Enhancement of motor performance by a novel training method combining motor imagery and neurofeedback

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Contributions

C.S. and T.O. conceived the idea and designed the study. C.S. and K.T. collected the data and performed the analysis. C.S. and K.T. wrote the draft with critical comments from T.O., and all authors discussed and finished the manuscript.

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Abstract

Motor imagery and neurofeedback have been proposed as motor training approaches, but their effects on the enhancement of motor performance are still controversial. This study aimed to enhance motor performance using a novel training protocol that combines motor imagery and neurofeedback. Seventeen participants were randomly assigned to the training or control group. The training group received real-time electroencephalography activity feedback relative to the motor imagery of the motor action. The control group reiterated the motor imagery of the intended motor action without feedback. The motor performance of the training group was enhanced significantly more than that of the control group. Subsequently, the proposed training protocol was tested in five elite male tennis players to investigate its applicability to sports activities. The motor performance was enhanced in three of these five professional tennis players. Using this novel training protocol, which combined motor imagery and neurofeedback training, we achieved enhanced motor performance.

Motor skills are essential for our daily life, and they need to be learned and developed to perform various activities. In sports, elite athletes must learn and develop specific motor skills at extremely high levels that are beyond those required for ordinary activities of daily living. To enhance motor performance, different training approaches have been investigated in many fields. In neuroscience, to enhance motor performance efficiently and effectively, motor imagery (MI) and neurofeedback (NFB) training have been proposed and studied.

Motor performance of a given action can be enhanced by imagining the action without its execution, by applying a method called MI[1]. In cases of rehabilitation, it has been reported that MI therapy supplements conventional physiotherapy or occupational therapy for patients with motor dysfunction disorders[2,3]. These studies have reported improvement of the movements of the upper and lower limbs among patients following stroke. Conversely, in studies involving healthy participants, MI training can yield effects that enhance motor performance[4–7]. These studies have reported that the duration of an actual movement is decreased by MI training. Thus, we can hypothesize that MI has the potential not only to improve the patients' motor functions but also to enhance the motor performance of healthy individuals.

The effect of MI training is still controversial. A recent review analysed 133 MI training studies and suggested that successful MI training could be achieved with an optimal protocol[8]. However, the authors lacked a neurophysiological viewpoint.

The characteristic brain activity of MI is event-related desynchronization (ERD) of mu-band (8–13 Hz) oscillation in sensory-motor areas. This mu-band ERD has also been observed during actual movement execution[5]. Many studies have shown that mu-band ERD was induced in the contralateral hemisphere of the hand with MI[9,10]. In sports, some studies have reported that mu-band ERD of elite athletes was larger than that of amateurs or novices during the MI of sports activity[9,11]. In this study, we used the term "mu-ERD" to define mu-band activity induced by MI. Based on these previous reports[9–11], we can speculate that mu-ERD is interrelated with motor performance of the imaged movement.

We hypothesized that motor performance can be enhanced by training mu-ERD. In most MI studies, the mu-ERD has been used to monitor the mental states during MI[10,12]. It has been reported that the vividness of MI and mu-ERD amplitudes were correlated[13]. The feedback of mu-ERD will enable the trainee to confirm the vividness of MI by themselves, and a better vividness of MI will lead to a higher motor performance enhancement[4]. For effective training, the vividness of MI estimated by mu-ERD should be conveyed to a trainee as rather than the trainer.

NFB training is a method of self-regulation of neural activities to control specific mind or brain states. In the NFB training paradigm, brain activities are transformed into external sensory stimuli, and the stimuli are fed back continuously. Individuals can learn to regulate their brain states by receiving continuous feedback. Several studies have reported the enhancement or improvement of cognitive function[14-16].

Although NFB training has been used in many types of sports, the effects differ according to the individual and the sport[17-19]. In a NFB-based study on archery, focusing on brain activities peculiar to elite athletes, the pre-elite athletes trained using the feedback of the EEG activity in the left temporal site (in which the elite athletes showed higher activation during shooting) had a higher enhancement of shooting accuracy in the correct NFB group than in the sham or no feedback groups[20,21]. A NFB study of table tennis players evaluated sensory-motor rhythm (SMR) in 10 elite athletes and reported that some athletes showed an increase in accuracy, which was not observed in other athletes[22]. Also, a NFB study of golf players calculated a personalized EEG profile during successful golf putts for 3-days of NFB training. The results showed that their performance was significantly enhanced from day 1 to day 2; however, they could not find significant enhancement on day 3[23]. To ensure that the effects are more stable, an effective training protocol should be established.

The large variation in the effects on motor performance may be caused by two factors: the training target (the kind of neuronal activity used in the brain to train) and the training strategy (the strategy used to change the neuronal activity during NFB training). In previous NFB studies on sports, training targets of EEG activities were not directly related to the intended motor action, and training strategies were not standardised by experimenters and were possibly unrelated to the intended action because strategies were selected by the participants. In most NFB studies including sports training, the strategies were freely determined by the trainee[24]. To enhance motor performance efficiently, the training target and training strategy should be directly associated with the intended motor action.

Based on our hypothesis that mu-ERD enhancement can enhance motor performance, we developed a novel training protocol combining MI and NFB (MI-NFB). This protocol will enable the training of vividness of motor imagery and mu-ERD regulation at the same time, and it will provide more stable effects than either MI or NFB alone. When trainees imagine a given motor action in the protocol, they receive mu-ERD feedback related to the action. An intended motor action to enhance its performance was imaged as the training strategy.

Our objective was to indicate that a novel training protocol, MI-NFB, can enhance motor performance more efficiently than the conventional MI training. First, we verified the effectiveness of the training protocol in a laboratory with university students. The motor action was designed originally by applying pegboard games. Subsequently, we investigated its applicability to sports performance with world-class tennis players individually as a case report. The tennis serve was the motor action, to enhance which training protocol was applied.

