Neurofeedback Training Improves Long-Term Memory Performance

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Abstract

Understanding and improving memory is vital to enhance human life. Theta rhythm is associated with memory consolidation and coding, but the trainability and effects on long-term memory of theta rhythm are unknown. This study investigates the ability to improve long-term memory using a neurofeedback (NFB) technique reflecting the theta/low-beta power ratio on an electroencephalogram (EEG). Our study consisted of three stages: First, the long-term memory of participants was measured. In the second stage, the participants in the NFB group received three days of theta/low-beta NFB training. In the third stage, the long-term memory was measured again. The NFB group had better long-term memory than the control group and significant differences in brain activity between episodic and semantic memory during the recall tests were revealed. These findings suggest that it is possible to improve the long-term memory abilities through theta/low-beta NFB training, which also improves episodic and semantic memory.

Introduction

Memory plays a key role in human life. Long-term memory is needed to retrieve necessary details for learning, working, and socializing in normal life[1]. Episodic and semantic memory, the famous types of long-term memory, refer to personal events and word meanings, respectively[2].

The intervention of cognitive function including memory has been investigated and many training methods have been proposed. Previous studies have proposed effective methods to improve cognition and avoid certain diseases. For example, exercise interventions have been reported to reduce cognitive decline and Alzheimer's disease[3]. Neurofeedback (NFB) is a powerful tool to improve memory ability. Real-time electroencephalogram (EEG) NFB has been shown to be effective for the self-regulation of individual brain activity and has been applied in cognition[4], sports[5], Alzheimer's disease[6], and memories such as working memory[7] and episodic memory[8]. Previous studies have reported that participants can modulate and increase the EEG band power via NFB training, resulting in improved m emory[9]. In particular, episodic memory, or the retrieval of encoded information in a short time, was markedly improved after NFB training[10]. However, the effects of NFB training on long-term memory are not well-understood as most studies regarding episodic memory include short timeliness[11,12] and do not report the forgetting rate.

Several previous studies have investigated the effect of memory training using NFB techniques. Results of those studies suggested that the gamma-band activity plays a role in managing the retrieval of episodic memories and affects episodic memory after gamma NFB training[13,14]. NFB training for the enhancement of episodic memory using the sensory-motor rhythm band, upper alpha band[8], or alpha band acitiviy[11] has been reported. Recent studies found that theta NFB training can effectively improve episodic memory[10].

The activities of the theta and alpha bands are associated with episodic[15] and semantic memory, respectively[16]; however, some studies have suggested that the theta band is related to both episodic and semantic memory[17] and that there are interdependencies between episodic and semantic memory[18]. To investigate the effect of NFB training on episodic and semantic memory in a long time frame, the consolidation of memory was measured. Frontal midline theta bands have been associated with encoding and retrieving episodic memory[19] and can improve[10] and consolidate episodic memory. The frontal midline theta waves, like the hippocampal theta waves, play a role in the processing of memory[20,21]. Theta/beta NFB training has been used to treat attention conditions[22], and previous studies suggest that the theta/low-beta NFB protocol can be used to affect the performance of episodic memory[12].

According to the above studies, we designed a theta/low-beta NFB protocol to train participants' long-term memory and investigated the forgetting rate in one week. In this study, the theta/low-beta NFB protocol with auditory feedback was used to train participants and determine the effect on episodic and semantic memory. In order to understand the changes in the forgetting rate of the participants over a longer time frame after participants encoded content on the first day, we set the test time for detecting memory ability to be extended to one week. We aimed to understand the trainability of long-term memory via NFB training and the ability of NFB to improve episodic and semantic memory.

Results

Ability of NFB to improve episodic and semantic memory

Prior to training, the episodic ($t(25) = 1.3$, $p = 0.22$) and semantic ($t(25) = 1.3$, $p = 0.20$) memory scores were not significantly different between the NFB and control groups. As assessed using the repeated measures analysis of variance (ANOVA), the effect of the group on scores for episodic memory was marginally significantly different $F(1,26) = 4.1$ ($p = 0.053$) and that for semantic memory was significantly different $F(1,26) = 5.1$ ($p = 0.033$) (Fig. 1a and 1b) between the NFB and control groups.

Effects of NFB training

Dunnett's test revealed significant increases in the theta/low beta power spectral density (PSD) ratio from the resting state to NFB training sessions on day 1 ($p = 0.018$) and day 2 ($p = 0.029$) (Fig. 2a). The theta PSD also showed significantly increased on day 1 ($p = 0.041$), day 2 ($p = 0.037$), and marginally significantly different on day 3 ($p = 0.052$) from the resting and NFB training sessions of NFB training (Fig. 2b).

EEG characteristics of the memory task

In the recall task of episodic memory, the repeated-measures ANOVA revealed a marginally significant main effect of group ($F_{(1,26)} = 3.7$, $p = 0.066$) (Fig. 3a) on the theta/low-beta amplitude in the third stage (after training). The main effect of group on the difference of theta/low-beta amplitude (third stage minus the first stage) was also marginally significant ($F_{(1,26)} = 4.1$, $p = 0.054$) (Fig. 3b). In the recall task of semantic memory, the repeated-measures ANOVA revealed a significant interaction between interaction effects ($F_{(1,26)} = 8.8$, $p = 0.0045$) (Fig. 3c) of the theta/low-beta amplitude in the third stage (after training). The difference of theta/low-beta amplitude (third stage minus the first stage) also significantly interacted with interaction effects ($F_{(126)} = 4.3$, $p = 0.044$) (Fig. 3d). These results suggest that participants in the NFB group achieved higher theta/low-beta PSD for episodic memory after training than participants in the control group. The theta/low-beta PSD for semantic memory were increased in the NFB group after training and were higher than those in the control group on the final day.

