Beta/theta Ratio Neurofeedback Training Effects on the Spectral Topography of EEG

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***Abstract*— Neurofeedback training (NFT) has shown positive effects on cognition and behavior enhancement as well as clinical treatment. However, little is known about the training effects in brain activity besides training location which is crucial for understanding the mechanism of neurofeedback and enhancing training efficiency. This study aimed to investigate beta/theta ratio (BTR) NFT effects on the spectral topography of electroencephalogram (EEG). Eleven healthy volunteers completed 25 sessions of NFT in consecutive five days with 5 sessions per day. The results showed that BTR NFT in occipital region did have significant effect on parietal, central and frontal regions, and the changes of BTR and theta amplitude detected in these regions were consistent with the changes at the training location. Moreover, the percentage changes of BTR and theta amplitude in parietal region were significantly greater than those in frontal region probably due to the shorter distance to the training location.**

I. Introduction

Neurofeedback training (NFT) is an operant conditioning procedure, in which participants are able to gain control over particular aspects of their electroencephalogram (EEG) [1]. An increasing number of studies are conducted to investigate the positive effects of NFT in clinical treatment of neurological and psychological disorders [2] as well as nonclinical performance enhancement in sports, artistic and other areas [3, 4]. However, the specific contribution of NFT to the training process has not been isolated systematically and therefore remains unknown [5].

Up to now, most NFT studies are interested in the training effect on the feedback training location and therefore only the EEG signals recorded from the training location are investigated. In contrast, the NFT effects on other untrained channels have not been provided with sufficient details in the literature. However, the investigation of the NFT effects on the spectral topography of EEG is important, since it gives us a better understanding on the complexity of the neural dynamics involved EEG self-regulation during NFT [5]. Previous work in [5] investigated the impact of EEG frequency bands NFT on spectral EEG topography presumed to mediate cognitive-behavioral training effects. Participants were trained on low beta (12-15 Hz), beta1 (15-18 Hz) and alpha/theta (8-11 Hz/5-8 Hz) protocols, and the results documented that NFT of frequency components did affect spectral EEG topography in healthy individuals, but these effects did not necessarily correspond to either the frequencies or the scalp locations addressed by the training contingencies.

On the other hand, among a variety of NFT protocols, beta/theta ratio (BTR) training has been applied in a number of studies in treatment for attention-deficit hyperactivity disorder (ADHD) patients [6] and improvement of physical balance performance [7]. Considering the importance of BTR NFT as well as the investigation of its effects on the brain activity, this work aims to investigate the effects of BTR NFT in the occipital region on the spectral topography of EEG.

II. Materials and Methods

A. Participants

11 healthy young volunteers aged from 19 to 29 (9 males; mean = 23.73, standard deviation (SD) = 3.20) years participated in the NFT experiment. Prior to the experiment, all participants signed an informed consent form after the experimental nature and procedure were explained and their questions were answered. The protocol was in accordance with the Declaration of Helsinki and approved by the Research Ethics Committee (University of Macau).

B. NFT Protocol

The NFT protocol in this experiment aimed to enhance beta (15-18 Hz) amplitude and inhibit theta (4-7 Hz) amplitude. Thus, their amplitude ratio (beta/theta) was set as the training parameter. The whole training procedure lasted for 5 consecutive days. Each participant completed 5 training sessions per day for a total of 25 sessions in 5 days. The time of the day for training was constant across 5 training days for each participant. Each session was composed by 4 successive trials of 1 min each and with an interval of 10 s between two consecutive trials. The participants had a short rest (several minutes) between two consecutive sessions. The resting baseline recording consisted of two 30-s epochs with eyes open and two 30-s epochs with eyes closed before and after NFT on each day. The resting baseline recorded before NFT on each day was defined as pre-baseline while the one recorded after NFT on each day was defined as post-baseline.

C. Experiment System Settings

The NFT was conducted employing a bipolar (sequential) montage. Two electrodes were placed directly below the locations O1 and O2, barely above the inion, and nine electrodes were placed on F3, Fz, F4, C3, Cz, C4, P3, Pz and P4. Impedance was kept below 10 kΩ for all electrodes. EEG signals were amplified by a 24-channel amplifier (Vertex 823 from Meditron Electomedicina Ltda, SP, Brazil) with an

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analog band-pass filter from 0.1 to 70 Hz. The signals were recorded by Somnium software platform (Cognitron, SP, Brazil) at a sampling frequency of 256 Hz and they were filtered by a band-pass filter from 0.5 to 30 Hz and a notch filter at 50 Hz in this system. The amplitudes of the EEG frequency bands were calculated by fast Fourier transforms (FFT) every 125 ms based on 2 s data windows.

