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Peripheral Visual Performance Enhancement by Neurofeedback Training

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Abstract Peripheral visual performance is an important ability for everyone, and a positive inter-individual correlation is found between the peripheral visual performance and the alpha amplitude during the performance test. This study investigated the effect of alpha neurofeedback training on the peripheral visual performance. A neurofeedback group of 13 subjects finished 20 sessions of alpha enhancement feedback within 20 days. The peripheral visual performance was assessed by a new dynamic peripheral visual test on the first and last training day. The results revealed that the neurofeedback group showed significant enhancement of the peripheral visual performance as well as the relative alpha amplitude during the peripheral visual test. It was not the case in the non-neurofeedback control group, which performed the tests within the same time frame as the neurofeedback group but without any training sessions. These findings suggest that alpha neurofeedback training was effective in improving peripheral visual performance. To the best of our knowledge, this is the first study to show evidence for performance improvement in peripheral vision via alpha neurofeedback training.

Keywords Alpha · EEG · Peripheral vision · Neurofeedback training · Performance enhancement

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Introduction

As an important part of the human sensory system, visual system is composed of central vision and peripheral vision. Central vision or fovea vision is an area in the center of the visual field where the objects are focused allowing instant recognition of objects. Peripheral vision occurs outside the central field of view and is responsible for the peripheral visual information collection. When an object exceeds the central visual field, people have to make saccadic eye movements to find the object, to bring parts of the object into the central vision. The orientation and span of the eye movements are based on the visual information from peripheral vision. Thus, peripheral vision is important for feature identification and object recognition because it directs eye movements in neutral search tasks (Torralba et al. 2006) and provides the visual information as important triggers for saccades (Luo et al. 2008). It is also a backup for people who suffer central vision loss, since it provides a rich source of visual information outside the central gaze.

High peripheral visual ability is very important to everyone, especially to patients with central vision loss, team sport practitioners and drivers who have higher requirement of peripheral visual ability than the others. For instance, when a driver drives a car on the road, he or she needs to pay attention to the vehicle and traffic signs in the front of the road and may not be free to notice the events in the surroundings. If drivers could notice the non-compliance with traffic rules in their peripheral vision, many traffic accidents would probably be avoided. For sports performance, e.g. soccer players' performance, it has been found related to the peripheral visual ability (Hazel 1995; Marques Jr 2010).

Due to the importance of peripheral vision, it is desirable to improve its performance somehow. In recent studies, several methods have been proposed to train and improve the ability in peripheral vision. For instance, it is reported that perceptual learning can improve the reading speed in peripheral vision among normally-sighted young adults (Chung et al. 2004), normally-sighted older adults (Yu et al. 2010) and elderly with long-standing central vision loss (Chung 2011). In addition, repetitive transorbital alternating current stimulation (rtACS) shows positive effects on visual field recovery (Schmidt et al. 2013).

In recent years, neurofeedback (NF) training has attracted much attention as it has shown positive effects on the improvement of cognition and successful treatment of many neurological disorders. NF refers to an operant conditioning paradigm in which the individual learns to self-regulate the electrical activity of his/her brain. In EEG-based NF, EEG is recorded from one or more electrodes placed on the scalp and the relevant components are extracted and fed back using an online feedback loop in the form of audio, visual or combined audio-visual information (Vernon 2005). A number of studies have demonstrated positive effects of NF training on treatment of psychological disorders such as attention deficit hyperactivity disorder (Moriyama et al. 2012), substance use disorder (Sokhadze et al. 2008), epilepsy (Egner and Sterman 2006), autistic spectrum disorder (Coben et al. 2010), and schizophrenia (Nan et al. 2012a; Bolea 2010; Surmeli et al. 2012). Besides clinical applications, benefits of NF training have also been reported in optimizing performance such as semantic working memory (Vernon et al. 2003), short term memory (Nan et al. 2012b), mental rotation ability (Doppelmayr and Weber 2011; Zoefel et al. 2011; Hanslmayr et al. 2005), cognitive processing speed (Angelakis et al. 2007), and microsurgical skills (Ros et al. 2009). Taken together, the evidence demonstrates that people indeed obtain benefits through altering the specific EEG activity by NF.

