International Journal of Psychophysiology 86 (2012) 83–87

Contents lists available at SciVerse ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Individual alpha neurofeedback training effect on short term memory

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ARTICLE INFO

Article history:
Received 20 January 2012
Received in revised form 15 June 2012
Accepted 25 July 2012
Available online 1 August 2012

Keywords:
Individual alpha band
Neurofeedback
Short term memory
Mental strategy
Digit span

ABSTRACT

Memory performance has been reported to be associated with electroencephalogram (EEG) alpha activity. This study aimed to improve short term memory performance by individual alpha neurofeedback training (NFT). With appropriate protocol designed for NFT, the experimental results showed that the participants were able to learn to increase the relative amplitude in individual alpha band during NFT and short term memory performance was significantly enhanced by 20 sessions of NFT. More importantly, further analysis revealed that the improvement of short term memory was positively correlated with the increase of the relative amplitude in the individual *upper* alpha band during training. In addition, effective strategies for individual alpha training varied among individuals and the most successful mental strategies were related to positive thinking.

1. Introduction

The relation between memory performance and electroencephalogram (EEG) alpha activity has been reported by several studies in the last two decades (Klimesch, 1996, 1999; Klimesch et al., 2006). It has been observed that memory performance is positively related to resting power in the alpha band (Klimesch, 1999). One interesting question from the association between memory and alpha is, whether short term memory performance can be improved through the enhancement of alpha power by means of neurofeedback training (NFT).

NFT is an operant conditioning procedure in which individuals learn to self-regulate their brain activity. During NFT, the 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 the positive effects of NFT on treatment of psychological disorders such as attention deficit hyperactivity disorder (Friel, 2007; Heinrich et al., 2007), substance use disorder (Sokhadze et al., 2008), epilepsy (Sterman and Egner, 2006; Egner and Sterman, 2006) and autistic spectrum disorder (Coben et al., 2010). Besides clinical applications, the benefits of NFT have also been reported in enhancement of cognitive and artistic performance in healthy individuals (Egner and Gruzelier, 2003; Gruzelier et al., 2006; Gruzelier, 2009). For instance, semantic working memory can be enhanced by sensorimotor rhythm (SMR) NFT (Vernon et al., 2003) or by individual upper alpha NFT (Escolano et al., 2011). For mental rotation ability, it can be improved by NFT using SMR (Doppelmayr and Weber, 2011) or using individual upper alpha (Hanslmayr et al., 2005; Zoefel et al., 2011). In addition, increasing peak alpha frequency (PAF) by NFT can improve the cognitive processing speed and executive function in the elderly individuals (Angelakis et al., 2007).

Even though an increasing amount of studies reported positive effects of NFT in some fields, there is still a lack of successful NFT for the improvement in short term memory which refers to the temporary storage of information without the attention component of working memory (Conway et al., 2002; Stipacek et al., 2003). The early work by Bauer (1976) investigated the effect of fixed alpha frequency band (8.5–12.5 Hz) NFT on short term memory in young adults. The participants were asked to produce alpha as long as possible during the training. Short term memory performance was assessed by a verbal free recall task and a digit span task. Although a significant increase in the percentage alpha was achieved by the end of the four sessions, neither digit span task nor verbal free recall task showed improvement. Vernon (2005) stated that this failure could be explained by the use of a fixed frequency band instead of individual alpha frequency range as proposed by Klimesch (1999). Due to the large inter-individual differences in alpha frequency band, the personalization of alpha band is the only way to observe and interpret any findings that involve alpha frequency band (Klimesch, 1999; Klimesch et al., 2003). Another possible reason for the failure in Bauer (1976) is that the feedback parameter was the percentage alpha in terms of time instead of the alpha power that is related to memory performance (Klimesch, 1999).

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0167-8760/$ – see front matter
http://dx.doi.org/10.1016/j.ijpsycho.2012.07.182

Moreover, the mental strategies used during the NFT have not been provided with sufficient details in the literature. Angelakis et al. (2007) only described two subjects' self-report during alpha amplitude NFT. Suggestions on mental strategies to be used during NFT shall contribute greatly to increase the rate of successful NFT learning.

