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Effect of a single session of sensorimotor rhythm neurofeedback training on the putting performance of professional golfers

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Abstract
Sensorimotor rhythm (SMR) activity has been associated with automaticity and flow in motor execution. Studies have revealed that neurofeedback training (NFT) of the SMR can improve sports performance; however, few studies have adequately explored the effects of a single session of such NFT or examined the possible mechanisms underlying these effects on sports performance. This study recruited 44 professional golfers to address these gaps in the literature. A crossover design was employed to determine the order of the participation in the NFT and no-training control conditions. The participants were asked to perform 60 10-foot putts while electroencephalograms (EEGs) were recorded before and after the tasks. In pre-and post-tests, visual analog scales were used to assess the psychological states associated with SMR activities including the levels of attention engagement, conscious motor control, and physical relaxation. The results revealed that a single NFT session effectively increased SMR power and improved putting performance compared with the control condition. The subjective assessments also revealed that the participants reported lower attention engagement, less conscious control of the motor details and were more relaxed in the putting task, suggesting that SMR NFT promoted effortless and quiescent mental states during motor preparation for a putting task. This study aligns with theoretical

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hypotheses and extends current knowledge by revealing that a single session of SMR NFT can effectively enhance SMR power and improve putting performance in professional golfers. It also provides preliminary evidence of the possible underlying mechanisms that drive the effect of SMR NFT on putting performances.

KEYWORDS
EEG, neurofeedback training, professional golf putting, sensorimotor rhythm, sports performance

1 | INTRODUCTION

1.1 | The importance of psychological factors for putting performance

Mental regulation can mean the difference between superior and inferior performance in precision sports activities such as golf putting. Putting is one of the most important determinants of golf scores at the elite level as approximately 43% of shots in an official golf game are putts.[1] Putting ability is also the most important skill in determining Professional Golfers' Association Tour earnings.[2] Although putting is a fundamental skill for professional golfers, the probability of achieving a one-putt hole at the median distance of 8–10 feet is <50%.[3] In addition, putting is a more mentally demanding task than other golf skills such as driving.[4] According to the psychomotor efficiency and neural proficiency hypotheses,[5,6] efficient cognitive states during motor preparation for a task are important psychological constructs that can promote superior precision sports performance (e.g., putting or shooting) of highly skilled athletes. In these mental states, the association areas of the cerebral cortex become progressively quiescent, minimizing interference with the motor control processes that are responsible for the intended cognitive-motor behaviors.[6,7] Therefore, it is necessary to find effective ways to assist professional golfers in maintaining these adaptive neurocognitive states during motor preparation for a putting task. The results of this research hold practical application for golfers and athletes in other precision sports.

1.2 | SMR and precision sports performance

Electroencephalography (EEG) is a valid tool for assessing the neural activity associated with different mental states during sports performance.[8] Sensorimotor rhythm (SMR) activity, which is considered an important EEG frequency band for motor performance, is measured over the central cortical regions and is employed to assess neural activity during motor preparation for precision sports performance.[9] SMR is expressed as a 12–15-Hz oscillatory time series that is inversely related to sensorimotor cortical activity[10] and is indicative of refined attentional states that yield minimal interference of somatosensory information with essential task-related neuromotor processes through the ventrobasal thalamus.[11] A study of expert and novice dart players (i.e., between-subjects design) revealed that SMR power during the preparatory period prior to throwing a dart was higher in expert dart players than in novice players.[12] A related comparison of experts' optimal and suboptimal performances (i.e., within-subject design)[13] revealed that higher SMR power was associated with more accurate shooting performance in highly skilled marksmen. These findings were supported by a recent golf-putting study,[14] which revealed that highly skilled golfers exhibited higher SMR power during preparation for successful putts than in their preparation for unsuccessful putts. These findings suggest that higher SMR power is associated with less neural noise in the essential neuromotor processes, which, in turn, results in optimal aiming-related task performance.