Our previous work has investigated peripheral visual performance by a new dynamic peripheral visual test where the appearance of stimuli objects presented in peripheral field has drastic changes (Rodrigues et al. 2012). The result indicated a significant positive inter-individual correlation between the peripheral visual performance and the relative alpha amplitude at Cz during the performance test. Following such a finding (submitted for publication), in this study we aimed to examine the effect of alpha NF training on the peripheral visual performance. Our hypotheses were (a) an increase of the relative alpha amplitude in the peripheral visual test, and (b) it is associated with the enhancement of peripheral visual performance. In order to ascertain that the enhancement of peripheral visual performance is due to the NF training instead of the task practice effect, a non-NF control group was included for comparison.

Methods

Subjects

A total of 35 volunteers (24 males and 11 females, aged 19–33 years, all right-handed) recruited without monetary reward at the University of Macau participated in the study. The subjects were selected according to the following criteria: no history of psychiatric or neurological disorders, no psychotropic medications or addiction drugs, and with normal or corrected-to normal vision. Informed written consent was obtained from all participants after explaining the nature, possible consequences and privacy issues of the study to them. They were randomly assigned to one of two groups: NF group (6 females and 12 males) and non-NF control group (5 females and 12 males). Five subjects in the NF group dropped out due to the timing of university holidays or course examinations. The final sample consisted of 13 subjects in the NF group (4 females and 9 males) and 17 subjects in the control group (5 females and 12 males). The two groups did not have any significant difference in age ($t(28) = 0.579$, $p = 0.567$). The protocol was in accordance with the Declaration of Helsinki and approved by the Research Ethics Committee (University of Macau).

Signal Recordings

Based on the relationship between the peripheral visual performance and the alpha at Cz, EEG was recorded from Cz during the performance test and NF training. To detect eye movements in the peripheral visual test, horizontal and vertical electrooculogram (EOG) was recorded at the outer canthi of eyes from two electrodes, one above an eye and one below another eye. The reference electrodes were placed on the left and right mastoids, and the ground was located at the forehead. The EOG signal and EEG from Cz were amplified by an amplifier (Vertex 823 from Meditron Electomedicina Ltda, SP, Brazil) and recorded by Somnium software platform (Cognitron, SP, Brazil). The sampling frequency was 256 Hz. Circuit impedance was maintained below 10 kΩ for all electrodes.

Procedure

Each subject in the NF group completed 5 training exercises within 20 days and each training exercise was composed of 4 sessions with an interval of 3–4 days between two successive exercises. In each session, there were 10 trials with 20 s each and an interval of 5 s between two successive trials. On the first training day, the resting baseline was recorded first and then the peripheral visual test was performed (as pre-test), after that the training session started. The resting baseline consisted of two 30-s epochs with eyes open and another two 30-s epochs with eyes closed, which enabled to determine the individual alpha band through the amplitude band crossings (Klimesch 1999). On the last training day, the participants repeated the baseline recording and then the peripheral visual test (as post-test) after completing all NF sessions. To ensure that the enhancement of peripheral visual performance was due to the NF training rather than the practice effect, the non-NF control group was measured with the same design and setup, but without any training sessions.

