Fractal Dimension Based Neurofeedback Training to Improve Cognitive Abilities

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***Abstract*—Currently, neurofeedback training can be used not only to treat the patients with attention deficit hyperactivity disorder, learning difficulties, etc. but also to improve cognitive abilities of healthy people. Training protocols based on alpha, theta, or theta/beta power calculated from Electroencephalogram (EEG) are commonly used in the neurofeedback training. However, when the standard neurofeedback protocols are used, the EEG recording is required before the training to obtain the training threshold for each subject. In this paper, we propose a fractal dimension (FD)-based neurofeedback training protocol with adaptive algorithm, which does not need any before-training recording. The algorithm is integrated in the Shooting game. The efficiency of the FD-based neurofeedback training in comparison with traditional individual theta/beta based neurofeedback training is assessed using Psychology Experiment Building Language (PEBL) tests such as matrix rotation (for spatial ability), change detection (for focused attention), math processing (for cognitive abilities) and test of attentional vigilance (for attention of vigilance). 40 subjects participated in the study. They were divided randomly into FD-based neurofeedback training group and theta/beta ratio-based training group. The results show that after neurofeedback training participants from FD-based training group has similar or better test performance than the one from ratio-based group.**

Keywords-Brain-Neuroscience; BCI in Games; Fractal Dimension; Neurofeedback; Cognitive Abilities

I. INTRODUCTION

Neurofeedback training is traditionally used to treat patients with Attention Deficit Hyperactivity Disorder, learning disability, etc. Electroencephalogram (EEG) data are used to monitor real-time brain activities. The feedback is given to the user to teach him/her to do self-regulation. The feedback can be visual, audio or even haptic. It can be implemented as a color change, bar increase/decrease, vibration and sound or it can be integrated in the neurofeedback game as character/object appearance, the target color in shooting game, etc. The feedback indicates whether the current brain state is the targeted one or not.

Currently, as inexpensive and easy-to-use EEG devices come into the market, this neurofeedback technique can also be applied to healthy subjects to boost their cognitive abilities. Neurofeedback training protocols based on alpha, theta, theta/beta enhancement are the most commonly used protocols. Besides using the standard frequency ranges to do neurofeedback training, calculating individual frequency ranges can improve efficiency of the neurofeedback training [1, 3, 6]. However, to use an individual frequency range, a pre-training eyes-open and an eyes-closed EEG recording are needed to get the individual alpha peak frequency and bandwidth [15].

In this work, we design and implement an experiment to assess and compare the use of an adaptive Fractal Dimension (FD)-based algorithm and individual theta/beta ratio-based algorithm for neurofeedback training. The Shooting game was developed and applied in neurofeedback training with both algorithms. The adaptive FD-based algorithm used in the game doesn't need any EEG recording before each training session. Our hypothesis is that the neurofeedback training based on the adaptive FD algorithm can obtain similar or better efficiency than the individual theta/beta based neurofeedback training.

This paper is structured as follows: Section II introduces neurofeedback training protocols. Section III introduces a Psychology Experiment Building Language (PEBL) test battery. Section IV describes the proposed and implemented experiment. Section V gives the results and Section VI concludes the paper.

II. NEUROFEEDBACK PROTOCOL

A. Power-based Neurofeedback Training

Among different neurofeedback training protocols, increasing alpha power [1, 2], and increasing beta activity while suppressing theta band activity [3-8] are the most widely used neurofeedback training protocols to improve cognitive abilities of both patients with mental disorders and healthy adults. For example, the training protocol in [1] for children with learning disability was decreasing theta power and increasing alpha power; for children with ADHD, the protocol in [3, 4] was suppressing theta power while increasing beta power; for healthy adults, the neurofeedback protocol is enhancing Sensory Motor Rhythm (SMR, ranges from 12 to15 Hz and is also part of beta frequency range) or Beta-1(12-18Hz) amplitude without concurrent increase in theta [5, 6]. The results show that both omission errors and reaction time variability in the divided attention task were reduced in the SMR group and the reaction time in the vigilance attention test was reduced in Beta-1 group. However, when the standard frequency range is used in the neurofeedback training, it is

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reported that subjects can have a headache and irritability [9]. It is reported that use of the individual frequency ranges helps to eliminate such cases. The effectiveness of neurofeedback training with use of individual frequency ranges is higher as well [9, 10]. With individual frequency bands, increasing upper alpha activity is proved to be effective in the neurofeedback training to improve the memory [11], visuo-spatial skills [10, 12], etc.