The difference in theta and the difference in memory score after training were not significantly correlated in the control group ($b = -0.43$, $p = 0.68$) (Fig. 4a). These differences were significantly correlated in the NFB group. ($b = -2.7$, $p = 0.018$) (Fig. 4b). The theta/low-beta and alpha were not significantly correlated in either group. These results indicated that the score difference was inversely proportional to the theta PSD difference after NFB training.

Discussion

In the present study, the efficiency of theta/low-beta NFB training improved the participants' episodic and semantic memory. The theta/low-beta PSD of participants in the NFB group significantly increased during training sessions. The participants in the NFB group showed better performance than those in the control group after training, and this effect lasted for one week. The brain activities of the NFB and control groups were different for episodic and semantic memory. NFB group showed higher theta/low-beta than control group during three times recall tests in episodic memory but such higher theta/low-beta only showed on the last day in semantic memory. The different brain activities might imply that the effect of NFB training on semantic memory would appear after one week. These results suggest that theta/low-beta NFB training is effective to improve long-term memory.

We designed the theta/low-beta NFB protocol and introduced auditory stimuli based on previous studies which proposed with visual stimuli[12]. Additionally, we referred other studies suggested that theta waves may be involved in the consolidation of episodic memory[12,23] for our training design. We considered that auditory feedback results in less disturbance than visual stimulation and allows participants to concentrate on appropriately regulating their cognitive control. During the NFB training sessions, the participants followed our instructions and regulated their cognitive process using real-time auditory feedback to improve the theta/low-beta PSD as much as possible. According to our results, the theta/low-beta PSD of participants in the NFB group increased, and the theta PSD were significantly increased during the three-day training sessions. The increments of theta/low-beta PSD and theta PSD did not induce low-beta, beta, alpha, or gamma PSDs during the training sessions. These findings are consistent with the previous study which suggested the specificity of target frequency bands.[24] Theta/low-beta

protocols can effectively improve episodic memory but low-beta/theta NFB protocols can not be seen the same trend[12]. The results of the theta/low-beta PSD and theta PSD did not increase over the course of the second stage linearly, similar to previously-reported findings that the brain activities increase unstable during training[10,11,25,26,27]. We assumed that synaptic consolidation is likely to occur in NFB training, and gaps of several days during training sessions affect neuronal changes[28]. Despite different timelines, the results of this study are consistent with those of previous studies, suggesting that cognitive control processes are related to theta oscillations[29,30] and that the theta oscillations can be trained using theta/low-beta NFB[12]. Taken together, these results indicate that the theta/low-beta NFB training protocol designed for use in this study to increase theta PSD is effective.

According to our results, the forgetting rate of participants in the NFB group significantly decreased for semantic memory and showed marginal significant in episodic memory after NFB training. In this study, the recall tests were conducted approximately 20 minutes, one day, and six days after memorization. The recall test results for episodic memory obtained 20 minutes after memorization were similar to previously-reported results[11,12]. The NFB group performed better in the recall tests than the control group at all time points. Although our training protocol required only three days to train the participants, the effects of NFB training remained for one week.

Previous studies have indicated that theta oscillations play an important role in the memory process[21,31]. Some studies have suggested that the hippocampus theta[15] and the increment of the theta band power in the posterior hippocampus[32] can be used to predict successful encoding in episodic memory. In this study, our experimental device could only record the brain activities from the surface of the brain; therefore, we could not identify differences in brain activities between the different groups during the encoding task for episodic memory. However, several previous studies have suggested that the increment of theta activity affects episodic retrieval[31,33,34]. In our study, the theta activities in the NFB group were higher than in the control group during the recall test in the third stage (after NFB training sessions). These results are consistent with those of previous studies[12] and suggest that the theta/low-beta NFB training affects subsequent recall tasks of episodic memory for at least one week.

Participants in the NFB group had improved performance for semantic memory after theta/low-beta NFB training. In this study, regression analyses revealed that the difference in memory scores and the difference in theta PSD before and after NFB training were negatively correlated. These differences were not correlated in the control group. This finding was unexpected and suggests that individual theta power, which is related to the sematic processes, was significantly changed after NFB training sessions in the NFB group. This study confirms that theta power is associated with encoding and retrieval in semantic memory. Retrieval of semantic information is commonly seen in language processing. Several studies have shown that theta power supports the process of semantic memory, and that theta power increases during the retrieval of semantic information[35,36,37,38,39].

To our knowledge, there are no previous reports of the use of NFB training to improve semantic memory, though several studies have reported improvement of episodic memory after NFB training[10,11,12]. In this study, we found that both episodic and semantic memory were improved by the theta/low-beta NFB training protocol we designed.

