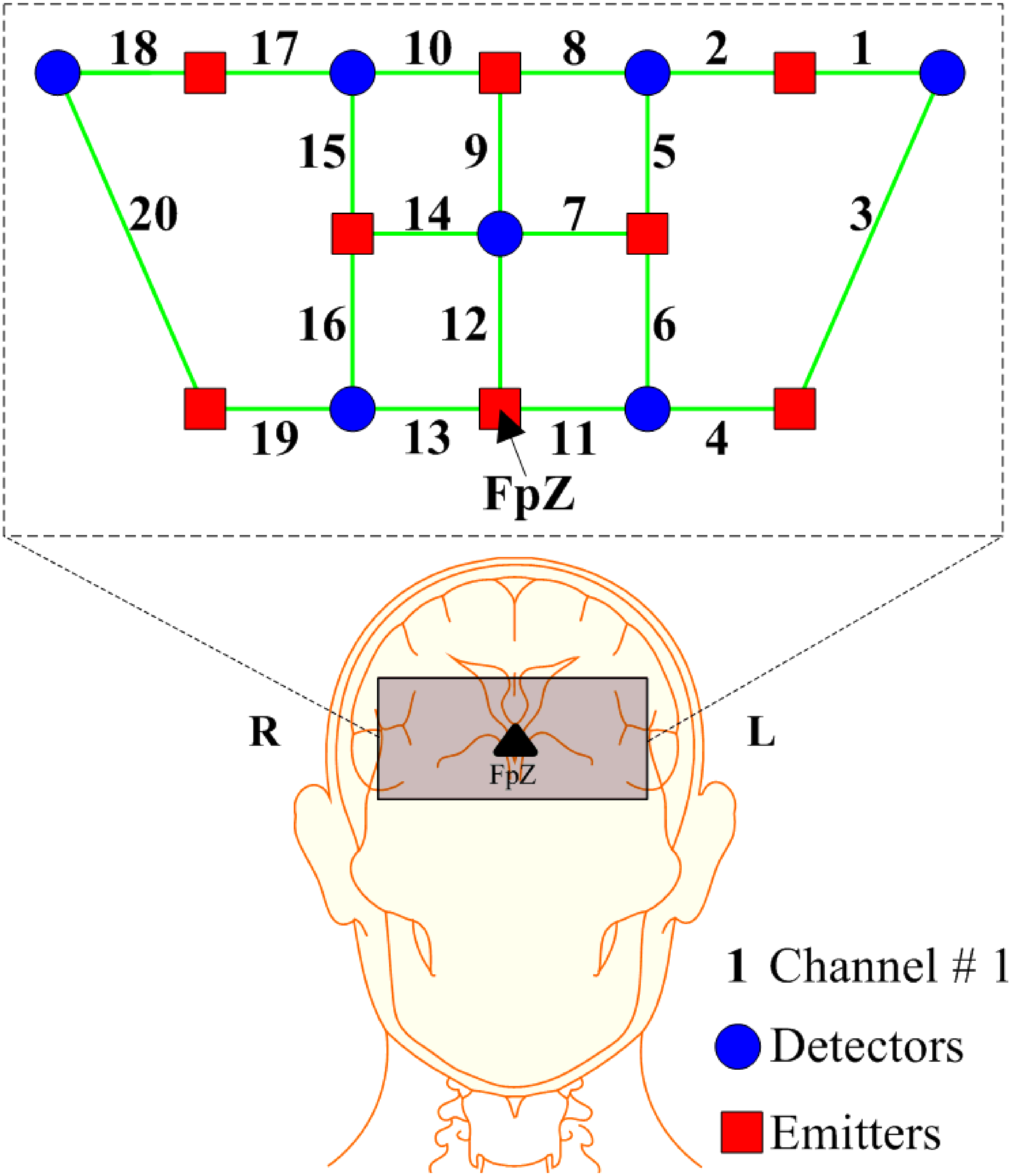


Figure 1

Emitter–detector configuration on the prefrontal cortex: FpZ is taken as a reference point in accordance with the International 10-20 System [27].