Considering the relation between memory performance and alpha power as well as the importance of personalization of alpha band (Klimesch, 1999), this study aimed to improve short term memory performance by individual alpha NFT. More specifically, we attempted to answer three questions, namely, (a) whether NFT can increase the relative amplitude in individual alpha band, (b) whether this increase in individual alpha band is correlated with short term memory improvement, and (c) which mental strategies are more effective for the training.

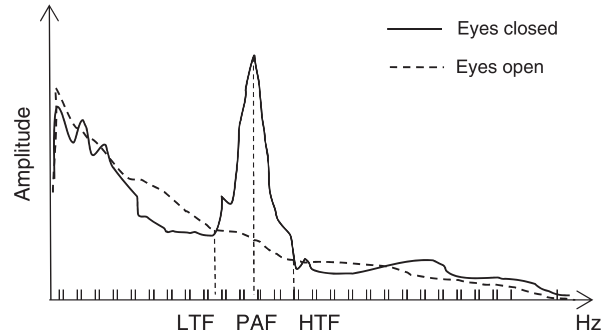

Fig. 1. The demonstration of individual alpha band. (individual alpha band: LTF–HTF, individual lower alpha band: LTF–PAF, individual upper alpha band: PAF–HTF).

2. Materials and methods

2.1. Participants

A total of 32 students (22 males and 10 females, aged 20–29 years: mean = 23.28, SD = 3.11) took part in the experiment. Informed written consent was obtained from all participants after the experimental nature and procedure were interpreted to them. The protocol was approved by the Research Ethics Committee (University of Macau).

2.2. EEG recordings

During the experiment, the participants sat in a quiet room. The EEG signal was recorded from Cz channel (according to the international 10–20 system) with a sampling frequency of 256 Hz, the ground was located at forehead and the reference was the average of left and right mastoids. The signals were amplified by a 24-channel system (Vertex 823 from Meditron Electomedicina Ltda, SP, Brazil) and were recorded by Somnium software platform (Cognitron, SP, Brazil). Circuit impedance was kept below 10 kΩ for all electrodes.

2.3. Design

The participants were randomly allocated to NFT and non-neurofeedback control groups. Both groups consisted of 16 subjects (11 males and 5 females) and there was no significant difference in age between the two groups. In the NFT group, prior to the beginning NFT, the participants did resting baseline recording (as Baseline 1) and short term memory test (as Test 1). Then the participants completed NFT sessions with 3 to 4 sessions per day for a total of 20 sessions. NFT was spread over a period of 15 days. After all training sessions, the participants repeated baseline recording (as Baseline 2) and short term memory test (as Test 2). To assess the influence of practice on this performance, the non-neurofeedback control group was measured with the same design on equivalent days and times, but without any training sessions. The participants in both groups were asked to inform us of exceptional stress and then we could reschedule their experiment when their states were normal.

The baseline recording consisted of two epochs of 30 s with eyes open and two epochs of 30 s with eyes closed during the resting period. The recordings of eyes open and closed in Baseline 1 provided data for the calculation of alpha desynchronization and synchronization respectively, which enabled to determine frequency bands individually through the amplitude band crossings. As shown in Fig. 1, LTF (low transition frequency) and HTF (high transition frequency) were the crossings of eyes open and eyes closed EEG amplitudes during the resting period, while the PAF was used as the cut-off point to separate the lower from the upper alpha band (Klimesch et al., 1994). The individual alpha band covered from LTF to HTF, while the individual lower alpha ranged from LTF to PAF and the individual upper alpha band was between PAF and HTF.