The hippocampus and prefrontal cortex (PFC) play important roles in episodic memory processing[40,41]. Previous EEG source estimation studies have suggested that frontal midline theta waves are generated by the anterior cingulate and medial PFC[42,43,44,45]. In addition, other reports have suggested that theta oscillations generated from the PFC in patients with epilepsy can predict the success of coding in episodic memory[46,47]. Individuals with stronger hippocampus-PFC connectivity can encode pictures into long-term memory better during working memory tasks, suggesting that the relationship between theta activity and memory encoding may depend on the connectivity between the hippocampus and PFC[48]. In this study, the theta PSD and memory scores were improved after NFB training, indicating that the training protocol used in this study may also affect the deep neural mechanisms including hippocampus and PFC.

The theory of synaptic and systems consolidation includes an important brain circuit that is necessary for transforming short-term memory into longer-term memory[28]. The transition from short-term to long-term memory is not instant and requires repeated consolidation and other factors (including sleep)[28,49,50,51]. In this study, we assumed that the mechanism of NFB training sessions included the process of synaptic consolidation. The study design (six sessions of NFB training per day for three days) allows for the enhancement of theta, leading to synaptic consolidation and the translation of the consolidated systems. Therefore, NFB training may not lead to short-term results but lead to long-term consolidation.

The results of the recall test for semantic memory were significantly different compared to those for episodic memory. Several studies have reported that theta/beta NFB protocols modulate the medial frontal areas, which are involved in some cognitive processes including the process of response inhibition[22]. In addition, the oscillating inhibition model explains the relationship between theta oscillation and retrieval processes that induce forgetting and proposes that theta oscillation inhibits competitive memory[52,53,54]. The theory of the process of response inhibition and the oscillating inhibition model may explain why the participants in the NFB group achieved better results for the recall test for episodic memory and had higher theta/low-beta amplitudes. The results of semantic memory in the recall test showed a difference with episodic memory, indicating that the mechanisms of these two types of memory are different. The oscillating inhibition model explains why participants in the NFB group had higher theta/low-beta PSD for semantic memory than those in the control group on the final day of the memory period. As test day lag increases, the theta/low-beta PSD increases to inhibit the interference with competing retrieval from target memories as task difficulty increases. The theory of synaptic and systems consolidation proposes that the influence of NFB training on deep neural mechanisms will not be immediately apparent.

Although the episodic and semantic memory were different in terms of memory system or memory recall mode, some interaction between these two types of memory during the memory process via theta oscillations has been reported[17,55]. In this study, we did not find evidence of a correlation between episodic and semantic memory in the participants' performances or brain activities. Future studies should focus on understanding how the episodic and semantic memory interacts during memory processing. A new method to differentiate the two types of memory is necessary to understand their independence and interaction.

In this study, participants received only three days of NFB training within one week. We believe that longer training periods would affect the long-term memory more significantly, so we plan to design a longer-term period for the training session in our future works. It had been difficult to encourage the participants to return after a one-month gap between memory tasks. Therefore, this study was designed to include a maximum of one week between the recall test and the encoding task for memory stage. We also plan to design a longer time period experiment for the recall test and encourage participants to come back again after one month, six-month and even one year.

This study explored the trainability of long-term memory and found that NFB training can effectively improve episodic and semantic memory. In addition, we found that the brain activities after NFB training have different performances on the retrieval task in two different types of long-term memory. These results can provide the cornerstone for understanding long-term memory and may be used to treat memory disorders such as patients with epilepsy and theta dysfunction or Alzheimer's disease.

Methods

Participants

Thirty-two students were recruited from Kyushu University (9 females, 23 males; all right-handed; age range = 18–35 years; mean age = 21.6 years, SD = 4.15 years) and randomly assigned into the NFB (n = 17) and control (n = 15) groups. All participants had normal hearing in both ears at 60 dB for all frequencies. Participants with a history of neuropsychiatric illness, hearing impairment, or a prior experience with NFB training were excluded from the study. All participants provided written informed consent for their participation in this study. The study was approved by the local ethics committee of the Faculty of Arts and Science, Kyushu University and was conducted in accordance with relevant guidelines and regulations. After excluding five participants' data from the analyses due recording errors, the final analysis included 15 participants in the NFB group and 12 participants in the control group.

Procedure

In the NFB group, three stages were conducted over a nine-day study period (Fig. 5). In the first stage, participants were asked to perform the first set of memory tasks (see "Memory Tasks" below). This stage was completed on the first, second, and seventh day of week one. In the second stage, the participants received three days of theta/low beta NFB training. The three days of training were scheduled within one

week (week two), as convenient for each participant. Each 30-minute training session was divided into six parts (see "NFB training tasks" below). In the third stage, the participants were asked to perform the second set of memory tasks. This stage was completed on the first, second, and seventh days of week three.

In the control group, the participants completed the first and third stages only; they did not participate in the second stage and did not receive NFB training. The sets of memory tasks completed during the first and third stages were different. The participants were not aware of the goal of the study or the purpose of the NFB training.

The study included three stages: before training, neurofeedback (NFB) training, and after training. The NFB group performed all three stages, and the control group performed the first and third stages. The first and third stages followed the same design, though the tasks differed. On days 1 and 7, participants performed the encoding tasks in both episodic and semantic memory, then performed the recall tests in both episodic and semantic memory after a twenty-minute wait. On days 2 and 8, participants performed the recall test in both episodic and semantic memory, then they performed the working memory task. On days 3 and 9, the participants performed another recall test in both episodic and semantic memory. This second recall test was completed after a four-day gap. In the second stage, participants in the NFB group underwent three days of NFB training. One session consisted of a 1-min rest period and 5 minutes of auditory NFB training. There were six sessions on each training day.