1.3 | Neurofeedback and precision sports performance

EEG-neurofeedback training (NFT) is an appealing technique for regulating such adaptive mental states by modulating EEG oscillations directly, and it has been shown to facilitate both cognitive and sports performance.[12,15,16] EEG-NFT consists of a set of procedures and provides individuals with real-time feedback on their cerebral cortical activity via sounds and/or visual displays. Cheng et al. (2015)[12] reported that highly skilled golfers improved their putting performance and attendant SMR power following eight sessions of SMR NFT. Recent studies have examined the effects of a single session of EEG-NFT on precision sports performance,[17–19] as this technology enables athletes to regulate their mental states in order to achieve optimal performance. Research on this process has many potential applications in the field of sports science. The results from previous studies suggest that EEG theta activity in the prefrontal cortex (i.e., frontal midline theta, Fmθ), which comes from the anterior cingulate gyrus or is related to prefrontal cortex activities,[20] is related to mental effort[21] and the process of top-down volitional control.[22] Chang, Huang & Hung (2020)[23] appear helpful as it was found that high-skilled golfers demonstrated lower Fmθ power before a superior putting performance, suggesting that lower working memory load and a reduction in top-down attentional control were conducive to sports performance.[24] In a neurofeedback study, Kao et al. (2014)[18] trained three professional golfers to reduce their frontal midline theta (4–7 Hz) power and demonstrated that a single session of EEG-NFT could change EEG activity in the resting condition and was associated with improved golf-putting performance. However, the effect of single sessions of NFT on precision sports performance, particularly in professional athletes, has not been determined because of methodological limitations in previous studies. First, most of these studies employed non-randomized trials so allocation bias may have affected the estimation of the intervention effect. Second, random errors, including individual and measurement variations, may have resulted in imprecise intervention effects. For example, the lack of a task familiarization step in the experimental procedures may have increased measurement variations during a formal test, potentially reducing the likelihood of detecting meaningful changes in performance that reflect the effects of NFT. Specifically, the lack of such a task familiarization step in the experimental procedures may have increased random fluctuations in a normal task making it impossible to determine whether the changes in performance reflect meaningful effects of the NFT. Third, the psychological measurements associated with the functionality of EEG indices have not been properly assessed. Previous studies have exclusively focused on one psychological measurement, such as attention engagement, to understand the effects of NFT on mental processing during motor preparation.[11,25–27] As EEG indices are associated with diverse mental states, it is necessary to consider multiple states to clarify the psychophysiological effects of NFT. Finally, most of the studies examined participants who did not perform at expert or professional levels of skill. As highly skilled individuals have different neural characteristics during superior performance than less skilled individuals,[28] the findings of previous studies may not be generalizable to professional athletes. Accordingly, examining the effects of a single session of SMR NFT on professional golfers' putting performance in a well-designed study design is necessary and is a useful effort as athletes at that level of skill may benefit in a compelling manner from mental training since they have acquired the requisite set of skills and are poised to achieve optimal performance.

This study addressed the limitations discussed above as follows. First, strict randomization procedures were employed to reduce undesired biases that might contaminate the intervention effects. Second, the effects of random variations were reduced through the use of a within-subjects design and a task familiarization step to isolate the hypothesized treatment effects. Third, this study measured the levels of attention engagement,[11] conscious motor control,[27] and relaxation,[25,29] which comprise psychological states conceptually associated with SMR. Assessment of multiple subjective measures was instrumental in identifying the possible psychological mechanism linking SMR NFT to improved putting performance. Finally, the study recruited a necessary number of professional-level golfers to ensure sufficient statistical power. Taken together, this study examined the effects of a single session of SMR NFT on the putting performance of highly skilled golfers with attention to the control of competing influence.

1.4 | Research hypotheses

As such, the aim of this study was to examine the effects of a single session of SMR NFT on the putting performance of professional golfers. The hypotheses were as follows. Hypothesis 1: Following a single session of SMR NFT, professional golfers would demonstrate better putting performance, including a higher probability success rate and lower mean absolute error from the hole, than that associated with the no-training control (CON) condition. Hypothesis 2: Following a single session of SMR NFT, professional golfers would exhibit higher SMR power during motor preparation for a putting task than in the CON condition. Hypothesis 3: Following a single session of SMR NFT, professional golfers would exhibit improved scores on some of the psychological measures associated with SMR functionality (i.e., lower attention engagements and conscious motor processing and higher physical relaxation) relative to those associated with the CON condition.