Neurofeedback Training

Considering the hypotheses in the "Introduction" section, the training parameter was the relative alpha amplitude at Cz, which was calculated by Eq. (1) where the Band Amplitude was the amplitude of the individual alpha band and the EEG Amplitude was the amplitude from 0.5 to 30 Hz. Fast Fourier transformation (FFT) was used to calculate the amplitudes every 0.125 s using the latest 512 samples, and the frequency resolution was 0.5 Hz. The subjects received this feedback information in visual format.

$$\text{Relative Amplitude} = \frac{\text{BandAmplitude}}{\text{EEG Amplitude}} \quad (1)$$

The feedback display contained two tridimensional objects: a sphere and a cube. The sphere radius reflected the relative alpha amplitude in real time and if this value reached the threshold (Goal 1), the sphere color changed. This sphere was constituted by several slices and the more slices it had, the smoother it appeared. The cube height was related to the period of 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), Goal 2 was accomplished and the cube rose up until Goal 1 stopped being achieved. Then the cube started falling slowly until it reached the bottom or Goal 2 was achieved again. Therefore, the participant's task was to make the cube as high as possible (Nan et al. 2012b; Rodrigues et al. 2010).

The feedback threshold was set to 1 in the first session, and it could be adjusted according to the session report which showed the percentage of time for which the feedback parameter was above the threshold in each session. If this percentage exceeded 60 %, the threshold would be increased by 0.1 in the next session. In contrast, if the percentage was below 20 %, the threshold would be decreased by 0.1 in the next session.

Peripheral Visual Performance Measurement

An LED screen with 102.5 cm diagonal length was used to display the stimuli objects. Five objects were presented at the central and four corners of the screen. Each object was framed in a square with a diagonal length of 5.8 cm. The sequence of the stimuli objects was determined by a script file programmed and loaded into the system before the experiment started.

Two types of image sets were presented in this experiment: targets and non-targets. For an image set to be considered as a target, three of the five objects must be the same in both color and shape, otherwise it was a non-target. The test consisted of two types of test sessions and each type was performed twice. At the beginning of each test session, images lasted for 4 s on screen and this exposure time progressively decreased with the test until it reached 500 ms. In the first type of test, the objects had the same shape but different colors. There were 13 target image sets and 43 non-target image sets. Regarding another type, the objects had different shapes and colors, and there were 14 target image sets and 42 non-target image sets. More details were given in Rodrigues et al. (2012).

The subjects were seated on a comfortable chair with adjustable height to keep their eyes centered with the screen and 84 cm away from the screen. The distance of 84 cm ensured that the horizontal vision angle and vertical vision angle were 60° and 33.75° respectively. To start each test session, the start button in the upper left corner was clicked by the subjects using eye scanning. Then the subjects looked back to the central object. The test began at 2 s after the click. This eye movement exercise was used as a calibration event for the EOG eyes movement detection. During the test, the subjects were required to track a moving object in the center of the screen binocularly with a mouse pointer and keep their sight on the central object all the time so that they could capture the corner objects with their peripheral vision. They were not allowed to use eye scanning, although most of the subjects did use it voluntarily or involuntarily. Once the subjects perceived that any three objects were the same, they needed to click on the central object as fast as possible to identify the test image set as a target.

For each test session, the following events were taken into account: True Positive (TP) stood for clicking a target; True Negative (TN) meant ignoring a non-target; False Positive (FP) was accounted whenever a non-target was clicked; False Negative (FN) stood for ignoring a target. These events were used to calculate the accuracy shown in

Eq. (2), where T was the total number of targets and NT was the total number of non-targets. If the subject did not click on any target or clicked on all (true and false targets), the accuracy was 0 %. If the subject only clicked on correct targets and did not miss any one, the accuracy was 100 %. If the subject clicked on every false target and did not click on any correct one, the accuracy was −100 %. To detect whether the subject recognized the image sets using peripheral vision and without any eye scanning, an EOG detection algorithm was developed (Rodrigues et al. 2012). By this way, we can calculate the peripheral visual accuracy for each test session.

$$accuracy = \frac{1}{2}\left[\left(\frac{TP}{T} - \frac{FP}{NT}\right) + \left(\frac{TN}{NT} - \frac{FN}{T}\right)\right] \times 100\,\% \qquad (2)$$

Data Analyses

For each subject, the relative amplitude in all training sessions and in the peripheral vision test was calculated offline in each of the following bands: delta (0.5–4 Hz), theta (4–8 Hz), standard alpha (8–12 Hz), individual alpha, and sigma (12–16 Hz). The mean peripheral visual accuracy in all the four test sessions was regarded as the subject's peripheral visual performance.