Memory tasks

Episodic memory task

The episodic memory task included an encoding task and a recall test (Fig. 6a). In the encoding task, 100 images of objects (for example, various types of food, tools, and animals) selected from the normative photo dataset (The Bank of Standardized Stimuli[56]) were each presented once per participant. A cross mark was shown for 1 s as a fixation point before the image was presented for 3 s. One fixation/image pair was considered one trial, and 100 trials were performed. Participants were instructed to memorize the images as well as possible. Then, the participants completed old-new judgment regarding the presented images in the recall test. The recall test included 25 images that were presented in the encoding task and 75 new images. Participants used a keyboard (Numeric Keyboard for Mac, BUFFALO, Japan) to indicate when they recognized an image as one that was presented during the encoding task. The recall test was repeated three times: approximately 20 minutes after the encoding task and one and six days after memorization. No image was repeated between the three recall tests. The percentage of correct answers was being the memory score in the recall tasks.

Semantic memory task

The semantic memory task followed a similar design as the episodic memory task except for the image stimuli (Fig. 6b). In the encoding task, we drew 40 monster illustrations with a two-digit identification number were each presented five times per participant. Participants were asked to memorize the 40

monsters and their IDs. During the recall test, 10 monsters from the encoding task were presented to the participants. Participants were asked to recall the identification number associated with each monster and enter it using a keyboard. The recall tests were conducted 20 minutes, one day, and six days after the encoding task. No monster image was repeated between the three recall tests. The percentage of correct answers was being the memory score in the recall tasks.

Working memory task

We used a backward digit span task to measure the storage capacity of participants' working memory including their ability to hold and manipulate information[57]. The task included twenty-five trials and each trial consisted of eight digits (Fig. 6c). An image with cross mark was presented for 1 s then the eight digits were presented for 1 s. After viewing the eight digits, the participants were asked to repeat the numbers in reverse order. One point was given for each correct digit for a maximum score of 200 points.

To understand the improvement of participants' long-term memory ability, we subtracted the score from the first day from that of the last day of the first and third stages separately (first stage: day 1 – day 3; third stage: day 7 – day 9). A greater difference during the first stage compared to during the third stage suggested that participants memorized more and performed better in memory tasks after NFB training.

NFB training task

The participants in the NFB group received three days of NFB training during the second stage of the study. NFB training included six sessions per day. Each session consisted of a 1-min resting state and 5 minutes of NFB training. During the resting state, participants were instructed to keep their eyes closed and at rest. The PSD of theta (4–8 Hz)/low beta (14–18 Hz) waves in 1-min intervals were averaged and used as the reference value. We recorded the EEG data (see "EEG recording" below) from the resting state and processed it with theta/low beta ratio (reference value). The threshold was adjusted to be 85% of the mean theta/low beta ratio as the baseline of subsequent training. The NFB training program provided real-time positive feedback using an auditory signal, and the height of the sound was determined using the following formula: ((theta/low beta – reference value)/reference value). To familiarize the participants with the sounds and possible ranges used in the NFB training, the different pitches of sound from minimum to maximum frequency were played for the participants using 22 musical scales prior to NFB training. During the NFB training, a 60 dB of sound pressure level pure-tone beep was played for 50 ms every two seconds using double-side speakers (Companion 5 multimedia speaker system, Bose Corporation, USA). Participants were instructed to keep their eyes closed and to raise the pitch of the sound as much as possible using different thinking strategies. The 1-min rest periods were scheduled between each training session.

EEG recording

Brain activities were obtained using a Quick-20 dry EEG headset (Cognionics Inc, San Diego, USA) during the memory tasks, training sessions, and 1-min resting state periods with the participants' eyes closed. Twenty active-dry electrodes were attached according to the International 10/20 system. The reference

electrode was placed on the right ear lobe (A1), and the neutral reference electrode was placed on the upper side of the forehead (Fp1 and Fp2). Additional electrodes were placed on right ear lobe (A2) for further analyses. The EEG channels were digitized at a sampling rate of 500 Hz. Electrode impedances were maintained below 500 kΩ.

EEG analyses

Online analysis

Raw EEG data were filtered using a 60 Hz notch filter. All data were transformed into frequencies using PSD in MATLAB (MathWorks, Inc., Natick, USA). The spectral amplitudes (μV^2/Hz) of the data were calculated and divided into the theta (4–8 Hz) and low-beta (14–18 Hz) bands from the Fz. The epoch duration was 2 s and 50% epoch overlapping was used in real-time analysis. The feedback to the participant was updated every 2 s. All data affected by eye movements or other artifacts were rejected if the absolute value of data in a half epoch (1 s) exceeded 100 µV.

Offline analysis

The recorded signals were re-referenced using the average of A1 and A2. All data affected by eye movements or other artifacts were rejected if the absolute value of data during 500 ms exceeded 100 µV. In addition to the previous theta and beta bands, the data were also calculated and divided in to alpha (8–12 Hz) and gamma (30–55 Hz) bands from the Fz.