RESULTS

Experiment 1: Training protocol for healthy volunteers

Participants were assigned to two groups: MI-NFB group and control group. The motor performance and related neural activities were analysed according to dominant and non-

dominant hand performance separately.

Clustering analysis

Many previous studies have reported that motor performance, even in skilled motor activities, is impaired by mental fatigue[25,26]. To verify the effects of the proposed training protocol without the influence of the harmful effects caused by mental fatigue, clustering analysis was performed for the fatigue reports and motor performance data. We used a data-driven method (a hierarchical cluster analysis of the mental fatigue during MI training of all participants). As a result, four participants were classified into the cluster of high mental fatigue (high-fatigue group), and they all participated in the proposed training (see Fig. 1A and 1B for the detailed results). The remaining data were separated according to the performed task, MI-NFB and control.

Dominant hand

We compared the working time of the motor performance using a pegboard before and after the training. With regard to the pre-motor-performance-training, there were no significant differences in the working time between the MI-NFB and control groups (U = 14.0, P = 0.21, α = 0.025) and between the high-fatigue and control groups (U = 10.0, P = 0.18, α = 0.025). After motor performance test (MPT), the working time of the MI-NFB group was significantly lower than that of the control group (U = 3.0, P = 0.007, α =

0.025), and there were no significant differences in the working time between the high-fatigue and control groups (U = 14.0, P = 0.40, α = 0.025). These results indicate that the MPT of the MI-NFB group was enhanced by training (Fig. 2A).

To evaluate the training effect, we compared the mu-ERD obtained during the evaluation session between the first and the last blocks. In the first block (pre-training, day 1), there were no significant differences in mu-ERD between the MI-NFB and control groups (U = 9.0, P = 0.062, α = 0.025) and between the high-fatigue and control groups (U = 20.0, P = 0.11, α = 0.025). In the last block (post-training, day 3), mu-ERD in the MI-NFB group was significantly lower than that in the control group (U = 6.0, P = 0.024, α = 0.025), and there were no significant differences in the mu-ERD between the high-fatigue and control groups (U = 31.0, P = 0.48, α = 0.025). These results indicate that the mu-ERD of the MI-NFB group during the evaluation sessions was markedly higher than that of the control group (Fig. 2B).

We conducted a correlation analysis to evaluate the relationship between MPT working-time changes and mu-ERD changes during the training. In the MI-NFB group, there was a significant positive correlation between MPT time changes and mu-ERD changes (r = 0.90, P = 0.037). In the high-fatigue and control groups, there was no significant correlation (high-fatigue: r = 0.80, P = 0.20, control: r = 0.45, P = 0.26) (Fig. 2C).

Non-dominant hand

There were no significant differences in the working time at both pre- and post-test assessment times between the MI-NFB and control groups (pre: U = 18.0, P = 0.41, post: U = 15.0, P = 0.26) and between the high-fatigue and control groups (pre: U = 15.0, P = 0.47, post: U = 15.0, P = 0.47) (Fig. 3A).

To evaluate the training effect, we compared the mu-ERD during evaluation session between the first and last blocks. There were no significant differences in mu-ERD in the first (pre-training, day 1) and last (post-training, day 3) blocks; between the MI-NFB and control groups (U = 10.0, P = 0.08, α = 0.025 and U = 18.0, P = 0.41, α = 0.025, respectively) and between the high-fatigue and control groups (U = 22.0, P = 0.16, α = 0.025 and U = 14.0, P = 0.03, α = 0.025, respectively) (Fig. 3B).

We conducted a correlation analysis to compare relative changes between MPT time and mu-ERD during the experiment. There was no significant correlation between time-related changes in pre- to post-test MPT or in mu-ERD changes during the evaluation sessions from the first block to the last block in all group (MI-NFB: r = 0.70, P = 0.19: High-fatigue: r = −0.2, P = 0.80: control: r = 0.17, P = 0.70) (Fig. 3C).

To evaluate the effect of MI-NFB on the MI subjective scale, confidence rates were measured. The self-confidence rate of the MI-NFB group was significantly lower than that

of the control group (P = 0.012).

Experiment 2: Effects of MI-NFB on tennis athletes

In the second experiment, we investigated the effect of the proposed training on elite athletes. Five world-class male tennis players (T01–T05) were enrolled (Table 1). Because of the small number of target participants, we analysed the training effects individually and did not perform any statistical analyses.

Motor performance test

Motor performance was evaluated objectively based on the number of serves that hit the target and the estimated service speed individually. Despite the lack of improvement in service speeds (Fig. 4B), the number of hits of three players increased from pre- to post-MI-NFB training. The number of hits of player T02 did not change, while the number of hits of player T03 decreased. (Fig. 4A). Motor performance was also evaluated subjectively based on the self-evaluation of each player for each service by visual analogue scale method. The subjective evaluations for services displayed an increase in players T02 and T04, while there was a decrease in players T03 and T05, and no changes in player T01 (Fig. 4C).

The mu-ERD

To evaluate the training effect, we observed daily changes in the mu-ERD during the evaluation session from pre- to post-MI-NFB (Fig. 4D). The mu-ERDs of players T01, T02, and T04 showed larger increases on day 2 than on day 1. The mu-ERD of player T03 showed a consistently larger increase over 3 days. The mu-ERD of player T05 decreased on day 2 but increased on day 3.

DISCUSSION

In this study, we aimed to enhance motor performance by using MI-based NFB training. We introduced an original performance test and developed a novel training protocol unifying all MI and NFB tasks into the original test. To verify the effectiveness of the proposed protocol, we compared motor performance following a training protocol with that following MI training alone. Both motor performance and mu-ERD amplitudes of participants trained using the protocol were more enhanced compared to those of the participants trained using MI alone. First, we discuss the group comparisons among the MI-NFB, high-fatigue, and control groups, and subsequently, we interpret the results of the professional tennis athletes individually.