2 | METHODS

2.1 | Participants

Forty-four professional golfers were recruited for this study (20 female, mean age = 26.83 ± 3.87 years). Their mean handicap and best round handicap were 0.44 (SD = ±2.14) and − 5.75 (SD = ±2.43), respectively. This sample size was determined by a priori power analysis. A previous study revealed a medium effect (Cohen's d≈0.462 covered from

$\eta^2 = 0.176$) of SMR NFT on precision sports performance[12*]; However, that study tested the effect of eight sessions of NFT, whereas this study examined the effect of a single session. Based on this effect size, the power analysis indicated that a sample size of 39 would be adequate to achieve a power estimate of 0.8, assuming $\alpha = 0.05$. On the assumption that 10%–20% of the participants would drop out or be excluded from the analysis due to EEG quality, 44 participants were recruited to ensure that the final sample size was adequate. All of the participants met the following criteria: (1) right-handed, (2) no history of mental and neurological disorders, and (3) Professional Golf Association of Taiwan or Ladies Professional Golf Association of Taiwan members (identification of professional golfers). The men held a handicap of less than eight in a 4-day competition, and the women needed to have a handicap of less than 12 in a 3-day competition. They all voluntarily participated in this research and understood the procedures. All of the participants provided informed consent that was approved by the Ethics Review Committees of National Taiwan Normal University.

2.2 | Measures

2.2.1 | Golf-putting task performance measure

The putting task protocol was developed by Chueh et al. (2022).[30] The participants performed a putting task in an indoor artificial golf green (572 cm × 200 cm). The hole diameter conformed to the standard size (10.8 cm). The distance between the starting point and the hole was 10 feet (3.05 m). This distance was based on typical golf games and putting performance in the Professional Golfers' Association Tour.[3] In official competitions, a golfer's primary goal is to help the ball roll into the hole and the average one-putt probability (success rate) of professional golfers at 10 feet is 40% in the Professional Golfers' Association Tour.[3] This distance challenges performance due to its medium difficulty. To better mimic real matches, putting task variability was introduced by instructing the participants to putt from three different starting lines,[†] separated by 25 cm, at their own pace. Their objective was to putt the ball into the hole. The putting performance measures, used to test Hypothesis 1, consisted of successful putts and absolute errors, which were defined as the number of balls going into the hole and the average distance between the ball and the hole in unsuccessful putts, respectively. The absolute error per putt was measured with a tape measure by a researcher.

2.2.2 | EEG recording

Electroencephalograms (EEGs) were recorded at 36 sites using an elastic electrode cap (Quick-Cap; Compumedics Neuroscan, Inc.). As specified in the modified International 10–20 System,[31] continuous EEG recordings used the left (A1) and right mastoids (A2) as the average reference, and the FPz site was used for the ground electrode. Vertical and horizontal electrooculograms (EOGs) were collected in bipolar configurations located superior and inferior to the right eye and to the left and right orbital canthi. EEG and EOG signals were sampled at 1000 Hz, using Neuroscan Nuamps and NeuroScan software, version 4.5 (Neuroscan), with a bandpass filter setting the DC to 400 Hz. All of the electrodes were kept with impedances <10 kΩ before data collection. To accurately measure the cognitive states before putting to test hypothesis 2, an infrared sensor was connected to an amplifier. When the participants moved the putter away from the ball to initiate a backswing, the event-marker data were initiated via an infrared sensor that detected the swing onset for each putt.

2.2.3 | Attention, control, and relaxation measures

To test Hypothesis 3, this study employed the visual analogue scale[32] (VAS) to assess three psychological states related to SMR function (attention engagement, conscious motor control, and physical relaxation) during the golf-putting task before and after NFT. The VAS scale was administered after each round (10 balls), and the participants provided the scores verbally without handwriting. Therefore, there were 18 rounds of VAS scores in one condition including pre-test, training/no training, and post-test. The measurements consisted of an 11-point Borg scale, ranging from 0 (not at all) to 11 (very much).[7‡] This measurement method was chosen to understand the effect of NFT on these three subjective feelings. We expected that in the post-NFT measures, the subjective feelings of attention and control

*Cohen's $d = \sqrt{\eta^2}/1 - \eta^2$

[†]The golfers adhered to the same order for every block of putts, maintaining consistency throughout the experiment.