The short term memory was evaluated by digit span which is a good measure of short term memory capacity (Conway et al., 2002). The digit span tests included a forward and a backward digit span. Each test consisted of a series of trials showing random digits at the rate of one digit per second. At each trial the number of digits shown was increased by one until the participant failed twice to recollect every digit. The last number of digits correctly recollected was the participant's digit span score. In each test, after all the digits had been shown, the participant was instructed to enter the digits with the same order (forward digit span) or with the inverse order (backward digit span) as they were displayed.

2.4. Neurofeedback training

Feedback is a determinant step for the protocol's success. Neural activity must be fed back by some parameter(s) and presented to the participant in a simple and direct representation of their value. In this study, the feedback parameter was the relative amplitude of the individual alpha band calculated as in Eq. (1) where Band Amplitude was the amplitude of the individual alpha band and EEG Amplitude was the amplitude from 0.5 Hz to 30 Hz. Using the amplitude spectrum instead of the power spectrum prevents excessive skewing which results from squaring the amplitude, and thus increases statistical validity (Sterman and Egner, 2006). Fast Fourier transformation (FFT) was used to calculate the amplitudes every 0.125 s using the last 512 samples, and the frequency resolution was 256/512 = 0.5 Hz.

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

The feedback display contained two tridimensional objects: a sphere and a cube. The sphere radius reflected the feedback parameter value in real time and if the value reached a threshold (Goal 1) the sphere color changed. This sphere was constituted by several slices, and the more slices it had, the smoother it looked. Initially, the sphere was only constituted by four slices, which was its minimum number. While Goal 1 was being achieved, slices were slowly added to the sphere. When Goal 1 was not achieved, the sphere loosed slices slowly until it only had four slices again. The cube height was related to the period of time that 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 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 (Rodrigues et al., 2010).

In order to obtain successful training, the participants utilized user control mode during the first two sessions. They can control the number and duration of trials within each session. At the end of each trial, they can input a comment on which cognitive strategies were used.

The comments were used to find out which cognitive strategies were more effective for the desired changes in the EEG. For the remaining 18 sessions, the duration of each session was fixed. Each fixed session consisted of 10 successive trials of 20 s each and with an interval of 5 s between trials. The participants were expected to apply the most successful cognitive strategies and try their best to achieve the desired changes within the time limit. We did not prescribe the specific strategies and the participants could perform any kind of mental strategy they like. Only one cognitive strategy should be performed in each trial, but it could or should vary between trials if the current one was not being successful.

The threshold value for the feedback parameter (i.e. the calculated relative amplitude of the individual alpha band) for the first session was set to 1 which was found empirically to be a good guess, and it could be adjusted during the user control mode sessions to achieve Goal 1 easily. After each session, a session report showed the percentage of time the feedback parameter was above threshold. If this value 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.

2.5. Data analysis

For each participant, in each training session and resting baseline the relative amplitudes were calculated in the individual alpha band and also other bands including delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), sigma (12–16 Hz), individual lower alpha band and individual upper alpha band.

To analyze the training effect on the EEG amplitudes, we firstly examined the EEG bands listed above during the training sessions. The Pearson correlation tests were used to investigate the relationship between the relative amplitudes in the above mentioned EEG bands and session number. Regarding the eyes open baseline in the two groups, 2-tailed paired *t*-tests were employed to examine the difference between Baseline 1 and Baseline 2.

For the short term memory performance, initially, 1-tailed paired *t*-test was employed to examine the increase between Test 1 and Test 2. Both the NFT group and the control group would probably show increased performance due to the short term memory task practice. Thus we further applied 1-tailed independent *t*-test to examine whether the NFT group obtained significantly larger increase than the control group. Finally, in order to find out which EEG band change was correlated with short term memory improvement, Pearson correlation coefficient was calculated between them.

With regard to the mental strategy analysis, considering that the number of each strategy used was different, we calculated the average score of each strategy to examine the effect on individual alpha training.