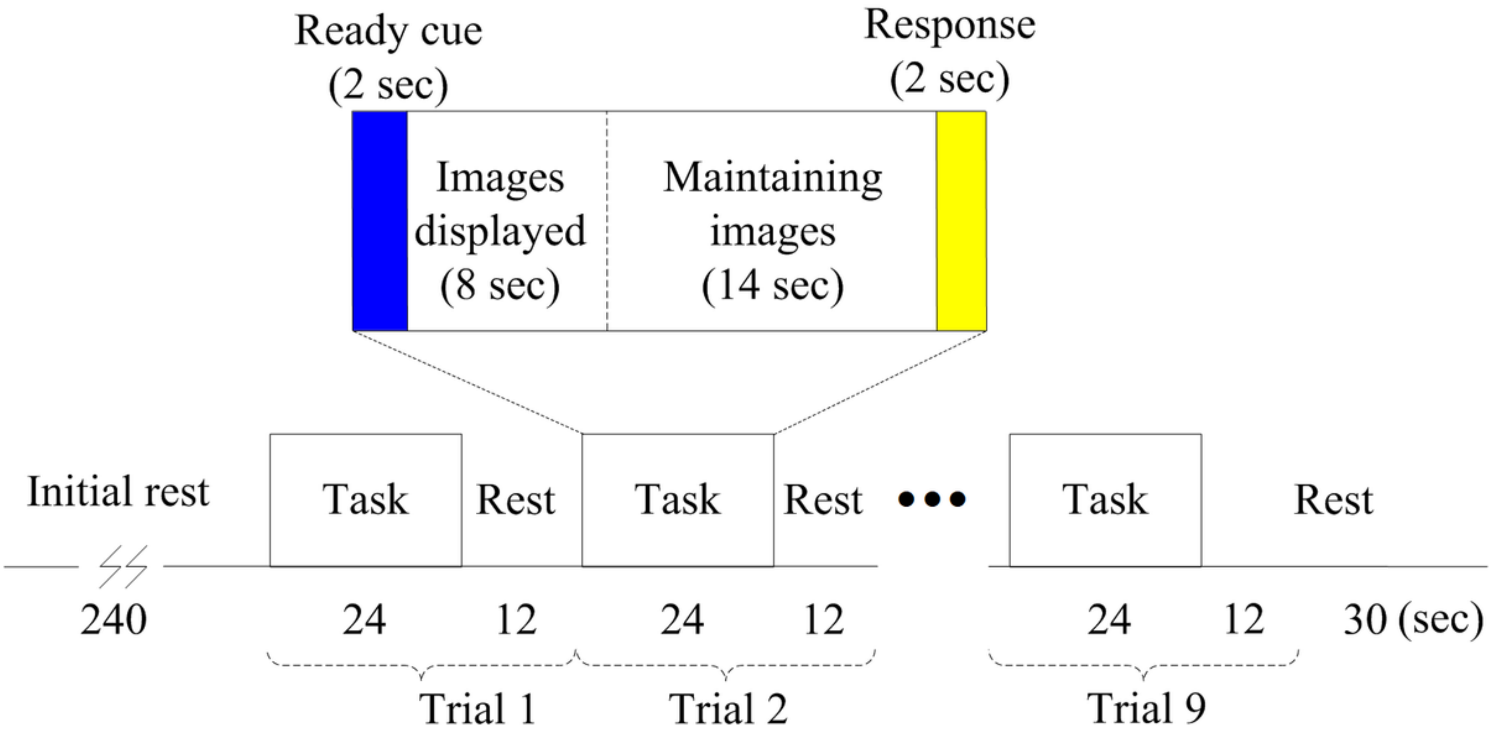


Figure 2

Experimental paradigm [27].

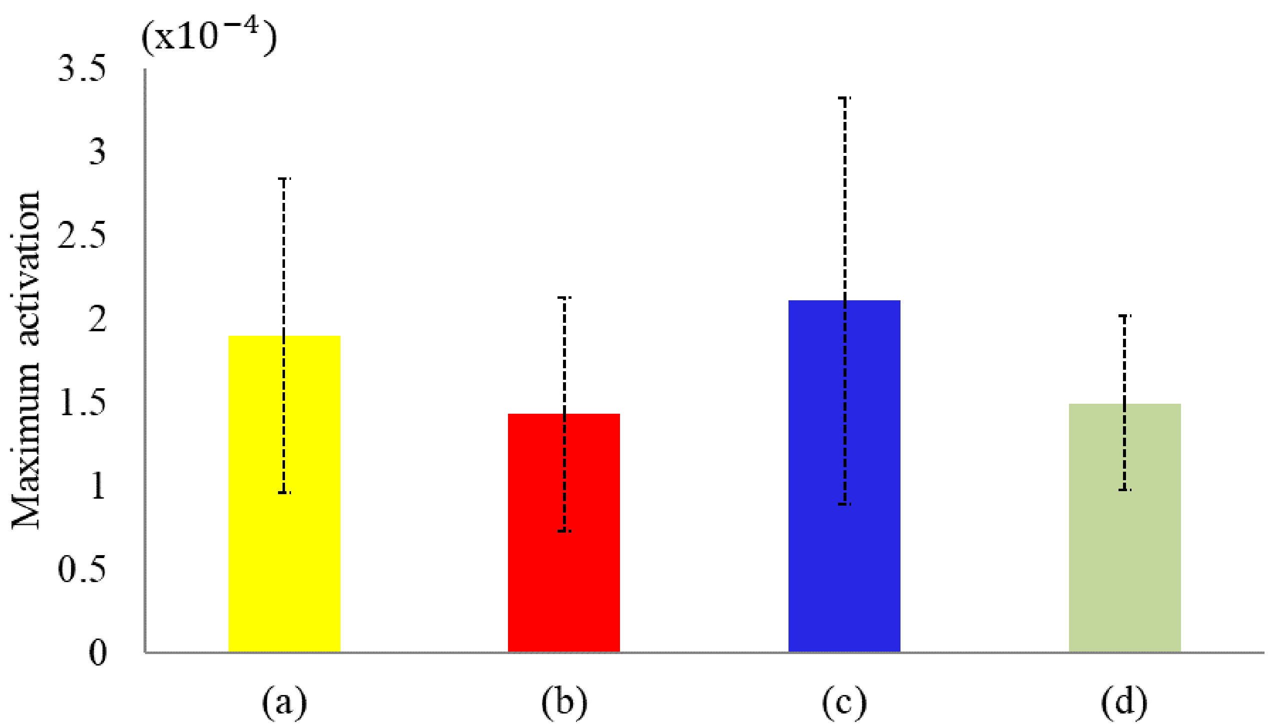


Figure 3

Comparison of the maximum activations of HbO over all the subjects and their standard deviations: (a) HC, (b) MCI-0, (c) MCI-1, (d) MCI-2.