[‡]For instance, in the question regarding degree of motor control, higher scores indicated a stronger inclination among participants to actively control their movements *before the backswing*. On the contrary, lower scores reflected a reduced level of conscious control over these details before the backswing, implying a decrease in control over the course of movement.

would be decreased and the degree of relaxation would be increased. This study employed the same scales as a manipulation check to provide an unobtrusive self-report measure. Specifically, the participants were asked to report the level of attentional focus before the backswing (e.g., How focused are you on movement execution before backswing?), degree of motor control (e.g., How much do you actively control the details of movement or movement adjustment before backswing?), and the level of relaxation before the backswing (e.g., How do you feel your body relaxes before backswing?). In addition, self-report measures were administered in the training session to assess participants' compliance with our instructions. First, participants were asked to report how they were focused on learning to control their brain's SMR activity before the backswing. Secondly, they were asked to assess how well they controlled the sound of neural feedback before the backswing. Thirdly, they were asked how they felt about body relaxation before the backswing. As a manipulation check, we expected that participants would demonstrate higher levels of these three subjective measures in the NFT condition relative to the CON condition, which would provide evidence that all of the participants had followed the instructions during the training session.

2.2.4 | Feeling measurement

As emotion could have influenced the focal relationship in this study, we measured it using the feeling scale (FS). In this part, the question was as follows: How do you feel before the backswing? The FS[33] subjectively assessed affective valence in the pre-test, training session, and post-test. It is a single-item indicator of affective valence scored on an 11-point scale (from −5 ["unpleasant"] to +5 ["pleasant"]). Time points were the same as attention, control, and relaxation. FS measurements were taken after each putting block (every 10 balls) throughout the study, including pre-test, training, and post-test. This resulted in a total of 36 scores collected. In other words, we measured VAS in all three dimensions and FS after every putting block (every 10 balls). We expected no significant differences in the FS scores between the NFT and CON conditions, which would support that the improved putting performance was not attributed to affective-related factors.

2.2.5 | NFT device and software

We monitored the SMR value, as an indexed objective manipulation variable, during NFT to confirm the effectiveness of our intervention. The ProComp5 Infiniti system physiological feedback trainer, produced by Thought Technology Ltd. of Montreal, Canada, was employed as the neurofeedback device. The BigGraph Infiniti editing program package was employed as the training program software to achieve a training instrument that allowed golfers to monitor their brain wave activity. The software was installed on a laptop computer, and the device was attached to the back of the participant's waist in the intervention conditions. One electrode was placed at Cz for SMR training, and references were placed on both ear mastoids. The device captured the change in the targeted EEG index and provided immediate auditory feedback when the participants reached the targeted values. The measurement device did not interfere with the golfers' putting as it was connected to the computer via a wireless Bluetooth connection.

2.2.6 | Credibility and expectancy

The modified credibility and expectancy questionnaire contains six questions that measure attitudes to treatment.[34] As this study employed a no-training control condition rather than a sham control, these results were used to assess the placebo effects of NFT on putting performance. Before each post-test, the participants in both the NFT and CON conditions were asked six questions about what effects they expected. The average scores of the first and last three questions were indexed as the credibility and expectation scores for each experimental condition, respectively. We expected no significant difference in the credibility and expectation scores between the two conditions, which would indicate that the placebo effects were controlled. The scale ranged from 0 (not at all) to 9 (very much). The first to fourth questions ascertained how the golfers "thought" about all the introductions and instructions given by the experimenters spanning the entire period from arriving at the laboratory to finishing the training, whereas the fifth and sixth questions ascertained how they "felt" about the NFT and its likely success after closing their eyes for a few moments. The six questions were as follows: (1) Do you think the training you have received is logical? (2) Do you think this training will reduce your putting errors? (3) Would you recommend this training method to friends who have similar problems? (4) At the end of the training, how much improvement in your putting performance do you think? (5) Do you feel this training will reduce your putting errors? (6) At the end of the training, how huge an improvement in your putting performance do you feel?

2.3 | Experimental procedure

This study employed a two-arm randomized crossover design to assess the effects of NFT on putting. The participants were randomly assigned to order A (participate in the NFT condition first and then participate in the CON condition) or order B (participate in the CON condition first and then participate in the NFT condition); the groups were stratified by sex. The random sequence was generated by a colleague who had no direct contact with any participants. To ensure that similar numbers of participants of different sexes were assigned to each sequence, block randomization was performed.[35] All of the random numbers were generated by Excel 2019 (RAND function). The random numbers were concealed in opaque envelopes by a colleague and the main experimenter opened each of them on the first intervention day for each randomized participant to eliminate any bias from the random number generation and concealment processes.[36] That is, the researchers were blinded to the condition order until the first trial, and the participants were blinded to the trial condition order until the commencement of the second trial visit.