In [13], it is shown that after neurofeedback training with individual theta/beta-1 ratio and upper alpha power training the individual alpha peak frequency is increased. However, in our work, we observed during the experiment that the upper alpha-based training is more likely to be affected by eye artefacts than the ratio-based training. Moreover, it is recommended that individual upper alpha based training should be done with eye-closed [14-17] as upper alpha is suppressed when eyes are open. Thus, the theta/beta-1 ratio training (suppressing individual theta and increasing beta-1) is selected to be used in the training to compare with the results of FD-based neurofeedback training.

To get the individual theta/beta ratio, the recording of 1 minute eyes-open and eyes-closed EEG data is needed. The parameters such as individual alpha bandwidth, theta, beta frequency range, and finally, theta/beta ratio threshold are calculated. The individual alpha frequency range is calculated as the suppressed frequency range when the power spectral density of eyes-open and eyes-closed EEG signals are compared [9, 18]. Then, the theta band range is defined from 3 Hz to the individual lower alpha boundary and the individual beta-1 band range is defined from the upper alpha boundary to 18 Hz.

B. *Fractal Dimension-based Neurofeedback Training*

We implement an adaptive neurofeedback algorithm based on fractal dimension calculation. The fractal dimension values can provide extra information that is not provided by power spectra. For example, the fractal dimension values of signals with the same power spectra could be different [19]. A fractal dimension (FD) analysis can be used in real-time EEG signal processing [20, 21]. Fractal dimension based neurofeedback training is first proposed in [22]. It is also shown in [22] that the FD can differentiate mental tasks better than the power features. The advantage of the method is that it does not need to calculate the individual frequency bands and threshold for the individual neurofeedback training.

Different algorithms can be used to calculate FD value. In this paper, Higuchi algorithm [23] is used. The FD-based neurofeedback system flow chart is shown in Fig. 1. EEG data are acquired from Emotiv device [24] and transmitted to computer via Bluetooth. A 2-42 Hz band-pass filter is applied first. Then, Higuchi fractal dimension value is calculated according to the most recent 128 samples. An initial (default) threshold is set up to 1.65 which corresponds to the relaxed brain status based on experiment's observation and it is changed adaptively as follows. The threshold is decreased in a stepwise manner if the subject cannot reach the reward criteria for 3 times; the threshold is increased in a stepwise manner if the subject can reach the reward criteria for 3 times.

In this work, the efficiency of FD-based neurofeedback training is compared with one of the best available neurofeedback training method – individual theta/beta ratio based neurofeedback training.

III. Psychology Experiment Building Language Tests

The Psychology Experiment Building Language (PEBL) test battery [25] is an open-source software that consists of a set of standard and novel psychological tests for research and clinical purposes. In our experiment, we select tests to assess spatial ability, focused attention, cognitive abilities and attention of vigilance to measure the subjects' performance before and after neurofeedback training.

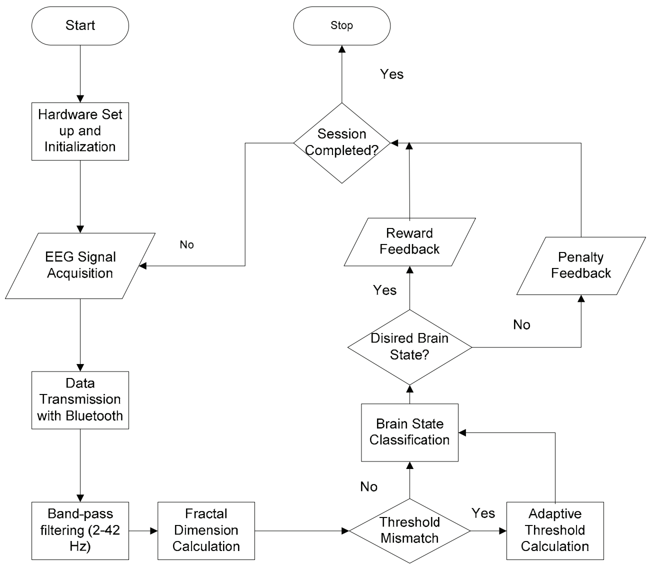

Figure 1. The flow chart of FD-based neurofeedback system.