Statistical analysis

Brain activity data are presented as PSD values. The average brain wave amplitudes were calculated separately between each task/training block of each session. The repeated measures ANOVA was used to analyse the results of the memory scores and brain activities to determine the effect of NFB training. Regression analyses were used to examine the relationship between the results of behaviour and brain activities. Dunnett's test was used to determine the positive or negative effects of NFB training. In all statistical analyses, the significance level was set to $p < 0.05$. The data are presented with error bars to represent the standard error of the mean (SEM). All analyses were performed using JMP software (SAS Institute Inc., North Carolina, USA).

Declarations

Data availability

The dataset analysed and code used during the current study are available from the corresponding author on reasonable request.

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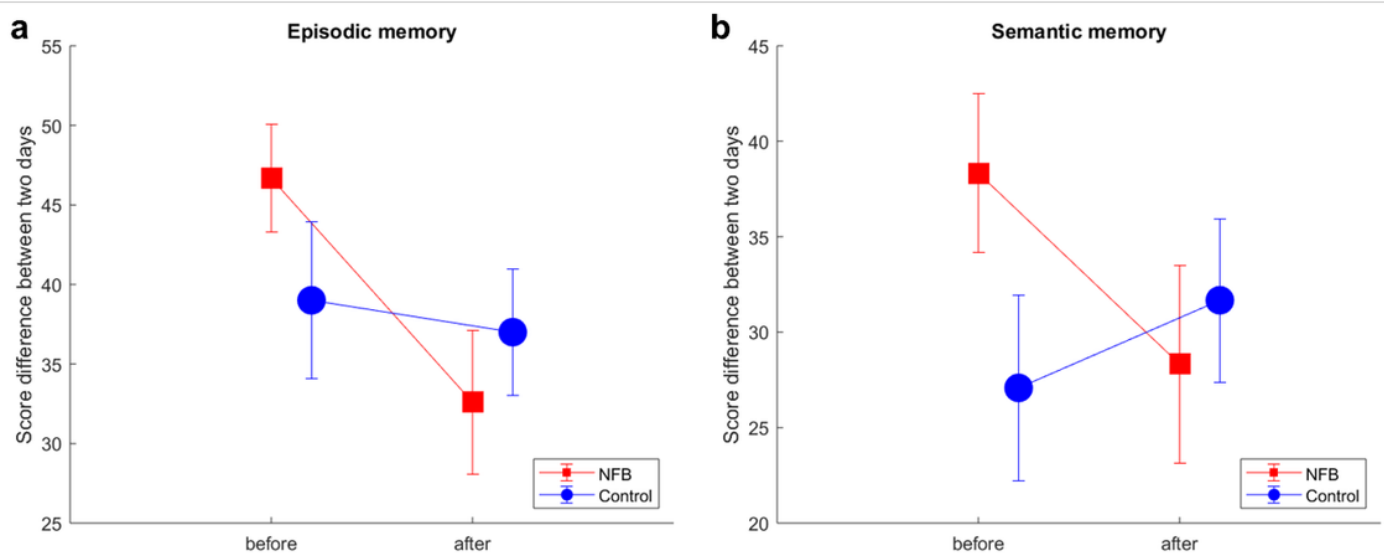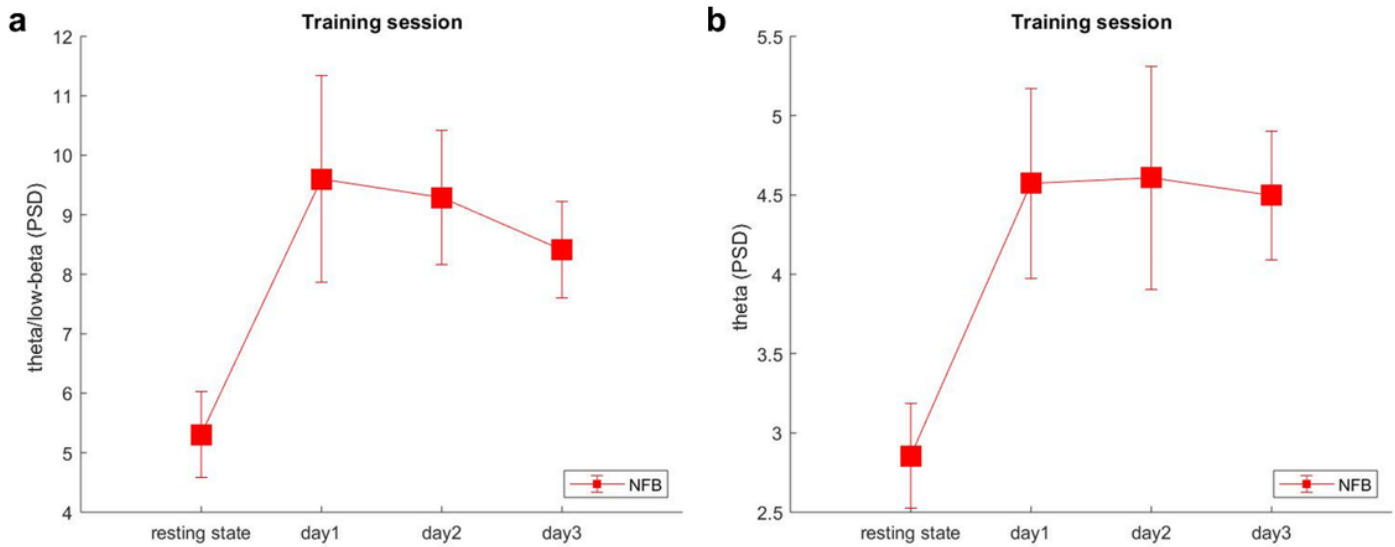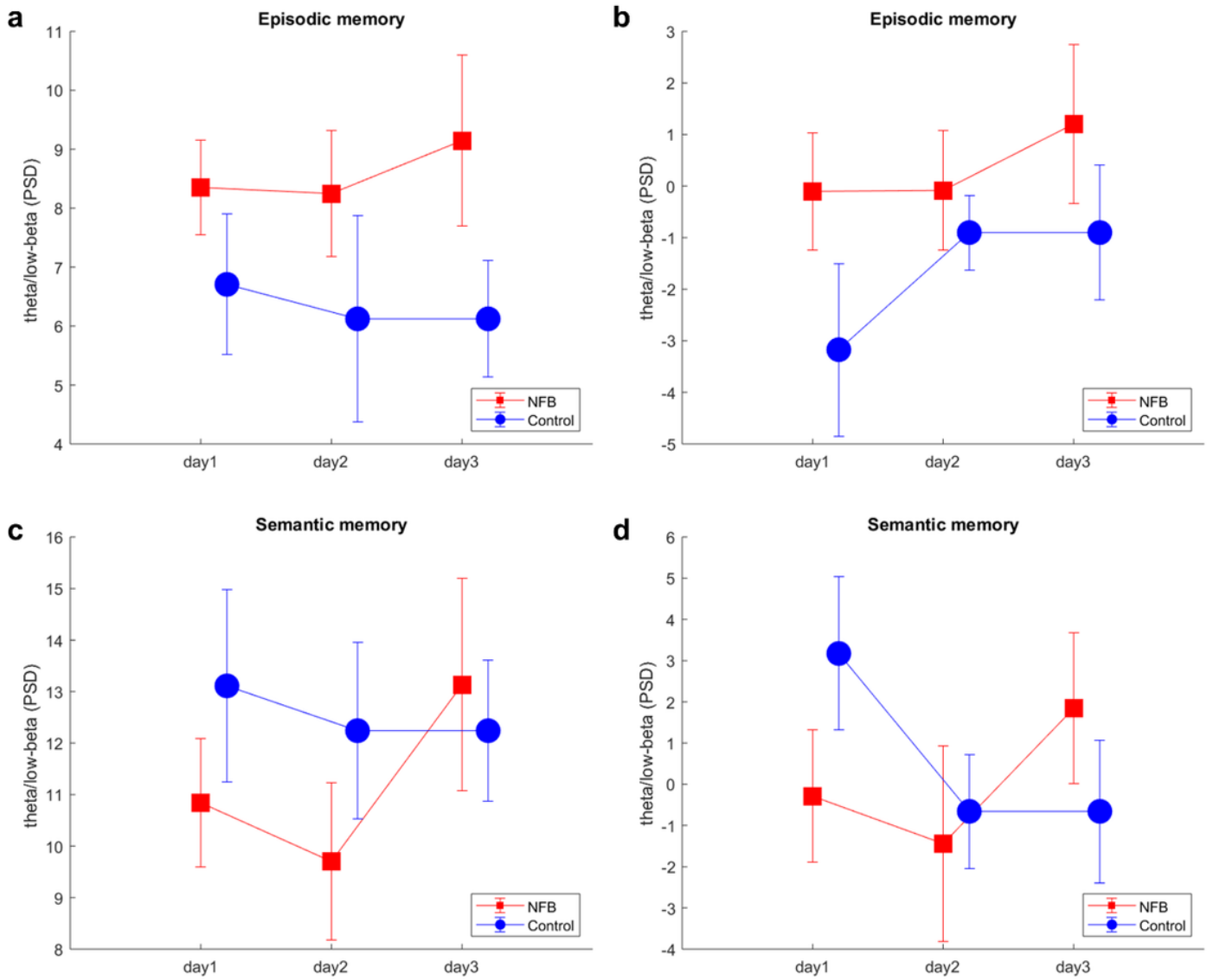
Figures