Figure 1 provides a flowchart of the experimental procedures. All of the data were collected within the artificial turf. The participants were required to participate in both conditions separated by at least 24 h. They were asked to refrain from drinking alcoholic or caffeinated beverages for at least 24 h before each session (NFT or CON). When the participants arrived at the artificial turf, a researcher provided a detailed presentation about the experimental procedures. The participants were provided an opportunity to ask questions about the experiment and were provided an informed consent form. The participants, who provided consent, were then fitted with a Lycra electrode cap (Quick-cap, Neuroscan, Charlotte, NC, USA) and a neurofeedback device (ProComp5 Infiniti system). After the participants' resting-state EEG data were recorded, they completed 20 practice putts before beginning the normal putting task (pre-test). The normal golf-putting task consisted of 60 self-paced trials in six separate blocks (10 putts for each block) during which their EEGs were recorded. After a 10-min rest, the participants were assigned to either the NFT or CON condition.

In the NFT condition, the participants focused on increasing their SMR above a specified threshold while repeating the putting task. The threshold was determined by the EEG data from each participant's best 10 balls during the pre-test. Specifically, the average of the SMR data in the 2-s period before the swing onset was employed as the designated threshold and the training target was −20% of the threshold. This adjustment was made to reduce the level of difficulty during the initial stages of training. To strengthen the effect of NFT on putting performance, a progressive increment of the training threshold was implemented. Specifically, an individualized standard deviation of the target threshold was employed to increase training difficulty if the targeted successful training rate was reached in one training block.[37] Success was defined as participants maintaining the power of SMR above the targeting threshold of 70% of the time during each training session. In addition, the information for the average percentage of success rate and target SMR power threshold for the first and the sixth round of the NFT condition was added to illustrate the magnitude of improvement the participants achieved.[§] This method was based on the findings of studies[12,18] on the optimal NFT protocols for improving cognitive-motor performance. Before starting the NFT, participants were instructed to recall their putting process in a standing position without putting. When the participant's SMR power exceeded the threshold, they received auditory feedback. To prevent the auditory feedback from being triggered by non-target activities, the participants were instructed to maintain a relaxed state and to initiate a backswing once continuous auditory feedback was presented. Specifically, the participants were instructed to determine factors that affected putting strategy (e.g., movement-related parameters) before taking the position for putting—for example, the grass pattern before the hole is reversed, so a little more force than usual is required; try to keep the muscles relaxed before putting, and reduce attention to detailed movement control; exert more force to putt than usual, or pay attention to the height of

FIGURE 1 Experimental procedures.

hand swings, etc. When the sound feedback lasted for 2s, the golfer was to perform the put.

Participants were also instructed to ignore the sound of the feedback once they initiated the backswing. The pre-test, training, and post-test each consisted of 60 self-paced putts in six separate blocks. The participants were allowed to rest briefly between each block and were asked about their subjective perceptions of the three dimensions of the VAS, including attention, control, and relaxation. To strengthen the effect of NFT on putting performance, the progressive adjustment of the training threshold was implemented. That is, an individualized standard deviation of the target threshold was used to adjust training difficulty upward if 70% of the successful training rate, defined as 70% above the threshold, was reached in one training block.[37] The procedures of the CON condition were similar to those of the NFT condition but without the specific instructions before the self-paced putting training or feedback during putting; that is, the participants were instructed to perform their normal putting routine during the CON condition. Although some NFT studies have employed a sham-control condition (i.e., false feedback) to eliminate the placebo effects, this was not suitable for this study. Specifically, the recruited participants as professional players participate in official games that impact their livelihood. False feedback can result in undetermined effects negative effects on their subsequent performance, and thus, such a research design is ethically problematic.[38] In addition, false feedback may cause additional confounders, which could interfere with the isolation of hypothesized intervention effects. Finally, the participants answered a credibility/expectancy questionnaire before the post-test (a 60-ball putting task).

2.4 | EEG data processing

The EEG data were processed using MATLAB 2018b (academic version) and EEGLAB v2022.0.[39] The preprocessing pipeline was as follows.