3. Results

3.1. EEG results

The average of the relative amplitude in individual alpha band of all subjects showed increase over sessions. Further Pearson correlation test indicated that it had significant positive correlation with session number, indicating that the subjects could learn to increase their alpha activity by NFT (successful neurofeedback learning). This was a positive answer to Question (a) in the Introduction section. Besides individual alpha band, alpha, sigma, individual lower alpha and individual upper alpha bands were significantly positive correlated with session number while delta was significantly negative correlated with session number. Fig. 2 shows the average relative amplitudes in the aforementioned bands over sessions. Regarding the eyes open resting baseline, all frequency bands including individual alpha band, individual lower alpha, individual upper alpha, alpha, sigma and delta had no significant difference between Baseline 1 and Baseline 2 in both the NFT group and the control group.

3.2. Short term memory results

The forward digit span in the NFT group increased from 8 (SD = 2.76) in Test 1 to 11.06 (SD = 4.55) in Test 2, while in the control group it was 10.19 (SD = 1.55) in Test 1 and 11.25 (SD = 1.52) in Test 2. For the backward digit span, the performance measures of the NFT group were 7.31 (SD = 2.26) in Test 1 and 10.44 (SD = 3.53) in Test 2. The performance measures of the control group were 9.56 (SD = 1.58) in Test 1 and 10.25 (SD = 1.98) in Test 2.

Paired *t*-test showed that both the NFT group and the control group increased short term memory performance. Further 1-tailed independent *t*-test showed that the increases in forward and backward digits of the NFT group were significantly larger than those of the control group ($t(30) = 2.944$, $p < 0.005$ in forward increase; $t(30) = 4.091$, $p < 0.001$ in backward increase).

Pearson correlation analysis indicated that the increase of short term memory performance was not correlated with the increase of the relative amplitude in the *whole* individual alpha band. Instead, it was found that the increases of digit span tests in the NFT group were significantly correlated with the increase of the relative amplitude, not in the other bands (individual lower alpha, alpha, sigma and delta), but in the individual *upper* alpha band between the first session and the last session ($r = 0.501$ ($p < 0.05$) in forward increase and $r = 0.543$ ($p < 0.05$) in backward increase). This result answered Question (b) in the Introduction section.

3.3. Mental strategies

During NFT, the participants can utilize any strategies they like, but they should use only one strategy in each trial. If the current one was not successful, they can change the strategy in the next trial. Different participants used different sets of thoughts. In an attempt to help participants find out the efficient strategy for self-regulating their EEG, they were asked to write down the strategy used and its effect after each training session. The effects were divided into five grades: best, good, normal, bad and worst. By this way, they would find the efficient strategies for themselves. It was observed that even for the same strategy, different subjects had different effects.

After all the training sessions, the strategies were summarized and scored. All strategies were divided into three types: positive, neutral and negative. Among them, positive type was 61.29%, which included several subtypes: nature (raining, travel, hometown, sunset, walk around and scenery), life (shopping, cooking, food and eating), entertainment (singing, music and movie), love (lover and kiss), family (parents, brothers and grandparents), friends and others (such as thinking about making the sphere bigger). Neutral type was 33.87%, which contained calculation, work, number, game and sports. Negative type was 4.84%, which consisted of quarrel, anger, accident, shooting and killing a person. According to strategy effects, the scores were 2 for best, 1 for good, 0 for normal, −1 for bad and −2 for worst. The average scores were 0.74 for positive strategies, 0.5 for negative strategies and 0.167 for neutral strategies. The effects of all subtypes are shown in Fig. 3. Among them, the most efficient strategies were friends (1.625), love (1.4) and family (1.1) while the worst were anger (−2.0) and calculation (−0.15). The effects of some positive strategy subtypes like love (lover (1.67)), nature (hometown (1.5)) and family (brothers (2.0)) stood out.