Two 3D objects, a sphere and a cube showed on the monitor as the feedback display. The sphere radius was a reflection of the training parameter (BTR) in real time, and the change of the sphere color indicated that the value of BTR reached a threshold (Goal 1). This sphere was made of several slices and the more slices it had, the smoother it looked. The cube height was associated with the period of the time for which Goal 1 kept being achieved continuously. If Goal 1 was being achieved continuously for more than a predefined period of time (2 s) which meant that Goal 2 was achieved, the cube kept rising up until it reached the top or Goal 1 stopped being achieved. Then the cube turned to fall slowly until it reached the bottom or rose up again if Goal 2 was accomplished again. The workings of the feedback loop were explained to the participants, and they were instructed to try different mental strategies to achieve Goal 1 or even Goal 2, but no specific instructions about effective mental strategies were given.

Threshold in the first session of each day was set individually based on the BTR in the pre-baseline on the corresponding day. Empirically it was set to 90% of the BTR in the pre-baseline in order to obtain a proper difficulty level for each participant. The percentage of time for the BTR above the threshold in one session would be found in corresponding session report after each training session. The threshold would be reset by increasing 0.1 in next session if the reported percentage of time was over 70%.

D. *Data Analyses*

For each participant, in each training session and resting baseline the amplitudes (relative to 4-30 Hz) were calculated in the theta (4-7 Hz), beta (15-18 Hz) and alpha (8-12Hz) bands. To investigate the effects of BTR NFT on the spectral topography of EEG, besides the training location, the EEG signals from another nine channels were also recorded and grouped into three regions including frontal (F3, Fz, F4), central (C3, Cz, C4) and parietal (P3, Pz, P4) regions. Then, to investigate the time effects on EEG frequency bands including beta, theta, alpha as well as BTR of each region, repeated measures analysis of variance (ANOVA) was performed with *time* as a within-subject factor for the whole training group. Here, the time effects were analyzed from two different aspects separately. One was across sessions (26 levels, pre-baseline on *day* 1 and *session* 1 to *session* 25) which investigated the EEG change in all training sessions compared to resting baseline before *session* 1. The other was within day (6 levels, pre-baseline of each day and *session* 1 to *session* 5 of each day) which investigated the EEG change in 5 sessions compared to resting baseline within each training day. For those regions in which significant training effects were detected, independent *t* tests were used to investigate the difference of percentage changes between regions where the percentage changes included the changes between *session* 5 and pre-baseline within each day and between *session* 25 and pre-baseline on *day* 1.

III. Results

A. *Across Sessions Compared to Baseline*

Fig. 1 presents the mean values of BTR and analyzed frequency bands across all participants from pre-baseline on *day* 1 to *session* 25 of three channels in each region. BTR showed an increasing trend while theta showed a decreasing trend in each region. Alpha increased during early training sessions and then over time reverted back to around baseline level and beta did not showed any change trend over time. Repeated ANOVA revealed a main effect of *session* in BTR, theta and alpha bands in each region except the alpha band in frontal region as shown in Table I. Regarding BTR in all regions, it showed the highest value at *session* 15 compared to pre-baseline on *day* 1 (Frontal: $p = 0.014$, $d = 0.12$; Central: $p = 0.014$, $d = 0.13$; Parietal: $p = 0.014$, $d = 0.16$; d indicates the mean difference between the pre-baseline on *day* 1 and *session* 15). Moreover, BTR was also significantly higher at *session* 25 compared to pre-baseline on *day* 1 (Frontal: $p = 0.03$, $d = 0.078$; Central: $p = 0.02$, $d = 0.095$; Parietal: $p = 0.01$, $d = 0.13$; d indicates the mean difference between the pre-baseline on *day* 1 and *session* 25). For theta, the amplitude at *session* 25 was significantly lower than pre-baseline on *day* 1 in central ($p = 0.011$, $d = -0.106$) and parietal ($p = 0.021$, $d = -0.123$) regions (d indicates the mean difference between the pre-baseline on *day* 1 and *session* 25).