In the control group, the relative alpha amplitudes of two subjects were found outliers and resulted in an unequal variance across groups. To ensure reliable statistical analysis results, these two subjects were excluded from further statistical analyses. Thus, the final sample of the control group consisted of fifteen subjects.

For all statistical analyses, the significance level was set as $p < 0.05$. Pearson correlation was performed on the aforementioned frequency bands separately to examine the EEG changes over training sessions. Independent t test was utilized to investigate the EEG difference and the visual performance difference in the pre-test between the two groups. For the peripheral visual performance and the relative alpha amplitude in the performance test, we conducted a repeated-measures analysis of variance (ANOVA) with TIME (pre vs. post) as the within-subjects factor and GROUP (NF vs. Control) as the between-subjects factor. If significant Group by Time interaction was found, one-tailed paired t test was followed up.

Results

EEG Results

The correlation analysis demonstrated significant correlations between session number and the relative amplitude in the individual alpha, standard alpha, and delta frequency bands. As shown in Fig. 1, the relative amplitude in the individual alpha band ($r = 0.834$, $p < 0.001$) and in the standard alpha band ($r = 0.850$, $p < 0.001$) increased over sessions while the relative amplitude in the delta band decreased over sessions ($r = -0.560$, $p < 0.02$). In the other bands no significant correlation was found.

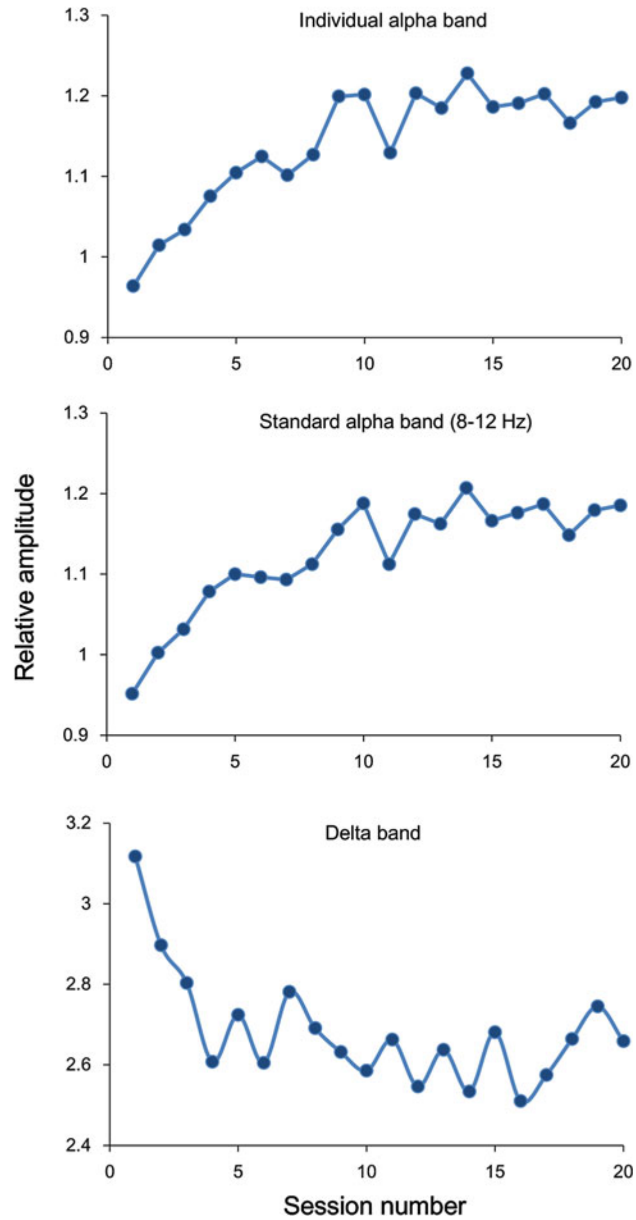

Fig. 1 The average EEG relative amplitude of all subjects over the training sessions. The *horizontal axis* represents the session number and the *vertical axis* represents the relative amplitude