(1) The EEG data were imported into a MATLAB workspace. (2) The data were referenced to the averaged mastoids (M1 and M2) using the EEGLAB function *pop_reref*. (3) The continuous EEG data were filtered using a 60-Hz notch filter (*pop_basicfilter*) and a digital bandpass of 1 and 40 Hz (6 dB/octave) with an FIR filter (*pop_eegfiltnew*) to remove line noise and slow drifts, respectively. (4) The EEG data were kept at −3 s and + 1 s of the swing onset (0 s) to ensure that the independent component analysis (ICA) computation was restricted to task-related activity. (5) Noisy channels were removed using the EEGLAB function (*pop_rejchan*) at the default settings (normal distribution and kurtosis, criteria: ±5 SD). The average numbers of bad channels rejected were similar for all the conditions (NFT pre-test = 0.4 ± 0.6, NFT post-test = 1.2 ± 0.6, CON pre-test = 0.5 ± 0.9, and CON post-test = 0.4 ± 0.7). (6) ICA decomposition was performed using the extended infomax algorithm to extract sub-Gaussian components using the default settings in EEGLAB with the block size heuristic (floor[sqrt(EEG.pnts/3)]). (7) Following ICA decomposition, the ICLabel classifier method from the EEGLAB plugin function[40] was used to remove eyeblink ICA components. The average number of ICA components removed was 1.1. (8) After removing the eyeblink artifact components, the rejected channels were interpolated using a spherical method. After this, the continuous EEG data were segmented into −2 s of the swing onset. Two participants were excluded from the following analysis as 50% of their epochs were rejected. Epochs were rejected for the following reasons. Epochs with amplitudes outside the range of ±150 μV were discarded. The mean number of artifact-free epochs for each condition was between 55.7 and 59 (NFT pre-test = 59 ± 9.2, NFT post-test = 56.9 ± 8.4, CON pre-test = 57.1 ± 5.4, and CON post-test = 55.7 ± 5.4). Finally, artifact-free epochs were fast Fourier transformed with a Hanning window to compute the spectral power of each frequency band within each 0.5-Hz bin. To test Hypothesis 2, the SMR power was extracted from the data in the 12–15-Hz range in the central scalp regions (Cz and CPz). The SMR power data were then naturally log-transformed (ln), as they violated the Shapiro–Wilk normality test ($p < 0.05$).

2.5 | Statistical analysis

(1) Manipulation Check Variables. Paired t-tests were performed separately to determine the differences in the changes in SMR power (the change score [Δ] was training session data minus pre-test data) between the two conditions. In addition, t-tests of the direct SMR results in the two experimental conditions were conducted, as well as tests of the differences in levels of attention engagement, conscious motor control, physical relaxation, FS, and credibility/expectancy.

(2) Dependent Variables. To test Hypothesis 1, the changes in putting performance (change [Δ] was post-test minus pre-test scores), including the percentage of successful putts and absolute error, were analyzed separately using paired *t*-tests. To test the intervention effects posited in Hypothesis 2, differences in the changes in putting states SMR power between the two conditions were assessed using paired *t*-test. To test Hypothesis 3, changes in attention engagement, conscious motor control, and physical relaxation were analyzed separately using paired *t*-tests.

SPSS 26.0 (IBM) was employed to perform all of the statistical analyses. To reduce Type I error inflation from the factors (familywise Type I error) (Luck & Gaspelin, 2017) and eliminate day-to-day fluctuations, this study decreased the time factor by subtracting pre-test data from the post-test or training session data (change scores). Thus, a paired t-test was employed rather than a two-way (time by conditions) analysis of variance (ANOVA) to determine the effects of a single session of SMR NFT on the outcomes of interests. To estimate the effect size, Cohen's d ($d = t/[\sqrt{n}]$) was used. An alpha level of 0.05 was used as the significance level.