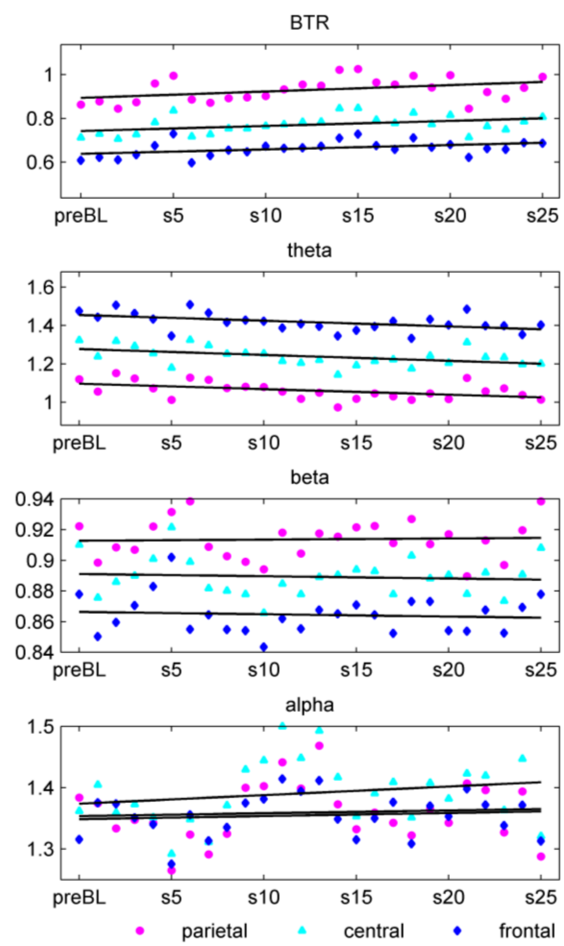

Figure 1. Mean values across all participants in BTR and analyzed frequency bands across the whole training procedure. *(preBL: pre-baseline on day 1, s: session)*

TABLE I. TIME EFFECT ACROSS THE WHOLE TRAINING PROCEDURE

Region	Frequency Band		
	BTR	***Theta***	***Alpha***
Frontal	$F = 3.451$, $p = 0.008$	$F = 2.706$, $p = 0.017$	$p>0.05$
Central	$F = 3.232$, $p = 0.01$	$F = 3.275$, $p = 0.006$	$F = 4.143$, $p = 0.001$
Parietal	$F = 3.484$, $p = 0.005$	$F = 3.097$, $p = 0.011$	$F = 3.316$, $p = 0.004$

B. Within Days Compared to Baseline

Each training day contained 5 NFT sessions which consisted of 4 consecutive trials of 1 min. The within-day analyses aimed to look for changes from pre-baseline to *session* 5 during each training day. Fig. 2 presents the mean values of BTR and analyzed frequency bands across all participants within days of three channels in each region. BTR increased while theta decreased over time and beta also showed a slight increasing trend within days. In contrast, alpha did not show a same change trend among all three regions. Repeated ANOVA revealed a main effect of *session* within days in BTR, theta and alpha bands in all regions, as shown in Table II. In contrast, it was not the case for beta. Further pairwise comparisons found significant differences of BTR, theta, and beta in all regions between the pre-baseline and *session* 5 in each day except for beta in frontal region, as shown in Table III (d indicates the mean difference between pre-baseline and *session* 5 of each day). On the contrary, alpha amplitude had no significant difference between the pre-baseline and *session* 5 within days in any region.

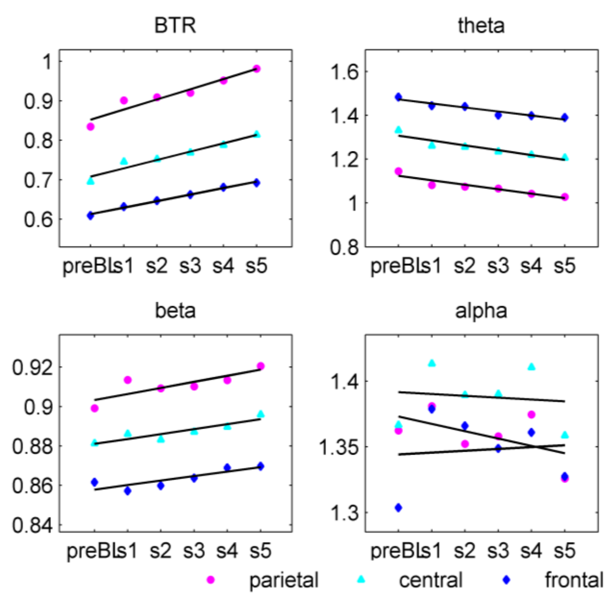

Figure 2. Mean values across all participants in BTR and analyzed frequency bands within days. *(preBL: pre-baseline of each day, s: session)*