There were no significant pre-test differences between the two groups in any EEG frequency bands. Regarding the relative amplitude of the standard alpha band, the results of repeated-measures ANOVA showed significant main effects of Time ($F(1, 26) = 5.596$, $p = 0.026$, partial

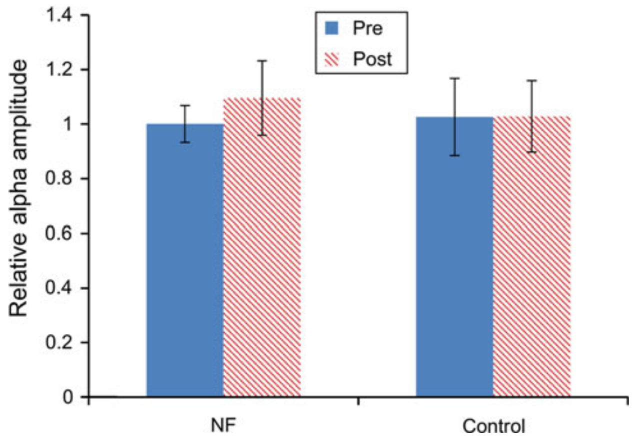

Fig. 2 The average relative alpha amplitude (8–12 Hz) in the pre-test (*blue bar*) and the post-test (*red bar*) for both groups. The *error bars* present the standard deviation of relative alpha amplitude (Color figure online)

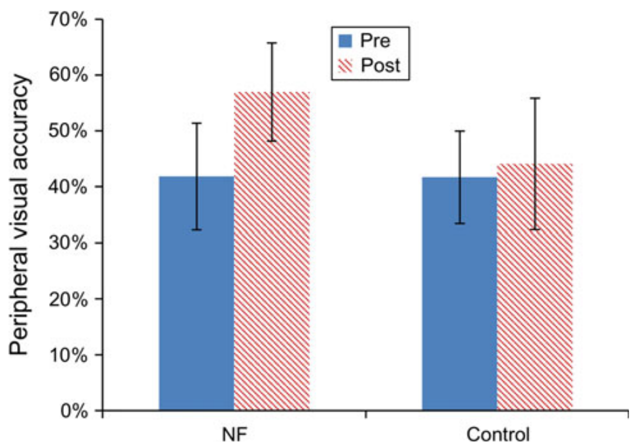

Fig. 3 The average peripheral visual accuracy in the pre-test (*blue bar*) and the post-test (*red bar*) for both groups. The *error bars* present the standard deviation of peripheral visual accuracy (Color figure online)

$\eta^2 = 0.177$) and Time by Group interaction ($F(1, 26) = 5.066$, $p = 0.033$, partial $\eta^2 = 0.163$). There was no significant main effect of Group. Paired *t* test revealed that only the NF group enhanced the relative amplitude in the standard alpha band ($t(12) = 3.674$, $p < 0.01$). For the individual alpha band, repeated-measures ANOVA did not yield significant main effects of either Group or Time, or Time by Group interaction. Figure 2 presents the relative amplitude of the standard alpha band in the pre- and post-tests.