Figure 1

Differences of recall scores in episodic and semantic memories a. Summary figure: The difference of recall scores in episodic memory during the first (before) and third (after) stages are shown for both groups. b. Summary figure: The difference of recall scores in semantic memory during the first (before) and third (after) stages are shown for both groups. The error bars represent ± 1 standard error of the mean.

Figure 2

Average brain activities during neurofeedback training sessions a. The average theta/low-beta power spectral density (PSD) during the resting state and the training sessions during neurofeedback (NFB) training. b. The average theta PSD during the resting state and the training sessions during NFB training. The error bars represent ± 1 standard error of the mean.

Figure 3

Power spectral density of theta/low-beta in the recall tests of episodic and semantic memories a. Summary figure: The average theta/low-beta power spectral density (PSD) during the third stage for episodic memory is shown. b Summary figure: The average difference in the theta/low-beta PSD for episodic memory between the third and first stages (third stage – first stage) is shown. c. Summary figure: The average theta/low-beta PSD in the third stage for semantic memory is shown. d. Summary figure: The average difference in the theta/low-beta PSD for semantic memory between the third and first stages (third stage – first stage) is shown. The error bars represent ±1 standard error of the mean.
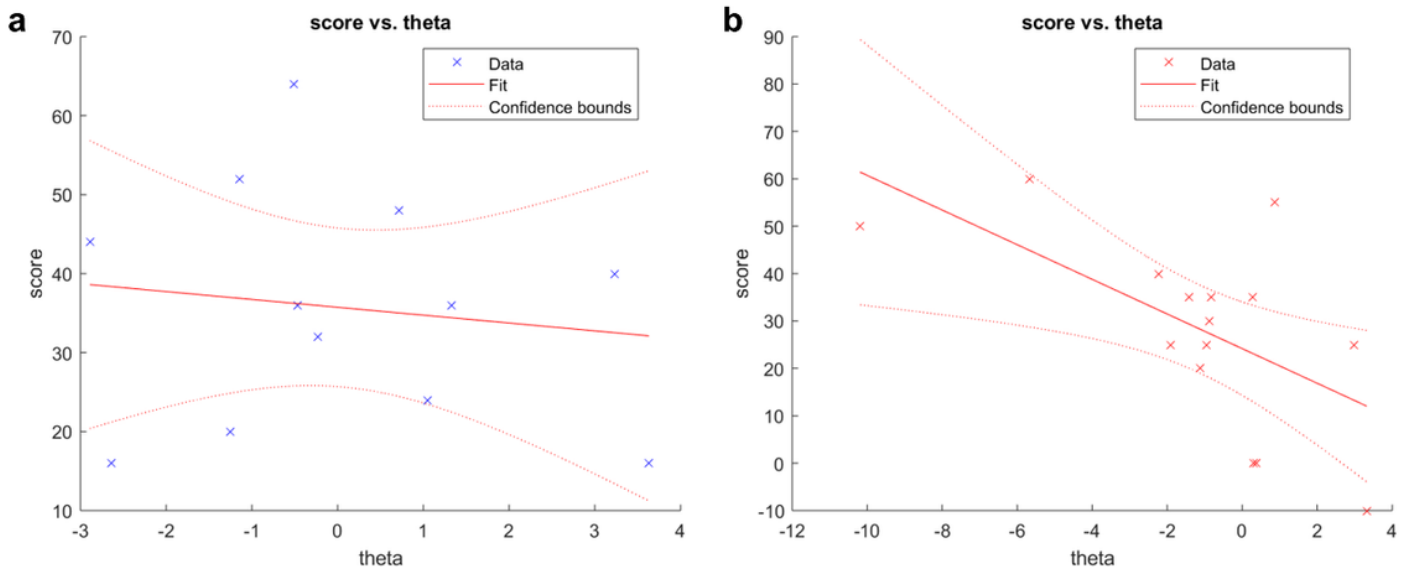
Figure 4