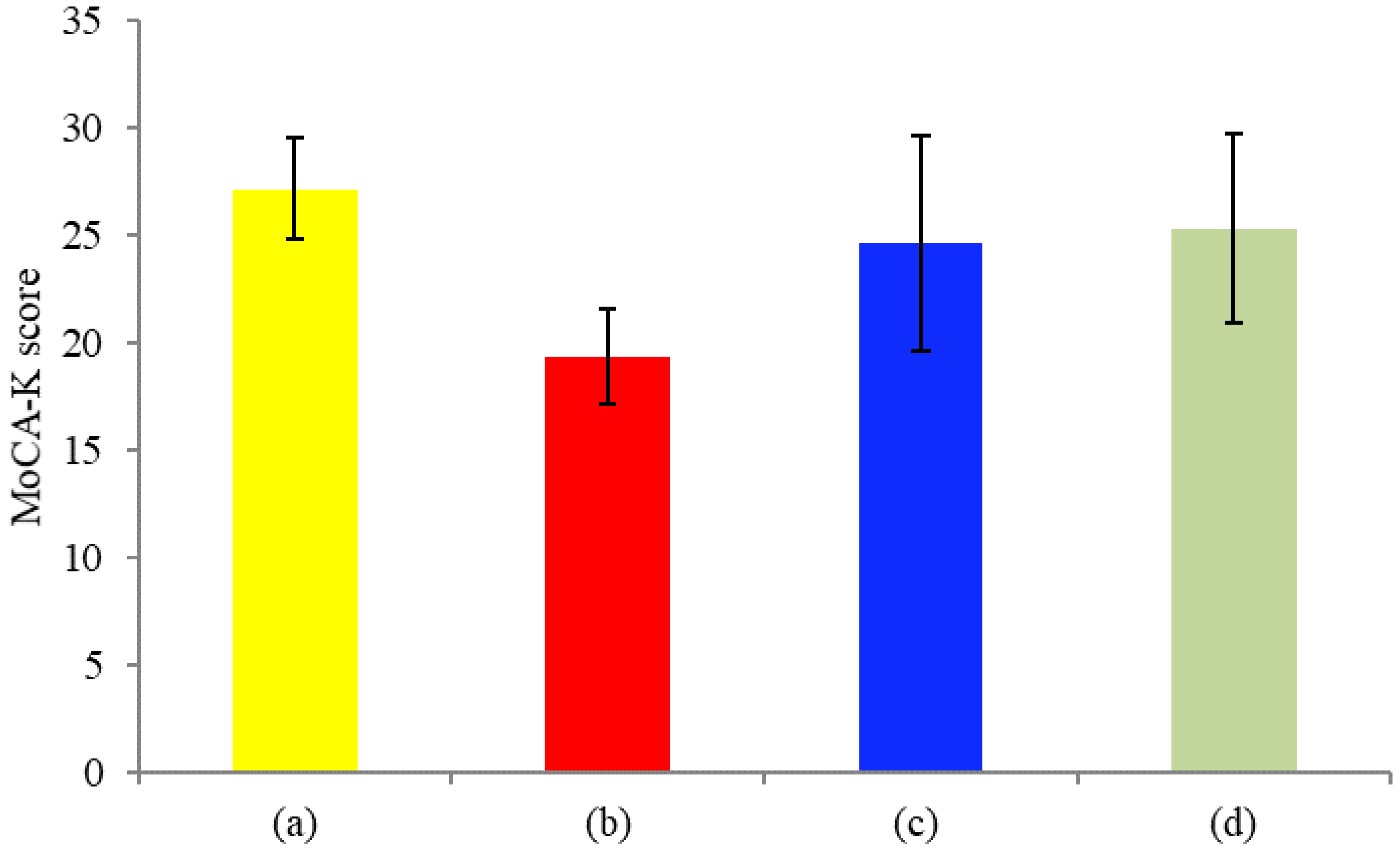


Figure 4

Comparison of the averaged MoCA-K scores along with standard deviations: (a) HC, (b) MCI-0, (c) MCI-1, (d) MCI-2.