Peripheral Visual Performance

Figure 3 demonstrates the peripheral visual performance for both groups. No significant difference was found in the pre-test between the two groups. Repeated-measures ANOVA revealed a main effect of Time ($F(1, 26) = 18.220$, $p < 0.001$, partial $\eta^2 = 0.412$), a main effect of Time by Group interaction ($F(1, 26) = 9.583$, $p = 0.005$, partial $\eta^2 = 0.269$), and a main effect of Group ($F(1, 26) = 4.528$, $p = 0.043$, partial $\eta^2 = 0.148$). Paired *t* test confirmed that only the NF group significantly improved peripheral visual performance ($t(12) = 4.376$, $p < 0.001$).

Discussion

The present study investigated the effect of alpha NF training on the peripheral visual performance. This effect was compared to a non-NF control group which only tested twice the peripheral visual performance. We hypothesized that only the NF group showed an enhancement of the peripheral visual performance as well as the alpha activity in the performance test.

For the EEG changes over training sessions, the relative amplitude in the individual alpha and the standard alpha bands showed a significantly positive trend. Alpha NF training has been used in the improvement of cognitive performance, and the participants were able to increase the alpha amplitude over multiple training sessions (Nan et al. 2012b; Zoefel et al. 2011; Angelakis et al. 2007). Furthermore, the relative amplitude in the delta band presented a decreased trend over sessions, which can be explained by the increased alertness during the training.

In line with our hypotheses, the NF group significantly enhanced the relative alpha amplitude in the performance test, indicating that NF training can elevate alpha not only in the training sessions but also in the performance test. This was not however found in the non-NF control group, further supporting the effectiveness of NF training on the alpha enhancement in the peripheral vision test. Additionally, only the NF group revealed a significant enhancement in the peripheral visual performance, suggesting that the increase in the peripheral visual performance was attributable to the NF training rather than the test–retest effect.

In summary, the NF group revealed a significant increase not only in the alpha amplitude during the peripheral visual test but also in the peripheral visual performance, which answered our hypotheses that an increase of the relative alpha amplitude in the performance test was associated with the enhancement of the peripheral visual performance. These results are in agreement with our previous study, which suggests that the peripheral visual performance is positively related to the relative alpha amplitude in the peripheral visual test. Moreover, our results are consistent to some degree with the work from Schmidt et al. (2013), which demonstrated the enhancement of alpha power and visual field recovery in the patients with visual field impairments after 10 days of rtACS stimulation.

In addition, the brain plasticity changes with NF have been demonstrated by some functional magnetic resonance imaging (fMRI) studies. Ros et al. (2013) using fMRI had shown the NF effect on the brain network dynamics. In their study, the subjects' task was to decrease alpha amplitude by instruction of audio feedback in a 30-min NF session. The results showed that NF induced a statistically significant up-regulation of functional connectivity within the salience network and the attentional task performance had positive change, indicating that adult cortex was sufficiently plastic that half-hour of NF was capable of intrinsically reconfiguring the brain's functional activity. In our case, about 67-min of NF in total was sufficient to modulate brain function and peripheral visual performance.

Finally, some evidence supports that visual cortex is possible to be enhanced by NF. Shibata et al. (2011) has employed a decoded fMRI NF to validate that the adult primate early visual cortex is sufficiently plastic to cause visual ability changes. Another study from Scharnowski et al. (2012) reported that perceptual sensitivity was significantly enhanced in the subjects who had previously learned control over ongoing spontaneous activity in visual cortex using real-time fMRI NF. Here, instead of fMRI, we utilized EEG-based NF to enhance peripheral visual performance successfully. EEG-based NF is low cost compared to fMRI, thus it holds realistic clinical promise as a treatment option (Hammond 2011).

In conclusion, this study revealed that alpha NF can increase alpha activity not only in the NF sessions, but also in the peripheral vision test. Furthermore, the enhancement of alpha activity was associated with the improvement of peripheral visual performance. Future studies will employ double-blind design and a larger sample size to replicate the presented findings. To the best of our knowledge, this is the first study to show evidence for performance improvement in peripheral vision by means of alpha NF training.

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