The relationship between recall score difference and theta power spectral density difference in semantic memory a. The relationship between the difference in recall scores and the difference in theta power spectral density (PSD) for semantic memory in the control group are shown. The differences are calculated as the score in the day7 minus the score in the day9. b. The relationship between the difference in recall score and the difference in theta PSD for semantic memory in the NFB group are shown. The dotted line represents the confidence bounds.
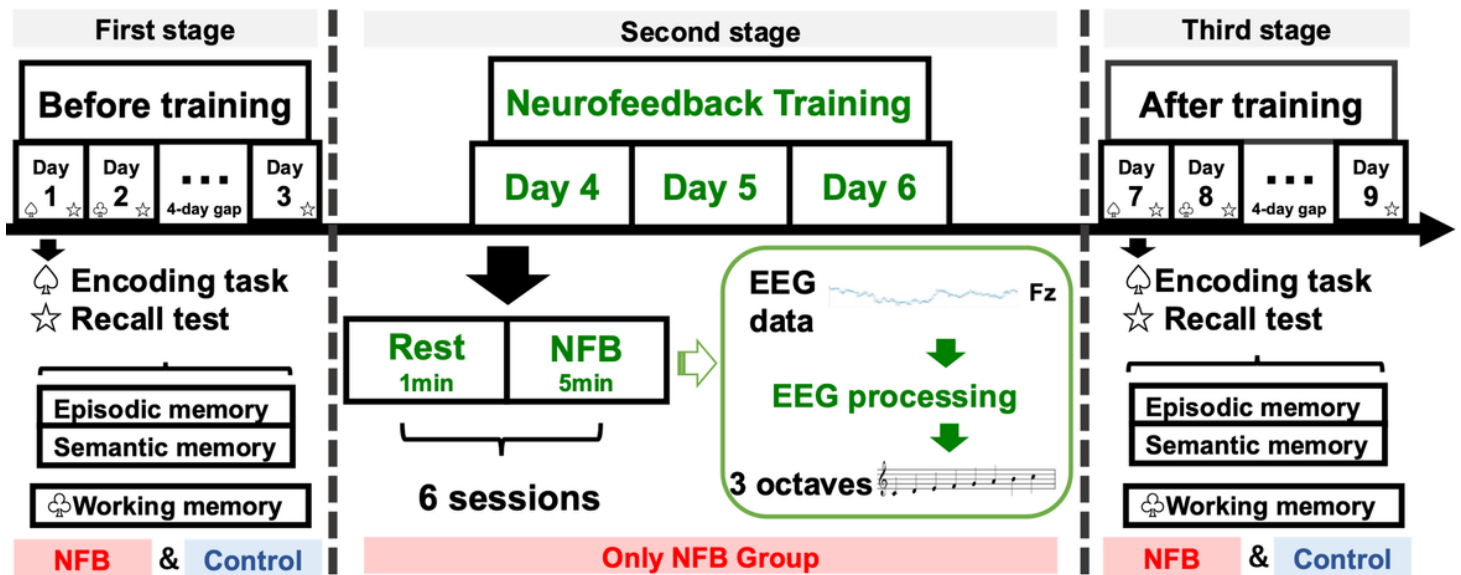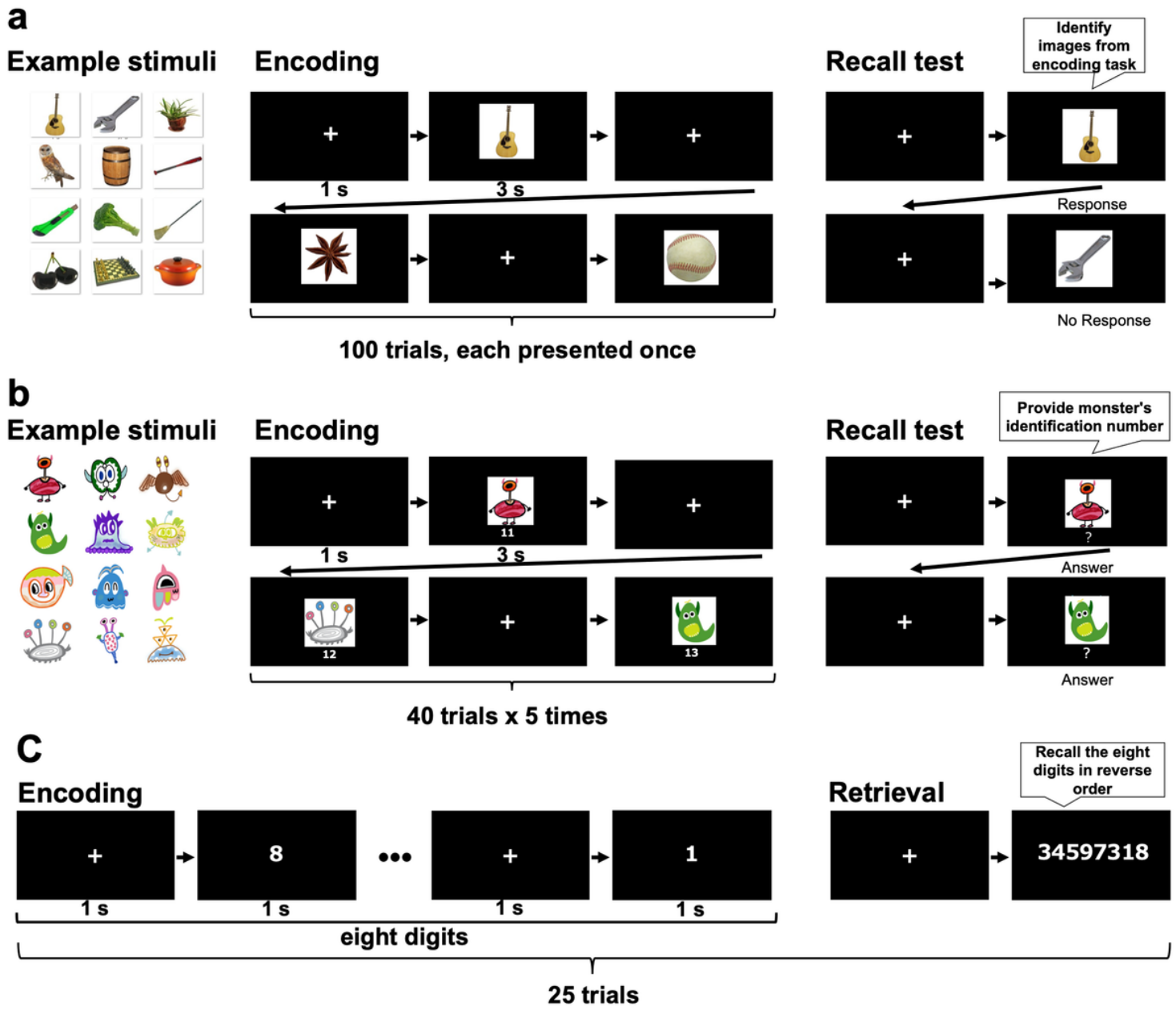

Figure 5

Study procedure

Figure 6

Examples of the memory tasks a. Episodic memory: In the encoding task, the participants were presented with 100 images. The recall test included 25 images from the encoding task and 75 new images. The participants were asked to identify the 25 images from the encoding task. b. Semantic memory: Participants were presented with 40 images of monsters each paired with a two-digit identification number. The monster and corresponding identification number were presented five times during the encoding task. The recall test included ten monsters from the encoding task. Participants were asked to provide the identification numbers of the monsters in the recall test. c. Working memory: In each trial of the encoding task, participants were presented with eight digits. Each digit was presented for 1 s. In the recall test, participants were asked to recall the eight digits in reverse order. This task included 25 trials.