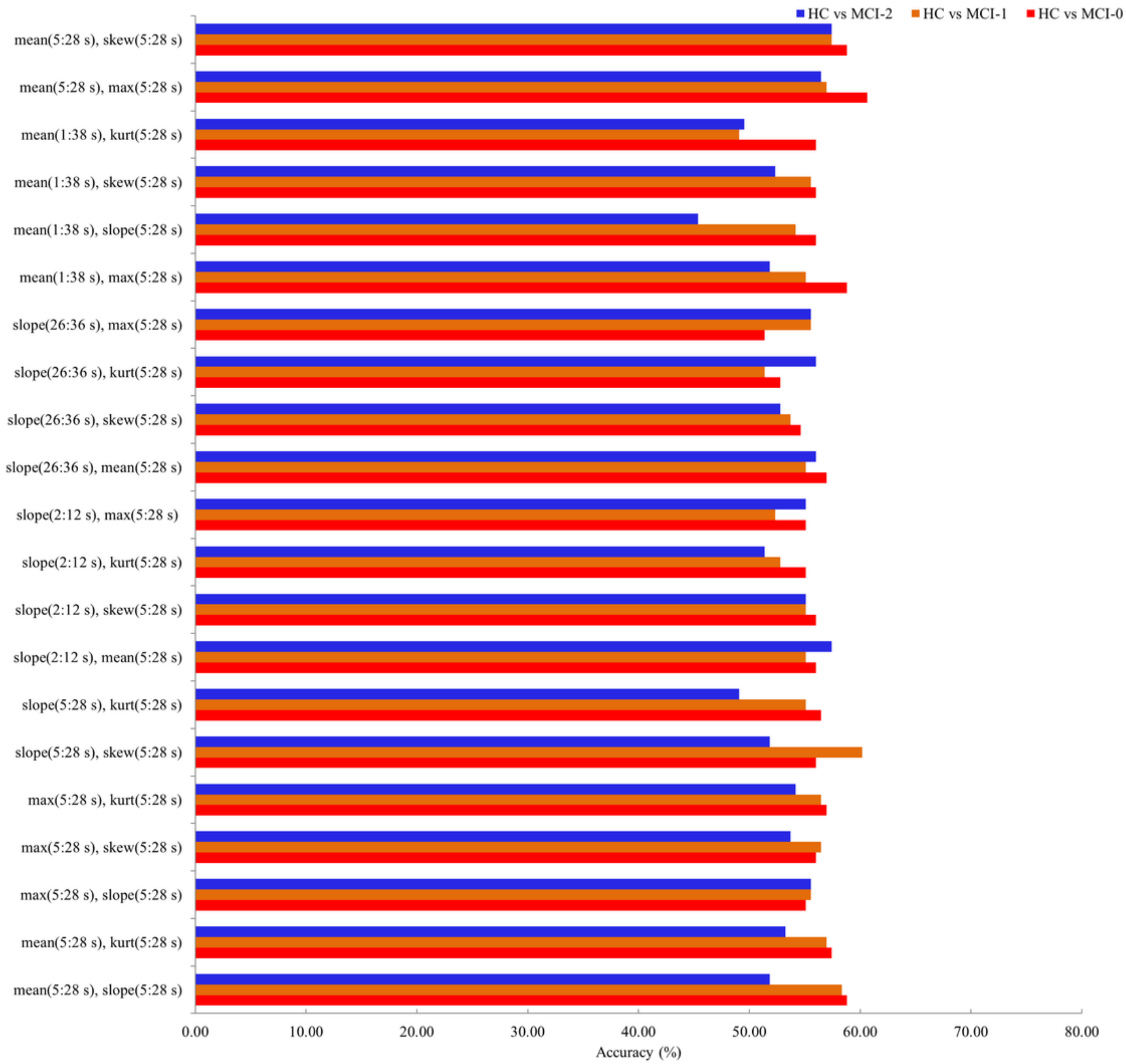


Figure 5

Comparison of classification accuracies for different feature sets: mean (i.e., mean(5:28 s) for brevity), maximum (i.e., max(5:28 s)), slope (i.e., slope(5:28 s)), skewness (i.e., skew(5:28 s)), kurtosis (i.e., kurt(5:28 s)), increasing slope (i.e., slope(2:12 s)), decreasing slope (i.e., slope(26:36 s)) and entire mean (i.e., mean(1:38 s)).