With regard to the MI-NFB and control groups, we found that the performance of the dominant hand was enhanced after MI-NFB training. The enhanced motor performance was derived from the mu-ERD feedback specified by the MI strategy of the given motor

action (Fig. 5A). The participants could enhance their own mu-ERD using the feedback. Several studies have reported that motor performance and ERDs of MI were positively correlated[27,28]. We can speculate that the mu-ERD feedback and strategy specification contributed to the success of the proposed training. In the control group, the motor performance was not enhanced, which suggests that participants were likely presented with irrelevant feedback to their own mu-ERD (Fig. 5B). In conventional MI training studies, effects on motor performance are still controversial and may be attributable to the lack of mu-ERD feedback. The degree of MI vividness varied individually. Conventional studies did not involve any feedback of mu-ERD as the degree of vividness, and the lack of the feedback might have provided ambiguous effect (Fig. 5C). In the conventional NFB-based studies on sports, both mu-ERD and motor performance could not be significantly enhanced. We speculate that there are two reasons for this: 1) the use of free strategies and 2) the irrelevant feedback to the motor action to be trained (Fig. 5D).

The mu-ERD is believed to reflect motor attention and multisensory integration, which are necessary to perform tasks more efficiently[9,29]. From these reports, the effects of our MI-NFB training could be interpreted as the enhancement of the mu-ERD, which means that enhancing motor attention and integrating multisensory information results in a more efficient performance of an imagined motor action and that mu-ERD enhancement may have affected the high-performance of MPT and tennis service skills.

In our results, there was a significant positive correlation between mu-ERD and motor performance in the MI-NFB group, as expected. In contrast, there was no significant

correlation between mu-ERD and motor performance in the control group. It was difficult to conduct MI because visual stimulation is involved in the experimental design used in the present study. The lack of correlation between the mu-ERD and motor performance in the control group may result from the interference of background visual stimulation with the concentration on MI. Although the participants in the MI-NFB group received the same visual stimulation as did those in the control group, the mu-ERD of the MI-NFB group was significantly correlated with motor performance. This significant correlation would support the effectiveness of the proposed protocol despite the use of the same background stimulation.

Contrary to our expectation, enhancement of motor performance while performing a motor action using the non-dominant hand was not observed following MI-NFB training. Generally, the efficiency of motor learning for a new action is lower in the non-dominant hand than in the dominant hand. Our motor performance test included an unfamiliar motor action to avoid the familiarity effect. We can expect that the participants failed to learn the unfamiliar action with non-dominant hand using the training protocol. During the last evaluation session, no significant difference in the mu-ERD was observed when an action was performed using the non-dominant hand. These results indicate that the training effect was not sustained until the last evaluation session. Failure to sustain the mu-ERD may inhibit the enhancement of performance. If we could prolong the training period long enough to sustain the mu-ERD enhancement until the last evaluation session, performance with the non-dominant hand would also likely be enhanced.

Self-confidence rates of MI were significantly higher in the control group than in the MI-NFB group. These results indicate that there was a gap between subjective evaluation and objective evaluation of MI. This cognitive gap was suggestive of a difficulty in estimating the ability of MI by subjective assessment alone.

The participants in the high-fatigue group who experienced increased mental fatigue during the training did not show enhanced motor performance and mu-ERD. Several previous studies reported that high mental fatigue worsens motor performance. The mu-ERD of the high-fatigue group was not enhanced by training. This result indicates that the four participants in the high-fatigue group could not adapt to the NFB training. The stress of not being able to adapt to the NFB training caused mental fatigue, which may have worsened the motor performance. Therefore, controlling the mental fatigue of trainees may be necessary for successful NFB training.

Experiment 2 with tennis athletes was performed to assess the extendibility of the proposed training protocol. As a result, we found some training effects in most of the players. Player T04 showed remarkable effects which included: 1) the number of services that hit the target and 2) the values of subjective evaluation increased. The mu-ERD was mostly not observed in either the evaluation or the training session before the training but was observed after the training protocol. These results indicate that the service performance was enhanced because of the mu-ERD achieved by the training.

In contrast, a decline in performance and ball speed was observed in player T03. The mu-

ERD of player T03 was not observed in the training session, but it was observed clearly in the evaluation session in each daily training session. Therefore, a training effect was observed during the evaluation session. Just before the post-performance test, player T03 could not do a warm-up exercise like the other participants; thus, the reduced warming up may have been the cause of the decline in performance.

The service performance of player T02 did not differ from that of the pre-performance test. The mu-ERD of player T02 was not induced during training on day 3 likely because he could not train satisfactorily as a result of a system error. This failure to train mu-ERD on day 3 may have inhibited the enhancement of the motor performance.

For players T01 and T05, the degree of mu-ERD during the training increased possibly because the difficulty of the MI-NFB training was increased with each day. Conversely, a mu-ERD obtained during the evaluation session increased during the training, and the number of serves that hit the target increased after the training. From these results, we could not conclude whether the motor performances of players T01 and T05 improved following training.

The limitations to the study should be considered. In experiment 1, mu-ERD of the MI-NFB group increased during the training session, and the post-training mu-ERD was significantly larger in the MI-NFB group than in the control group. These results strongly supported that the enhancement of mu-ERD was a result of MI-NFB training. Thus, we suggest that mu-ERD induction enhanced the motor performance. However, we cannot

reject the possibility that the motor performance was enhanced by a placebo effect and not by MI-NFB training itself. In our protocol of experiment 1, we told the participants in the MI-NFB group that the visual stimuli were associated with their vividness of MI. Conversely, the control group were not told the meaning of the visual stimuli but were only told to ignore them. The difference in instructions might have led to the performance enhancement as a placebo effect.