A. *Matrix Rotation*

The test is aimed at measuring spatial ability of the subjects. In this test, a matrix is first displayed and the subject has to memorize the pattern of the matrix first. Then, the first matrix disappears and another matrix which can either be the original matrix rotated 90 degrees or a totally different one appears on the display. The subject is to respond whether the second matrix is the same as the first one just rotated. The mean time of the first matrix memorization, mean reaction time to confirm whether the second matrix is the same as the first one, and accuracy of the response are recorded.

B. *Math Processing*

The test is aimed to measure the cognitive ability of the subjects. This task requires subjects to process simple addition and subtraction mentally within a given time limit. The participants need to answer whether the answer is greater or less than 5. This task has 3 variations, requiring computation of 2, 3 and 4 digits respectively. The mean reaction time and accuracy of response are recorded.

C. *Change Detection*

The test is aimed to measure the focused attention of the subjects. In each trial of the test, the subject is to identify the singular change between two images that are flashed back and forth. The change can be one of the following: change in location of a circle; presence/absence of a circle; change in colour of a circle; and change in size of a circle. The subject is allowed to take time as long as required to identify the change. The mean reaction time across all trials and the accuracy of response are recorded.

D. *Test of Attentional Vigilance*

The test is aimed to measure the attention of vigilance ability of the subjects. The test lasts approximately 24 minutes in which a white small window appears briefly on the screen, with a black square within it. Participants should respond only when the black square appears on top of the white window and not respond when the black square appears on the bottom of the white window. For the first half of the test, targets are appeared rarely; for the second half, they are appeared more frequently. The number of commission and omission errors and the mean reaction time are all recorded.

IV. EXPERIMENT

A. *Subjects*

40 male subjects are divided randomly into 2 groups, one is a FD-based neurofeedback group and the other one is an individual theta/beta ratio-based group.

B. *Neurofeedback Protocol*

Emotiv device [24] is used to acquire the EEG data due to the convenience in setting up of the device. Channel P8 (classified according to American Electroencephalographic Society guidelines for standard electrode position nomenclature [26]) is selected in the neurofeedback training system to calculate the features according to the research in [9] where parietal lobe channel was used in the neurofeedback training. Additionally, in [27], it is also shown that the parietal lobe P8 channel outperforms other channels in mental workload classification. Thus, channel P8 was chosen for the FD and theta/beta ratio values calculation for the neurofeedback training.

In week 1 and 2, the subjects from both groups had 2 assessment sessions (pre-try and pre-train) to avoid the learning effect [28]. In the pre-try and pre-training assessment sessions, the tests from PEBL as introduced in Section III were given to the subjects in the following sequence: matrix rotation, math calculation, change detection, and Test of Attentional Vigilance. From week 3 to 6, the subjects were asked to play a Shooting game for 40 minutes twice per week (10 minutes game play x 3 times with 5 minutes rest in between). The Shooting game was developed with possibility to use different neurofeedback algorithms. As it was introduced in Section II A and B the neurofeedback protocols for both groups are as follows: for the FD-based group, a default threshold is set at the beginning and the threshold is gradually adjusted during the training. For the ratio-based group, 1 min eyes-open and eyes-closed EEG signals are recorded before NFT session to obtain the individual frequency ranges and to set the threshold for theta/beta based training. The FD and ratio values are calculated during the training and compared with the thresholds and if they are larger than the thresholds, it means the current brain state is desired one. The Shooting game is implemented as follows. The feedback to the player is given in a form of the color change of the robots in the game as it is shown in Fig. 2 and 3. When the brain state of the player is not in the targeted state, the robots' colour stays blue and all robots keep running around on the game map, and the player is not able to shoot them. When the brain state of the player changes to the targeted one, these robots turn to red, and the player can shoot successfully. To provide more immersion and relevance to the player's task, a numerical score counter was located to the top center of the screen to allow the player to better monitor their performance, as shown in Fig. 4. Furthermore, the score changes colour from white to yellow to red and finally resetting to 0 if the player continually shoots the blue robots, shown in Fig. 5. This change was implemented to encourage the player to focus more attention on the task and not fire indiscriminately. Lastly each tier of the audio "reward" plays based on the cumulative score of the player, to encourage the player to seek a higher game score and by extension, a more successful training session.