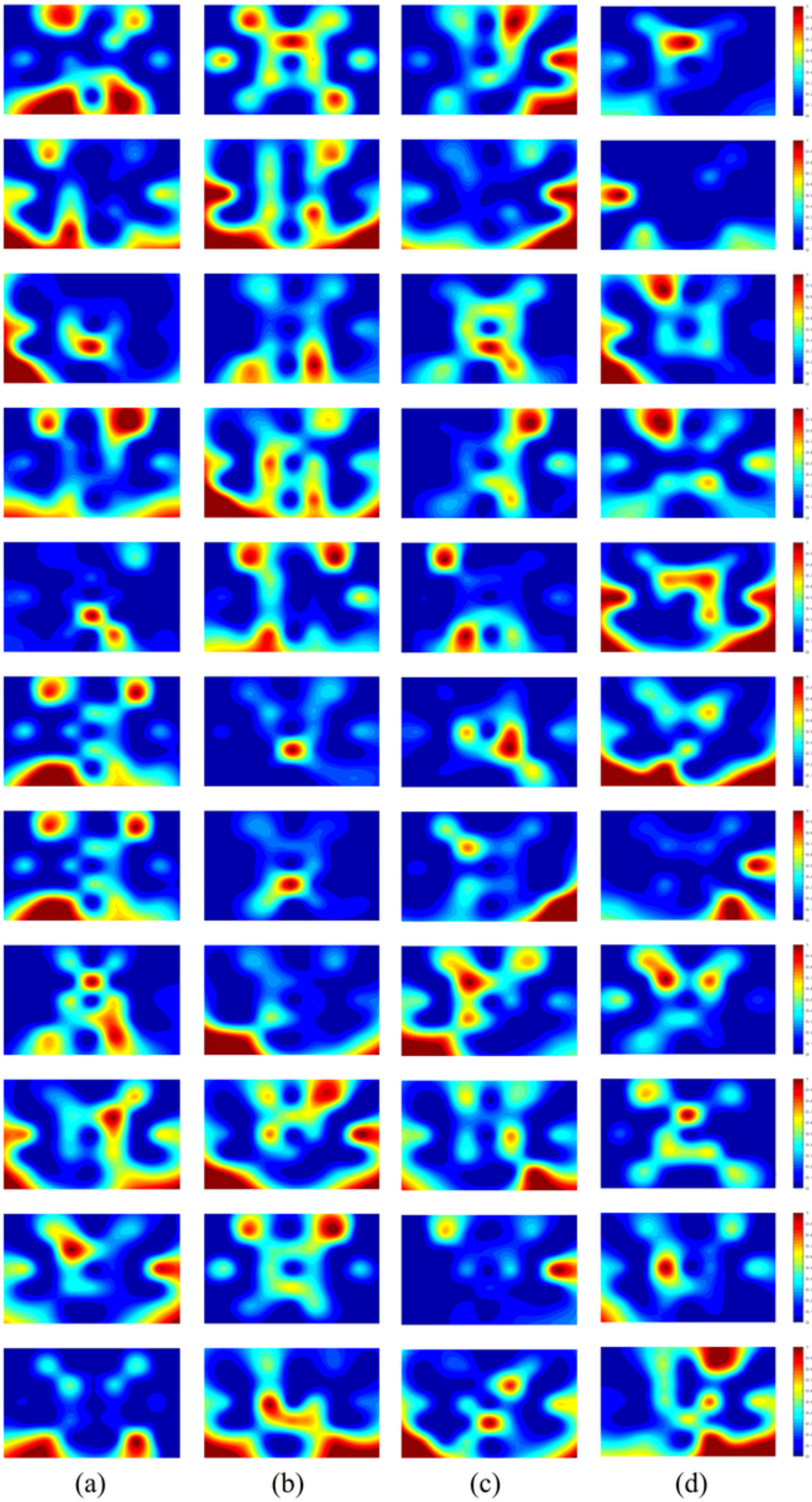
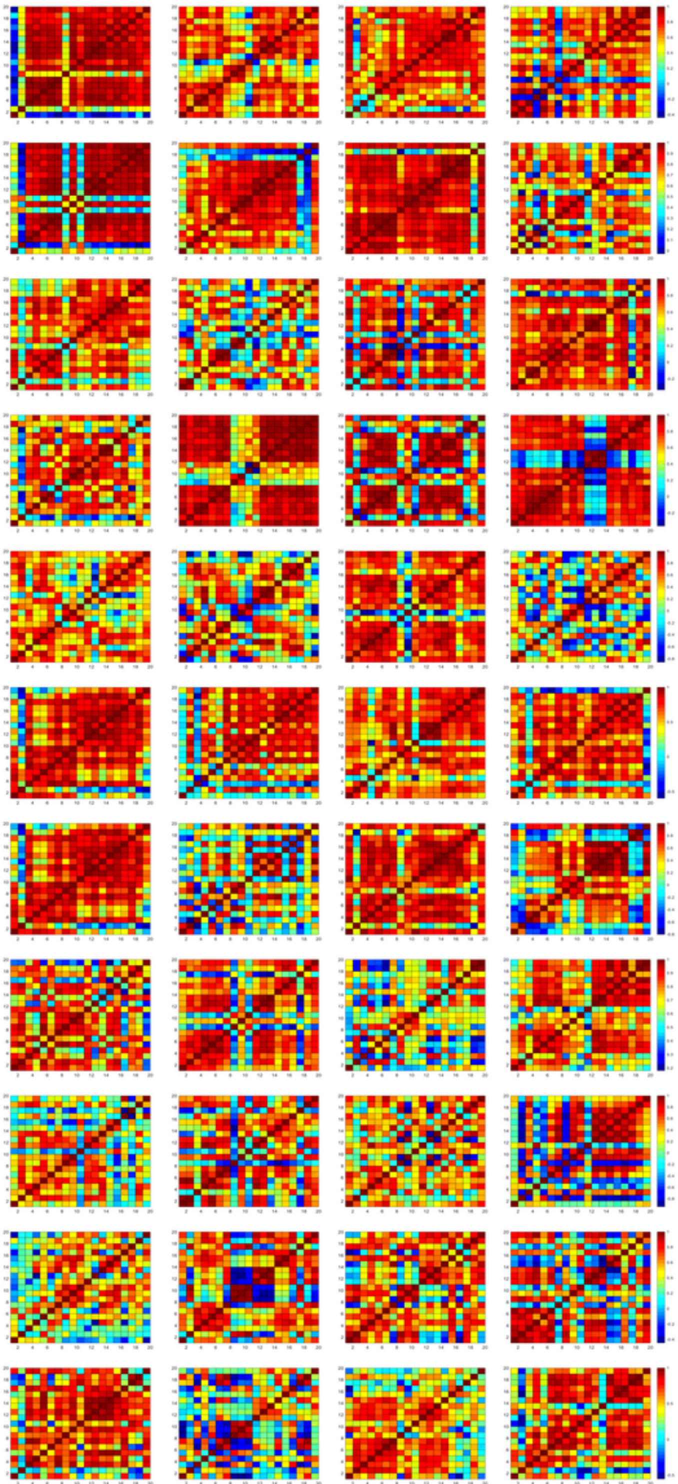


Figure 6

Activation maps of all participants: (a) HC, (b) MCI-0, (c) MCI-1, (d) MCI-2.