An additional limitation was the small sample size. In the training protocol (experiment 1), non-parametric tests were conducted because of our sample size; the statistical power would have declined if a parametric test were used for this population. In a future study, additional data should be analysed to obtain enough statistical power to detect significant effects using the same protocol. Regarding the effects of MI-NFB on tennis athletes (experiment 2), the results of the training in world-class tennis players indicated that the proposed training protocol could easily be applied to sports and could contribute to the enhancement of motor performance. We did not conduct group analysis in the tennis players experiment, because it was difficult to recruit enough world-class players. It is necessary to measure data from more elite players and to compare the effect statistically in a future study.

In both experiments, we did not measure electromyography, and we could not confirm whether the participants performed MI without the actual motion. We cannot reject the possibility that the observed mu-ERD was induced by an actual movement and not by imaging. We removed noisy data containing amplitudes exceeding 100 μV at Fp1. Most

artefacts generated by body movements should have been rejected automatically, but it may not be enough to reject motor artefacts.

In conclusion, in the present study, we succeeded to enhance motor performance with the proposed training protocol using MI-NFB. We verified the hypothesis that the combination of MI and NFB would provide stable effects. The novelty of the proposed protocol was the specification of the strategy used for the MI of the intended motor action, which enabled feedback of EEG related to the MI and enhanced its performance. Notably, the protocol was effective for the trainees who did not experience increased mental fatigue during the training. If mental fatigue can be controlled appropriately, the proposed protocol can contribute to the development of more effective methods with application in the fields of therapy and sports.

MATERIALS AND METHODS

Experiment 1: Training protocol for healthy volunteers

Participants

Eighteen Kyushu University students (9 women, 9 men; mean ± standard deviation (SD) aged, 20.3 ± 1.7 years old; right-handed) were recruited for this study. One female participant was removed from our analysis because she could not perform our motor

performance test because of an injury to her left thumb. Therefore, we analysed the data from 17 participants (8 women; age, 20.4 ± 1.7 years old; right-handed). All participants performed the Flanders handedness test in Japanese to assess individual handedness[30]. All participants were healthy and had no previous history of neurologic disease or history of participating in similar MI experiments. All participants provided written informed consent. The study was approved by the Local Ethics Committee of Faculty of Arts and Science, Kyushu University.

Participants were divided into two groups: MI-NFB group (5 women, 4 men; 20.3 ± 1.9 years old) and control group (3 women, 5 men; 20.5 ± 1.6 years old), to avoid any biases of age ($t(15) = -0.20$, $P=0.85$), sports experience ($t(15) = 0.68$, $P = 0.51$), and the time period after retirement from sports ($t(15) = 6.39$, $P = 0.70$).

Experimental training procedure

The participants sat on a comfortable armchair in an air-conditioned soundproof room. A monitor was placed at approximately 1.2 m in front of the participants (1920 × 1080 pixels).

The participants were asked to come to the experimental room for three days over a one-week period. On the first day, all participants engaged in a pre-test session, to undergo the assessment of motor performance; an evaluation session; a training session; and another evaluation session. On the second day, they participated in the first evaluation session,

training session, and second evaluation session. On the third day, they first participated in the evaluation session, and then in the training session, second evaluation session, and post-test session on motor performance.

Motor performance test

We designed a MPT to control for unfamiliarity of the bilateral performance using a pegboard, similar to that used in previous studies for rehabilitation scenarios[31,32]. In the performance test, the participants were instructed to insert 4 pegs into 4 different holes on the right or left side, as quickly as possible. Immediately after the insertion, they were required to perform a 180° rotation of the pegs and reinsertion in the holes on the opposite side. Finally, they removed all pegs from the holes and pressed a key to measure the performance time (Fig. 6A). In the right-hand trial, in which the participants were specified to use their right hand, they moved the pegs from the right to the left side, and in the left-hand trial, they moved the pegs from the left to the right side. Each trial started with the presentation of an instruction to 'Relax' on the monitor for 5 s. Then, indication of 'Left' or 'Right' appeared for 3 s to specify the lateral trial. Next, a fixation cross was presented, and the participants started the sequence of MPT. The fixation cross was presented while performing the task until a key was pressed. Before the beginning of the next trial, a blank screen re-appeared. The duration of the blank screen was randomly changed in the range of 2.1–2.5 s (Fig. 6B). Five trials of the performance test were conducted with each hand. The performance time was recorded from the time of presentation of the fixation cross to that of key pressing, and this performance time was

used to evaluate motor performance bilaterally. A shorter performance time indicated high motor performance.

Training session

In the MI-NFB training session, the participants performed MI using the same motor action as in the MPT. The displayed instructions and timings were designed to be the same as in the MPT trials (Fig. 6B). After laterality was specified, a circle was presented behind the fixation cross as a visual feedback, the participants started MI. In the MI-NFB group, the radius of the circle varied according to their mu-ERD (see EEG analysis section below and equations 1 and 2). Participants were told that when they performed a better MI, the feedback circle would be smaller. They were instructed to attempt to make the circle smaller than the fixation cross as much as possible by performing better MI. When the length of the fixation cross was same as the circle radius, it indicated 10% mu-ERD. In the control group, the radius of the feedback circle varied according to mu-ERD of another participant as a sham stimulation. They were instructed to ignore the feedback circle and to concentrate on the MI.

A one-day training session consisted of 5 blocks, and one block included 5 MI trials for each hand. Therefore, a total of 50 MI trials was conducted in a training session. After each block, the participants took a 60-s break and answered questionnaires using a 7-point scale indicating the difficulty of the MI (1: very easy, 7: very difficult), degree of mental fatigue (1: no fatigue, 7: high fatigue), and concentration (1: no concentration, 7: high

concentrated). Then they provided a self-confidence rate in the range of 0–100% for the performance of MI.

Evaluation session

In the evaluation session for the training effect, the participants performed MI similar to the MPT trial without any visual feedback. The display instructions and timing were like those of the MPT trials (Fig. 6B). Participants in all groups were instructed to concentrate on MI by focusing on the fixation cross in each trial. There were no differences in instructions or display indications for all groups.