TABLE II. TIME EFFECT WITHIN DAYS

Region	Frequency Band		
	BTR	***Theta***	***Alpha***
Frontal	$F = 8.157$, $p < 0.0001$	$F = 9.243$, $p < 0.0001$	$F = 5.123$, $p = 0.002$
Central	$F = 21.348$, $p < 0.0001$	$F = 18.629$, $p < 0.0001$	$F = 3.857$, $p = 0.007$
Parietal	$F = 20.802$, $p < 0.0001$	$F = 18.14$, $p < 0.0001$	$F = 2.796$, $p = 0.038$

TABLE III. MEAN DIFFERENCE BETWEEN PRE-BASELINE AND *SESSION* 5

Region	Frequency Band		
	BTR	***Theta***	***Beta***
Frontal	$d = 0.084$, $p < 0.0001$	$d = -0.094$, $p < 0.0001$	$p > 0.05$
Central	$d = 0.119$, $p < 0.0001$	$d = -0.125$, $p < 0.0001$	$d = 0.017$, $p = 0.029$
Parietal	$d = 0.148$, $p < 0.0001$	$d = -0.117$, $p < 0.0001$	$d = 0.021$, $p = 0.007$

C. Percentage Change Comparison between Regions

Percentage changes of BTR and theta amplitude between pre-baseline on *day* 1 and *session* 25 and between the pre-baseline and *session* 5 within each day were calculated. The results of independent t test revealed that the percentage changes of BTR between frontal and parietal regions were significantly different both between pre-baseline on *day* 1 and *session* 25 ($p < 0.05$) and between pre-baseline and *session* 5 within days ($p < 0.05$). And there were also significant differences of the percentage changes in theta band within days between central and frontal regions ($p < 0.0001$), and between frontal and parietal regions ($p = 0.001$). As to the percentage changes in theta band between pre-baseline on *day* 1 and *session* 25, marginal differences were also detected between central and frontal regions ($p = 0.051$), and between frontal and parietal regions ($p = 0.05$).

IV. DISCUSSION

The objective of this work was to investigate the BTR NFT effects mainly on the spectral topography of EEG in healthy individuals. 11 participants performed BTR NFT in 5 consecutive days and the training protocol (i.e. enhancement of BTR at the locations below O1 and O2 by NFT, bipolar montage) had main effect on the training locations, with BTR significantly increasing [8]. For the purpose of examining whether the enhancement of BTR also had effects on other locations, EEG signals in nine more channels were recorded and grouped into three regions for analyses.

It turned out that in all analyzed regions BTR significantly increased and the amplitude in theta band significantly decreased while there was no significant change found in beta band, which was similar to the training location. Even though within-day analyses indicated that the amplitude of beta had significant change after the training of each day, when it came to the whole training period no significant difference was detected in beta band. Thus, the enhancement of BTR was mainly due to the decrease of theta.

Furthermore, from the results of the percentage changes comparison, it was found that although NFT had main effects on the EEG signals in all analyzed regions, the changes varied from regions. Both in the analyses of across sessions and within days comparison to baseline, the percentage changes of BTR and theta in parietal region were significantly different from those in frontal region; also, the percentage change of theta in central region had significant difference from that in frontal region, probably resulting from the distance between the training location and each region. The training location was in occipital region which was closest to the parietal region while was farthest to the frontal region relatively. Thus, the percentage change in parietal region was significantly greater than that in frontal region.

It was worth noting that in the analyses of across sessions compared to baseline, although alpha had significant difference in parietal and central regions over time, no significant change in pairwise comparison between pre-baseline on *day* 1 and *session* 25 was found. As such, the significant change of alpha over time was in fact due to an increase during early NFT sessions and that over time the amplitude merely reverted back to around baseline levels. These results reflected that BTR NFT had no effect in neighbor frequency band, consistent with the independence mentioned in [3].

V. Conclusion

To summarize, this study mainly focused on the investigation of the BTR NFT effects on the spectral topography of EEG in order to achieve a better understanding of the brain activity during the NFT. Eleven young healthy volunteers completed 25 sessions of BTR NFT in consecutive five days with five sessions per day. The results showed that BTR NFT in occipital region had significant effects on parietal, central and frontal region. Further, the effects were significantly different among these regions probably due to the distance to the training location. Future study will investigate the training effects in more regions.

Acknowledgment

This work is supported in part by FCTPEst-OE/EEI/LA0009/2013 Grant and the Macau Science and Technology Development Fund under Grant FDCT036/2009/A and FDCT055/2015/A2 and FDCT087/2012/A3 and the University of Macau Research Committee under Grants MYRG139(Y1-L2)-FST11-WF, MYRG079(Y1-L2)-FST12-VMI, MYRG069(Y1-L2)-FST13-WF, and MYRG2014-00174-FST and MRG014/MPU/2014/FST.

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