(a) (b) (c) (d)

Figure 7

Connectivity maps of all participants: (a) HC, (b) MCI-0, (c) MCI-1, (d) MCI-2.

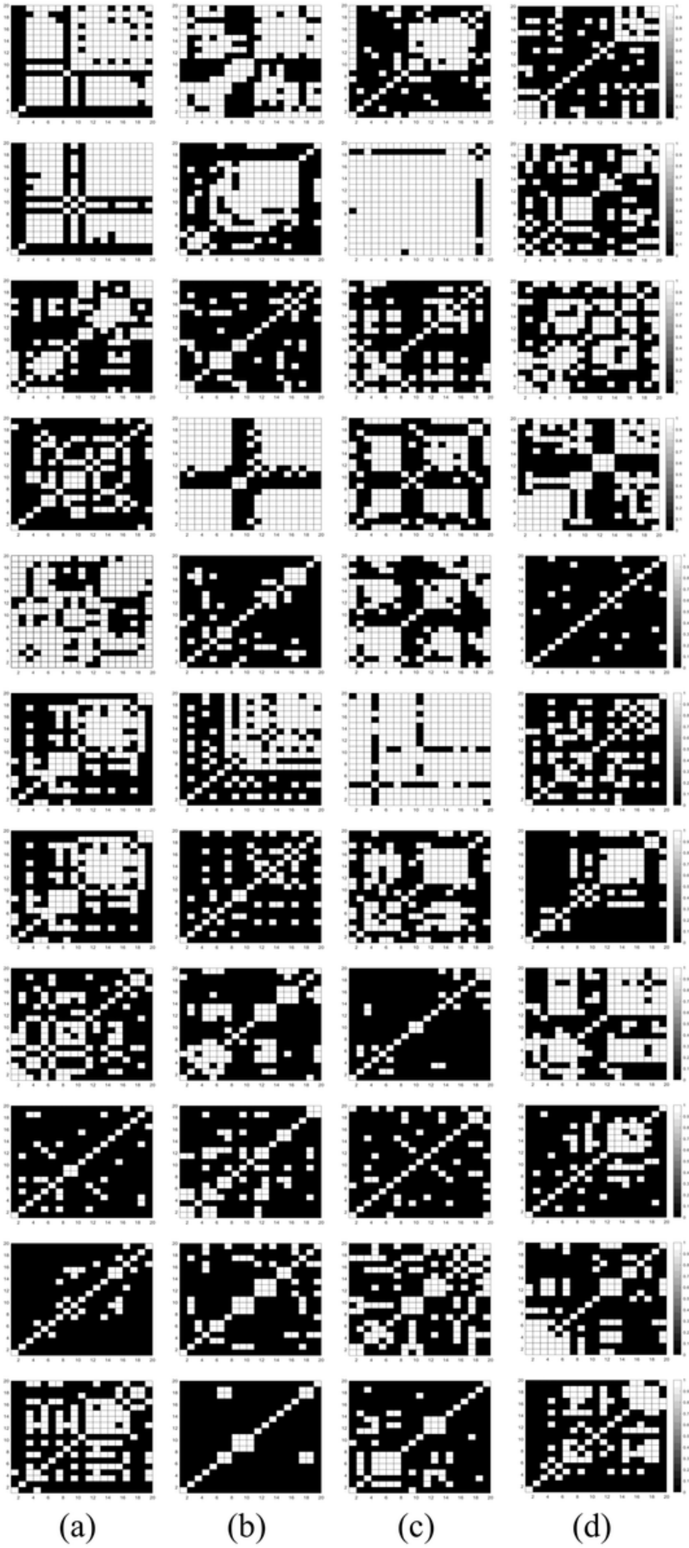


Figure 8

Binary matrices of all participants with threshold of 0.8: (a) HC, (b) MCI-0, (c) MCI-1, (d) MCI-2.