One evaluation session had a block including 5 MI trials for each hand, and this session was conducted before and after the one-day training session. After each evaluation session was completed, the participants took a 60-s break.

EEG recording

EEG data were recorded using Cognionics Quick-20 headsets (CGX, San Diego, CA, USA), consisting of 20 active-dry electrodes. These electrodes were placed according to the international 10-20 system, and the recorded signals were digitized with a sampling rate of 500 Hz. The reference electrode was placed on A1, at the left earlobe, and the ground electrodes were placed near Fp1 and Fp2 at the forehead. An additional electrode,

A2 at the right earlobe was placed and measured (Fig. 6C). Impedance levels were maintained below 500 kOhm. We recorded EEG data using a Data Acquisition Software (CGX, San Diego, CA, USA). EEG was recorded during the training and evaluation sessions.

Clustering analysis according to performance and fatigue levels

To classify the participants, the fatigue levels and motor performance data were subjected to Ward's hierarchical cluster analysis using Euclidean distances.

EEG analysis

Real-time analysis

The decrease in real-time mu power from baseline (mu-ERD increased) was computed from the streaming EEG data. The recorded stream EEG data were stored for 1.024 s (512 points) before the onset of updating visual feedback, and the 1.024 s data were used to compute mu-ERD to define the radius of feedback circle. We defined 8–13 Hz as the mu band. The baseline interval was defined a relaxation period of 5 s just before a hand cue was presented (−8 s to −3 s before the hand cue onset) and the MI task interval was defined the period from the presentation of the fixation cross to pressing of a key pressed (0 to key pressed). We computed the mu-ERD using the following equation:

$$\text{mu-ERD}(t) = \frac{A(t)-R}{R} \times 100, \quad (1)$$

where $A(t)$ is the power spectrum density of the time window during an MI trial at time t, and R is the baseline power at the trial. The radius of the feedback circle was computed from mu-ERD by using the following equation:

$$\text{radius}(t) = 5 \times \text{mu-ERD}(t) + \text{radius}_{\text{BL}}, \quad (2)$$

where $\text{radius}_{\text{BL}}$ = 300 pixels. The visual angle when the $\text{radius}_{\text{BL}}$ was presented was approximately 10.5°. The analytic time window during an MI trial was a sliding window with approximately 90% overlap. Accordingly, the feedback was updated approximately every 100 ms, and the analytic time window during the relaxation periods (baseline interval) was the sliding window without overlapping. The data in the baseline interval was computed as mu power in each window and averaged. The averaged data was used for the baseline power calculation (R in equation 1). The mu power spectrum density was computed by using the 'psd_array_multitaper (array data, sampling rate)' function in the Python MNE module. To remove eye-blinking artefacts, the time windows containing data in which absolute value exceeded 100 μV at the Fp1 electrode were rejected. If the 1-s data to feedback was rejected because of the occurrence of artefacts during an MI trial, the data before the last feedback was used to compute the radius of the visual circle. Therefore, the size of the circle did not change when the data feedback contained artefacts. The data recorded at C3 were used to compute the mu-ERD of the right-hand MI, and the data at C4 were used to compute the mu-ERD of the left-hand MI. These analyses and feedback systems were self-developed using Python.

Offline analysis

Raw EEG data were band-pass filtered (3–50 Hz) and notch-filtered at 60 Hz. The recorded signals were re-referenced to the average of A1 and A2. The data were divided by −8 s to 15 s after the onset of MI start as one epoch. The mu-ERD was computed using equation (1). The EEG power from −6 s to −3 s was used as the baseline (R), and the power from 1 s to 5 s was used as an MI task activity (A).

Statistical analysis

We used non-parametric tests for all statistical analyses because the sample population did not show normal distribution due to the small sample size. In MPT, the performance times of the MI-NFB, high-fatigue, and control groups were compared between the pre- and post-training tests separately to evaluate the enhancement of motor performance for each group, using the Mann-Whitney U test. The mu-ERD during the evaluation session was assessed separately for the first block (pre-training, day 1) and the last block (post-training, day 3) using the Mann-Whitney U test. To evaluate the relationship between the changes in MPT and mu-ERD during the evaluation session, Spearman's rank correlation analysis was conducted. The significance α-value was set to 0.05, and Bonferroni correction was used for all statistical analyses. These tests were conducted in SciPy module (ver. 1.2.1) in Python (ver. 3.7.2).

Experiment 2: Effects of MI-NFB on tennis athletes

Participants

Five world-class male tennis players were enrolled, and they ranked in the top 200 of ATP men's tennis ranking on 13th May 2019. The demographic data are summarised in Table 1.

Because of the inclusion of a small number of targeted participants, we analysed the obtained data individually and did not perform group comparison.

Experimental procedure

Only a few modifications were made to the experimental procedure used for healthy volunteers. The MPT was designed for tennis athletes as follows.

Training effects were evaluated by the performance of tennis serves. All participants hit 10 services before and after the training from right or left side on a tennis court. After each service, a participant evaluated the service subjectively using a Visual Analog Scale ranging from 'worst performance' to 'best performance'. In the MPT, a service side was specified for each participant, from which he was not good at shooting a serve. The service side to shoot was determined according to the pre-training questionnaire of each participant. To evaluate the service performances, an 81 cm × 81 cm target area was designated on the tennis court. All players were instructed to hit the target area. The players' motions and ball trajectories during services were recorded with three cameras from different locations. Ball speeds were estimated from videos recorded in 480 fps using the number of frames between the hit ball and grounded ball. We evaluated motor

performance using the number of hits on target and estimated ball speeds. After all tasks were completed in the training protocol, we interviewed the participants.

MI-NFB training

The MI-NFB training procedure was the same as that used for healthy volunteers. For the MI task in the athletes, participants were instructed to image the motion of serving from a side that was specified in the MPT. In this task, hand laterality of imaging was the same as the hand used by each participant to grip a racket.