In summary, it can be observed that most participants utilized positive strategies during training and the efficient strategies varied among individuals. On average, most successful thoughts were related to positive strategies, namely friends, love and family, while neutral strategies had limited success although game had a medium effect

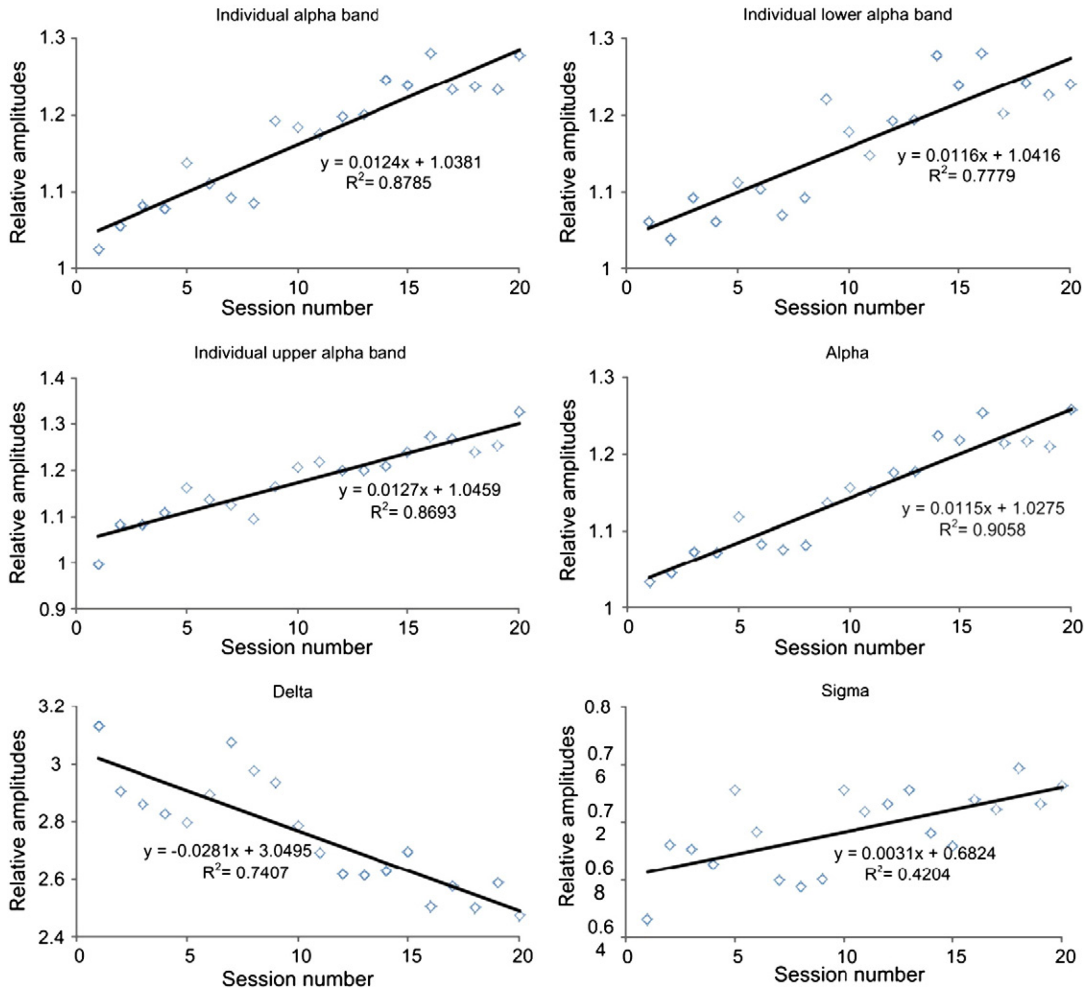

Fig. 2. The average relative amplitudes in the examined bands of all subjects over training sessions. The straight line results from a linear regression and indicates a linear sustained change.

and negative strategies had contrasting effects. This provided an answer to Question (c) in the Introduction section.