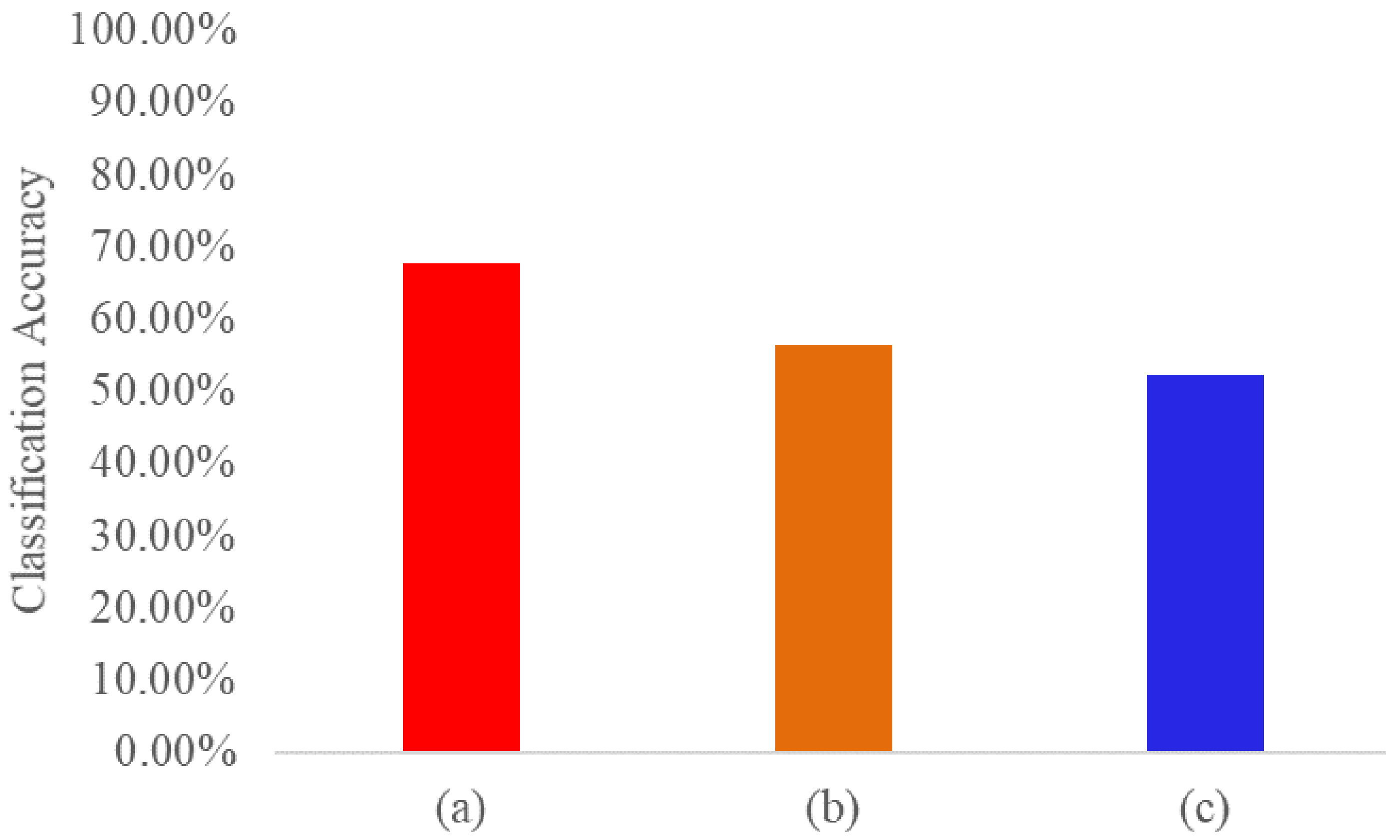


Figure 9

Comparison of CNN-based classification results obtained using t-maps: (a) HC vs. MCI-0, (b) HC vs. MCI-1, (c) HC vs. MCI-2.