Online analysis

On day 1 of the training protocol for athletes, the size of the feedback circle was computed by equation (1) as in the case of healthy volunteers, and the coefficient of ERD in equation (1) was changed to 4 on day 2 and to 3 on day 3. This change was intended to increase the difficulty of MI-NFB training, because we hypothesized that elite athletes had higher proficiency of the imaged movement.

References

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Figures and Tables

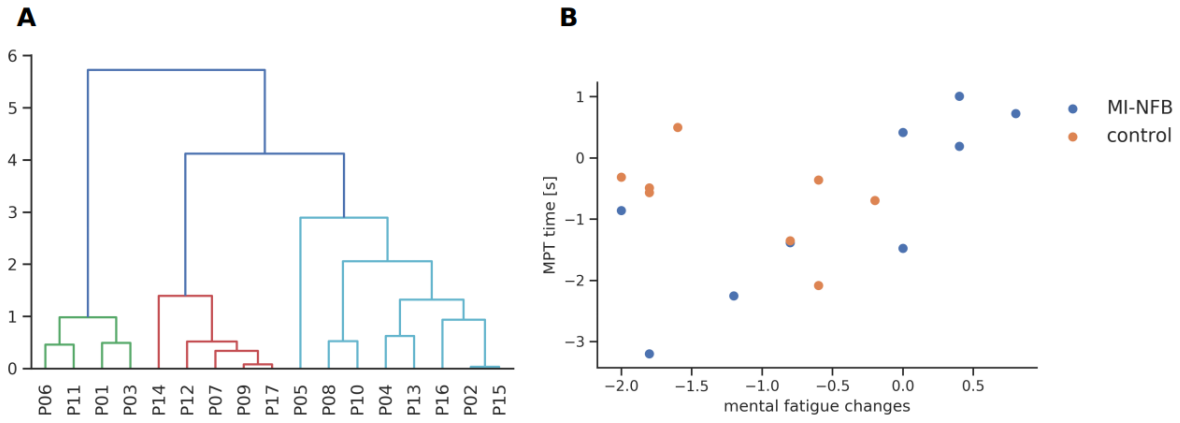

Figure 1. A: Dendrogram of the hierarchical clustering analysis of mental fatigue and MPT time. B: Scatter plots showing changes in mental fatigue according to MPT time.

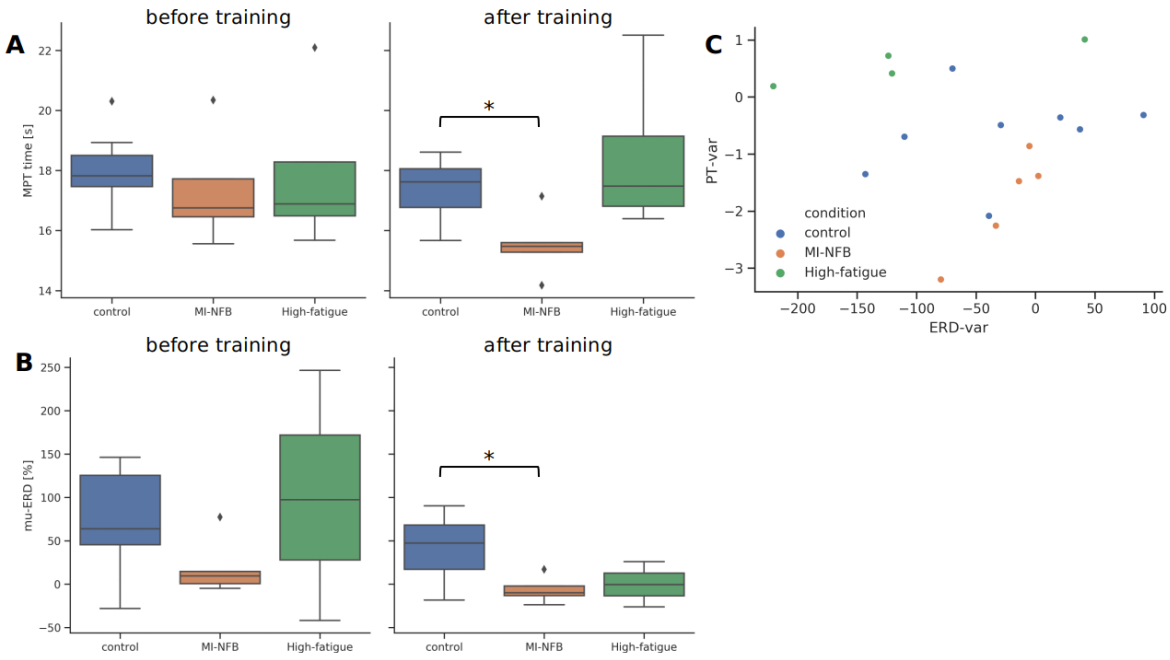

Figure 2. Results of MPT and mu-ERD with the dominant hand. A: Changes in the working time of MPT between before (left side) and after (right side) training. *: P =

0.025, with a Bonferroni correction. B: Changes in the time of mu-ERD between before (left side) and after (right side) training. *: P = 0.025, with a Bonferroni correction. C: Scatter plots of mu-ERD and MPT time with the dominant hand.