In week 7, another assessment session with PEBL tests was given to the subjects to see any test performance improvements in both groups.

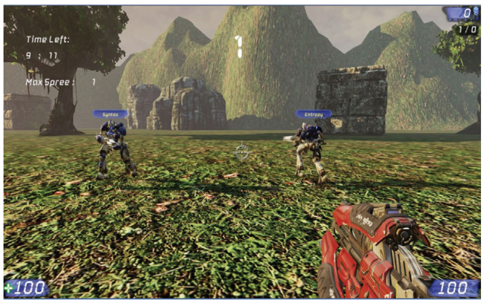

Figure 2. The robot color "blue" corresponds to the non-targeted player's brain state. The player can not shoot.

Figure 3. The robot color "red" corresponds to the targeted player's brain state. The player can shoot.

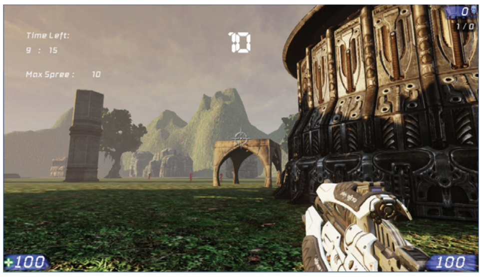

Figure 4. Score display.

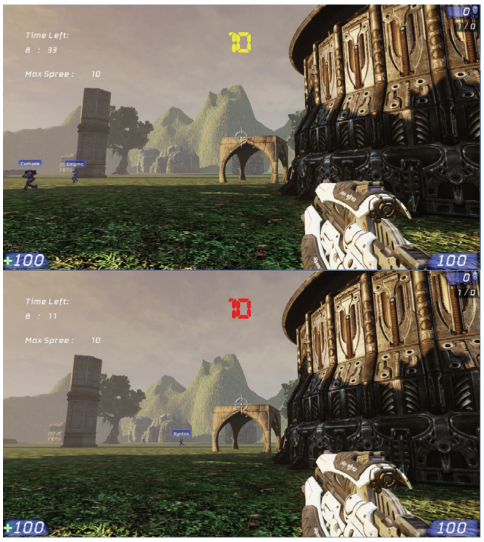

Figure 5. Score colour changes.

V. RESULTS

The performance results of PEBL tests of the subjects in both groups before and after neurofeedback training are used to measure the efficiency of the FD-based training in comparison with the individual theta/beta based training. 18 out of 20 subjects' data from FD-based neurofeedback group and 19 subjects' out of 20 subject's data from ratio-based group are used in the data analysis. 3 subjects' data are not available as the subjects did not complete the experiment.

Kruskal-Wallis test is applied to the pre-training scores of both neurofeedback training groups. The resulted p values show that there is no significant difference of the performance scores between FD and ratio group before training ($p>0.05$). Then, the difference of pre- and after-training scores is analyzed as follows. The FD-based neurofeedback training group has higher increase in scores of each test as it is shown in Fig. 6-9. Here, the increase in score is obtained by first calculating the differences between the pre-training and after training tests scores and then by averaging across the subjects who have improvement. The error bars in the figures show the standard deviation (SD). It is shown that in all cases except the accuracy of the matrix rotation test and accuracy of the math calculation test (Fig. 6), commission error in the part 2 of the TOAV test (Fig. 7), and reaction time of the change detection test (Fig. 9), FD-based neurofeedback group has better test improvement after the neurofeeback training than ratio-based group. When paired t-test was applied to the pre- and after-training scores, only ratio-based group's improvement of the accuracy of Change Detection ($p=0.02$) and Matrix Rotation tests ($p=0.03$) is significant. If the difference between pre- and after-training scores follows normal distribution, a "+" is added in Fig. 6-9 to denote that data follow normal distribution. Another Kruskal-Wallis test is applied to the after-training test scores of both neurofeedback training groups. The resulted p values show that there is no significant difference of scores in all tests between FD and ratio group ($p>0.05$) except the accuracy of Matrix Rotation test ($p=0.03$) and reaction time of Matrix Rotation test ($p=0.03$).