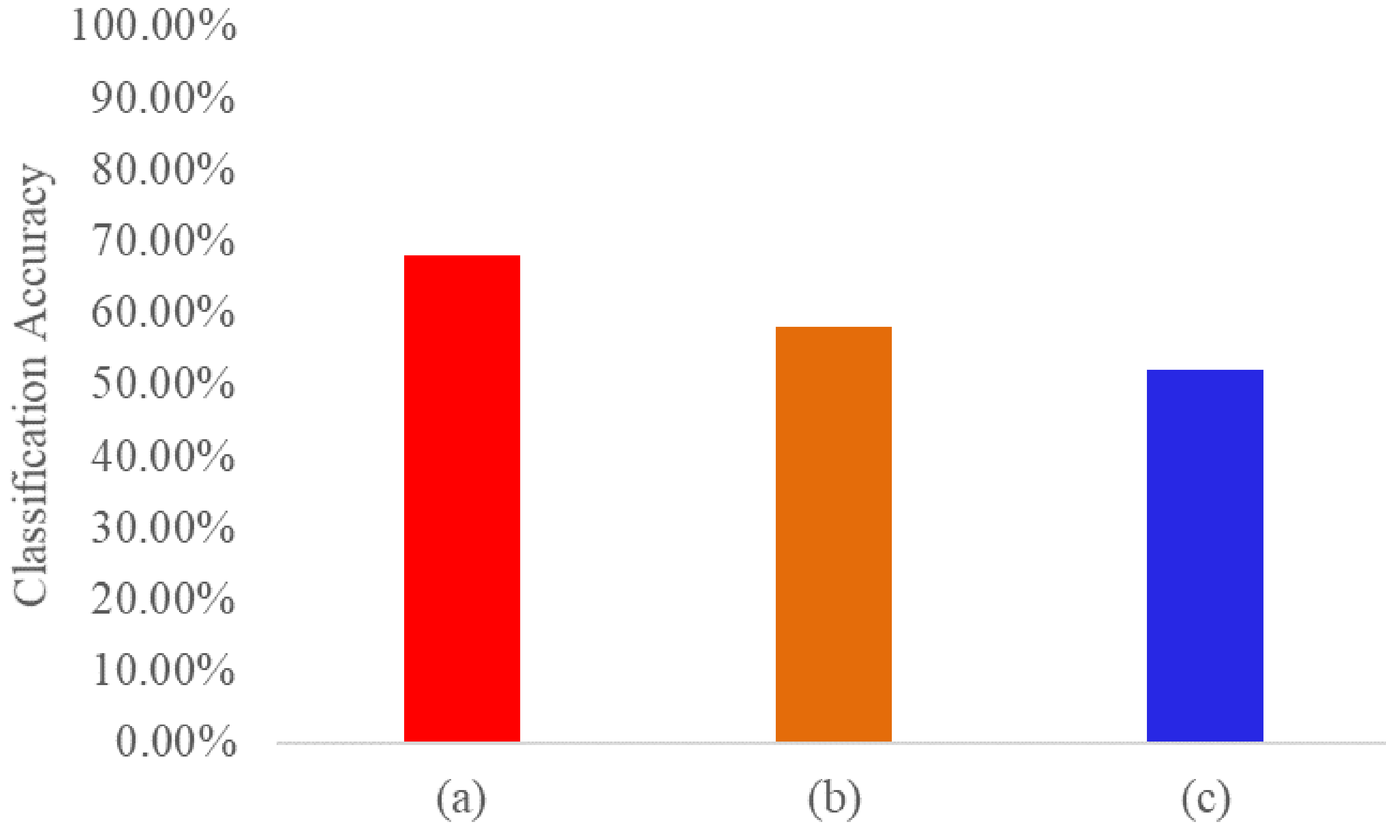


Figure 10

Comparison of CNN-based classification results obtained using connectivity maps: (a) HC vs. MCI-0, (b) HC vs. MCI-1, (c) HC vs. MCI-2.

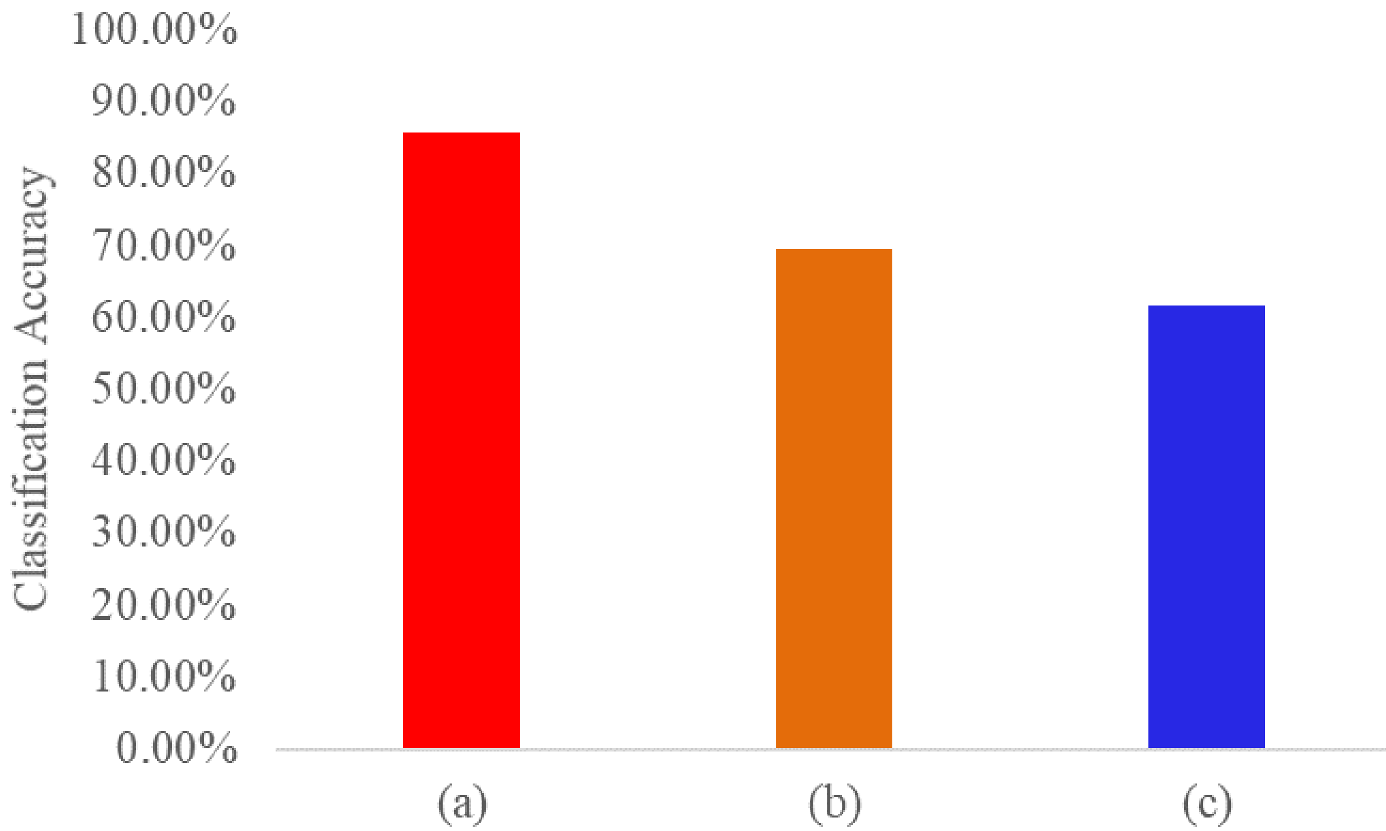


Figure 11

Comparison of CNN-based classification results obtained using binary maps: (a) HC vs. MCI-0, (b) HC vs. MCI-1, (c) HC vs. MCI-2.