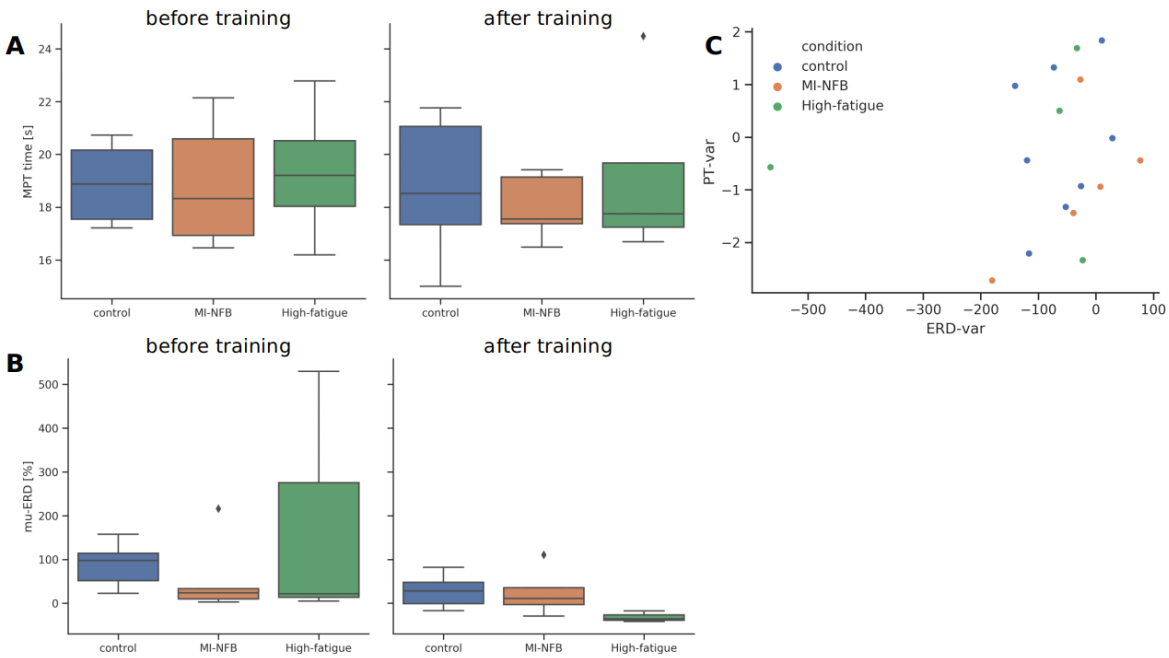

Figure 3. Results of MPT and mu-ERD with the non-dominant hand. A: Changes in the working time of MPT between before (left side) and after (right side) training. B: Change in the time of mu-ERD between before (left side) and after (right side) training. C: Scatter plots of mu-ERD and MPT time with the non-dominant hand.

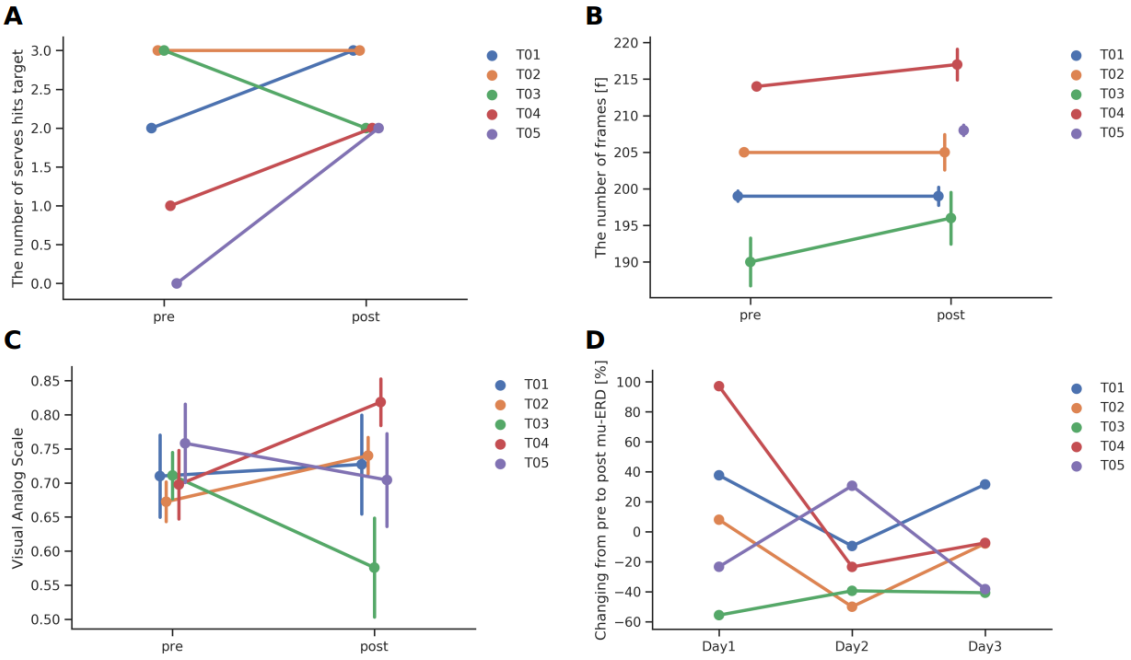

Figure 4. Results of experiments involving tennis athletes A: Changes in the number of hits on target before and after the MI-NFB training. B: Changes in the estimated speeds of serves before and after the MI-NFB training. C: Changes in subjective evaluation before and after the MI-NFB training. D: Over-time changes in the difference in mu-ERD before and after each training session. Error bars represent S.E.M.