4. Discussion

As expected, the participants in the NFT group can learn to increase the relative amplitude in individual alpha band during training sessions. Several key features in this training protocol were responsible for the successful neurofeedback learning. Firstly, the participants were familiar with the training display through the first two user control sessions, and they could try any strategies they like to observe the training effect. After this, they can gain some experience on how to self-regulate their brain activity. Secondly, the training duration of each trial of 20 s with 5 s of interval between trials proved to be a good strategy. It was easier to maintain concentration in shorter trials compared to longer ones, where subjects could be bored and distracted with ease. Finally, tracking of the cognitive strategies during training provided an adequate guidance for the participants to achieve successful self-regulation strategies. In the literature, no study has reported the cognitive strategies during individual alpha NFT. Thus, the strategies in this work can provide precious guidance for future study on NFT in the individual alpha band. From the analysis of self-comments, it can be concluded that the useful strategies varied among individuals and the most successful strategies were related to positive thinking such as thoughts about lover, friend and family.

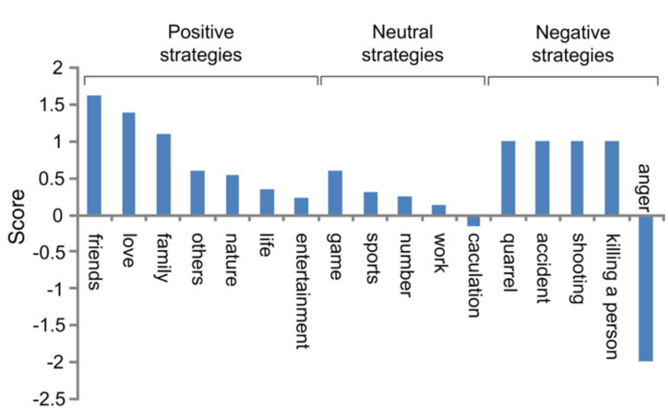

Fig. 3. Strategy types and their scores.

Besides individual alpha band, sigma and delta also showed changes over training sessions, which maybe resulted from some mental strategies used. In general, alpha is associated with alertness and meditation, while delta appears during sleep and sigma reflects mentally alert and physically relaxed (Friel, 2007). In our case it was expected that the mental thoughts would decrease delta and increase sigma due to the elevated alertness. The increase of alpha (8–12 Hz) was also expected since it was very close to individual alpha band, and the increase of individual lower alpha and individual upper alpha was natural since they were components of individual alpha band.

In addition, the resting baseline in all examined bands had no significant difference between Baseline 1 and Baseline 2 in the NFT group. This is somewhat different from the result in Zoefel et al. (2011) that the baseline in the trained individual upper alpha band (PAF to PAF + 2 Hz) gained significant increase after training. The failure of baseline enhancement in our study may attribute to the much less training density and duration compared to that in Zoefel et al. (2011), where the participants completed one session per day with each session consisting of five 5-min training blocks, the total training duration was 125 min in 5 days. By contrast, in our study the total training duration of the fixed sessions was 60 min within 15 days, i.e. 10 to 15 min per day, in total 4 to 6 times spread over the whole training course. Therefore, to enhance individual alpha amplitude during resting condition, an intensive training and longer training time would be recommended.

Even though the baseline improvement was not found in the NFT group, the short term memory was improved significantly. The control group also displayed significant improvement that could be explained by the short term memory test practice. More importantly, the increase of the NFT group was significantly higher than the control group, indicating that NFT did have positive effect on short term memory improvement beyond the test practice effect.

Another interesting finding is that the increase of short term memory performance was positively correlated with the increase of the relative amplitude in the individual upper alpha band during training. It suggests that the individual upper alpha can be a promising parameter in the future short term memory NFT study.

In conclusion, this study reveals strong evidence that with appropriate protocol and adequate guidance, the participants can learn to increase the relative amplitude in individual alpha band during training. Most importantly, the increase of short term memory was positively correlated with individual upper alpha increase during training.

Acknowledgments

This work is supported in part by FCT SFRH/BSAB/1101/2010 and PEst-OE/EEI/LA0009/2011 grants and the Macau Science and Technology Development Fund under grant FDCT 036/2009/A and the University of Macau Research Committee under grants MYRG139(Y1-L2)-FST11-WF and MYRG079(Y1-L2)-FST12-VMI.

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