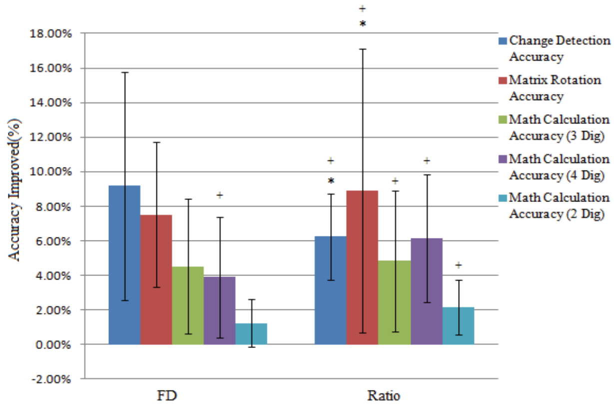

Figure 6. Improved accuracy in PEBL test. * The improvement of the scores in the test is siganificant ($p<0.05$). + The dataset follows normal distribution.

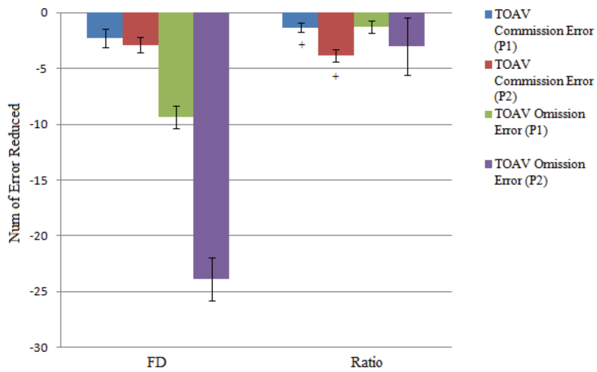

Figure 7. Reduced error in PEBL test. + The dataset follows normal distribution.

VI. CONCLUSION

In this paper, we propose a FD-based neurofeedback training protocol. An experiment with 40 subjects is carried out. The subjects are partitioned into two groups where one group follows the FD-based training protocol and the other one uses the standard individual ratio-based training protocol. The efficiency of both neurofeedback training protocols is measured in two assessment sessions which are done before and after the 8 sessions of the corresponding neurofeedback training. The PEBL tests such as matrix rotation (for spatial ability), change detection (for focused attention), math processing (for cognitive abilities) and test of attentional vigilance (for attention of vigilance) are taken by the subjects during the assessment sessions. The test scores are analyzed. The results of the data analyses show that the improvements in the tests scores after neurofeedback training are similar in both groups. It confirms that the FD-based neurofeedback training protocol can be used for cognitive abilities training. Besides that, the FD-based neurofeedback training protocol has an advantage over standard individual ratio-based training protocol as the FD-based training does not need extra EEG signal recording to calculate the individual frequency bands before each neurofeedback session as the individual ratio-based training needs.

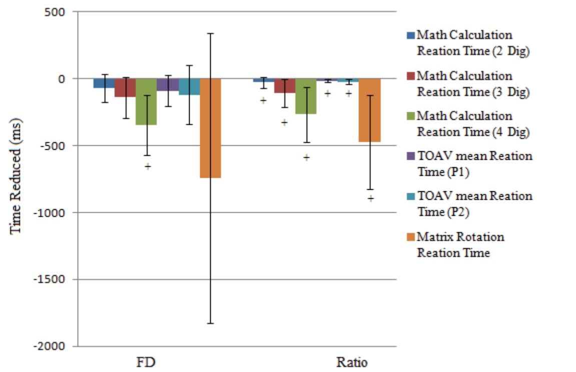

Figure 8. Reduced reaction time in PEBL test. + The dataset follows normal distribution.

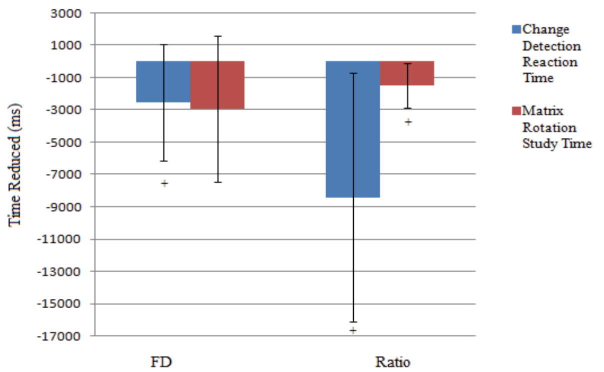

Figure 9. Reduced reaction time and study time in PEBL test. + The dataset follows normal distribution.

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