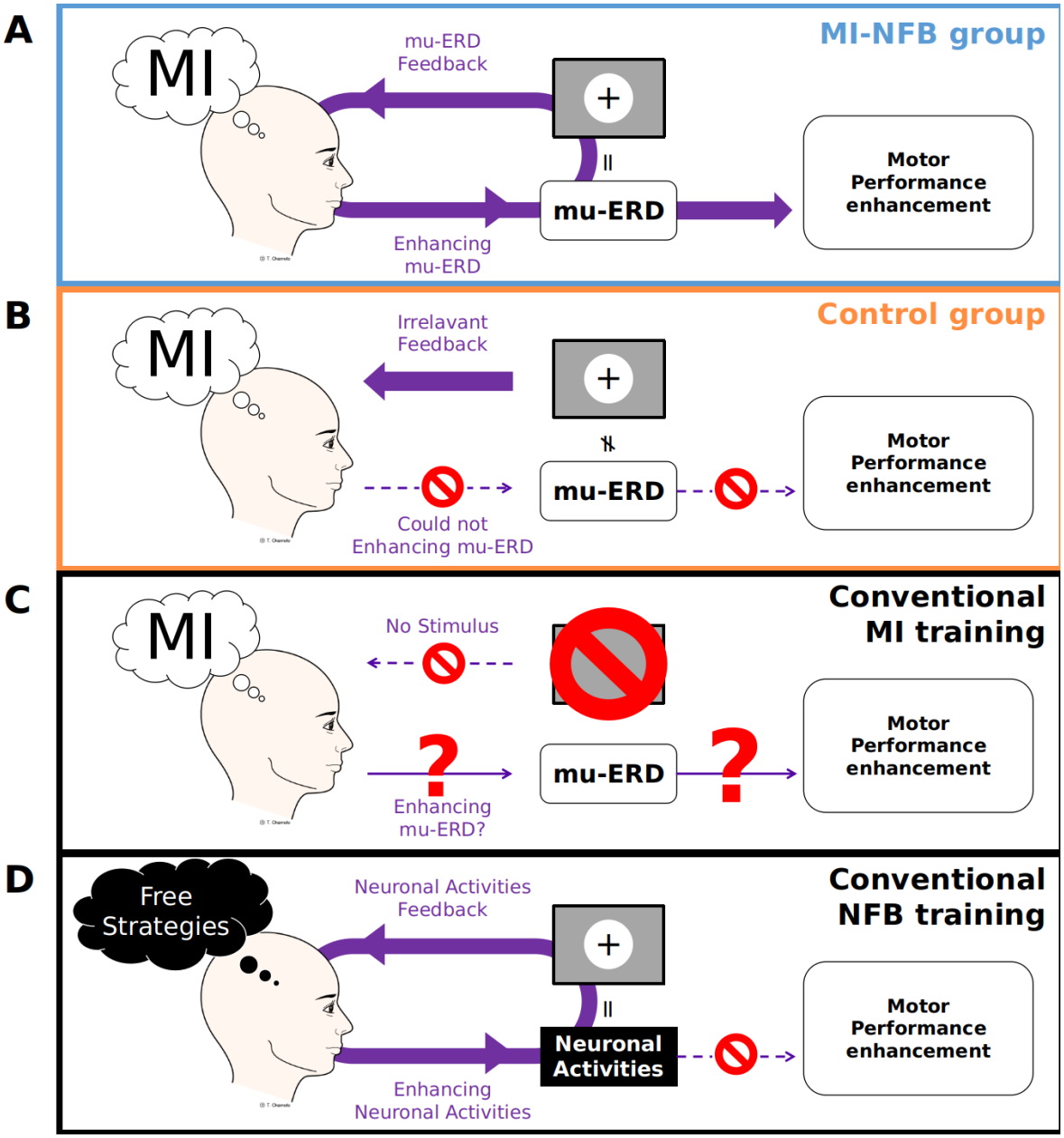

Figure 5. Conceptual scheme of the mechanism for the enhancement or non-enhancement of motor performance. A: MI-NFB group. B: control group.

C: Conventional MI training. D: Conventional NFB training.

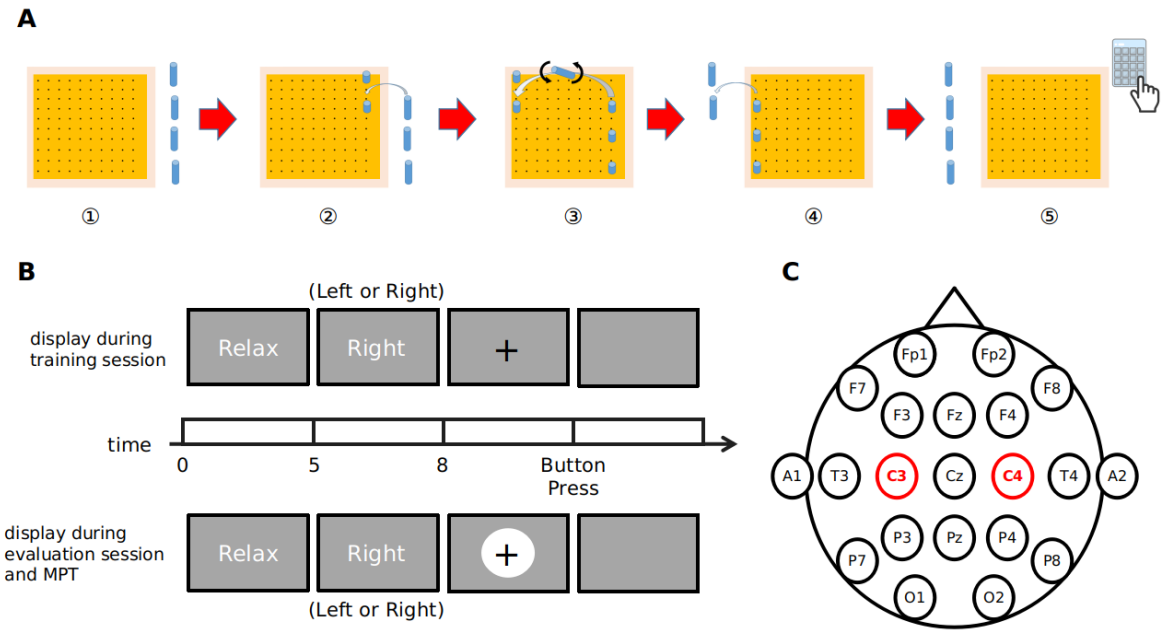

Figure 6. Experimental design. A: Motor performance test procedure. B: Procedure of each trial. C: Electrode setup.

Table 1. Demographic information of the tennis players

Participant's ID	Age	Racket hand	Serve side	Best world ranking
T01	26	Right	Left	64
T02	31	Right	Left	36
T03	21	Right	Left	171
T04	24	Left	Right	58
T05	27	Right	Left	78

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Ethics declarations

Competing interests

The authors declare no competing interests.