3 | RESULTS

3.1 | Manipulation check

In the objective manipulation measurement, there was a significant difference ($t = 3.367$, $p = 0.002$) between the NFT and CON conditions in Δ SMR power during the training session (NFT $= 2.14 \pm 3.93$, CON $= -0.02 \pm 0.9\,\mu V^2$). In the subjective manipulation measurement, the participants were more engaged in maintaining a quiescent state (NFT $= 7.28 \pm 2.2$ points, CON $= 1.41 \pm 1.47$), reported a higher ability to control this regulation (NFT $= 6.71 \pm 2.35$ points, CON $= 1.39 \pm 1.5$), and expressed higher physical relaxation (NFT $= 6.65 \pm 2.31$ points, CON $= 4.61 \pm 2.28$) during the NFT training session than they reported in the CON session. There was also a significant difference between the two experimental conditions ($t = 2.289$, $p = 0.027$) in Δ FS (NFT $= 2.32 \pm 1.71$ points, CON $= 1.89 \pm 1.89$ points).

With regard to the credibility/expectancy questionnaire, neither belief ($t = 1.596$, $p = 0.118$) nor expectation ($t = 1.761$, $p = 0.085$) was statistically different between the NFT (belief $= 7.99 \pm 1.1$, expectation $= 7.11 \pm 1.75$) and CON (belief $= 7.8 \pm 1.21$, expectation $= 6.87 \pm 1.67$) conditions.

3.2 | Putting performance

Analysis of the changes in successful putts revealed a statistically significant difference between the two conditions ($t = 3.514$, $p = 0.001$, $d = 0.53$). The participants exhibited greater improvement in successful putts following the NFT (6.86 ± 7.78 balls) session than following the CON session (-1.07 ± 11.93 balls) (see Figure 2)[¶] For the change in absolute error, there was a statistically significant difference between the two conditions ($t = -2.605$, $p = 0.013$, $d = -0.39$). The change in absolute error was smaller after the CON session (1.36 ± 6.36 cm) than after the NFT session (-3.5 ± 9.32 cm), resulting in a less absolute error in the NFT session (see Figure 3).

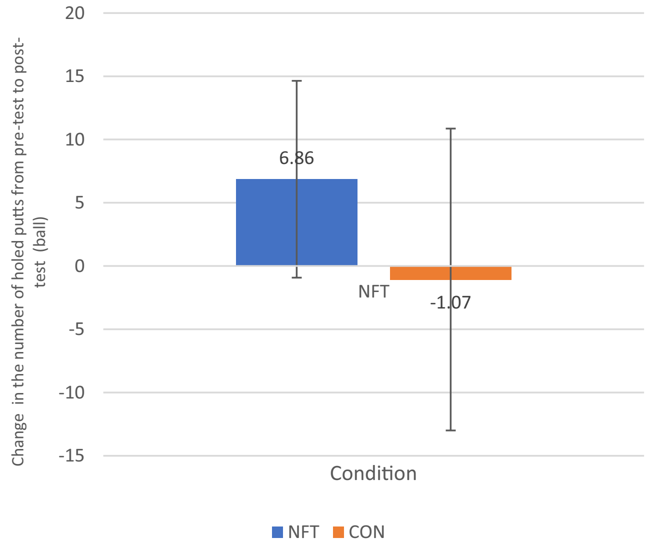

FIGURE 2 Changes in successful putts in the NFT and CON conditions.

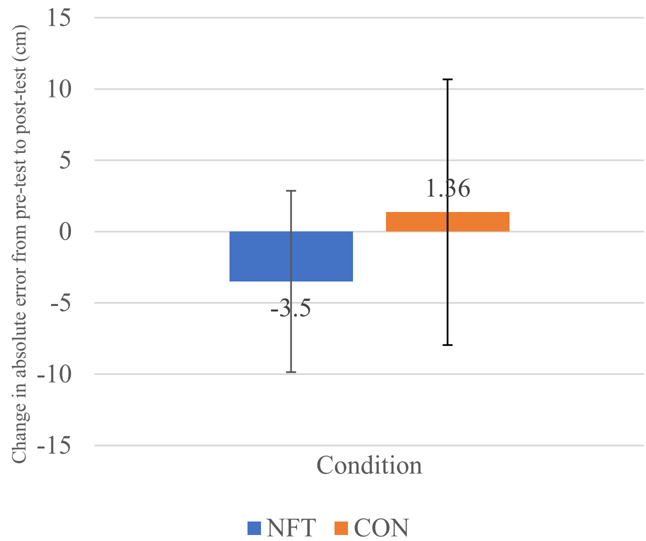

FIGURE 3 Changes in the absolute error in the NFT and CON conditions.

3.3 | Putting-state SMR power

The changes in SMR power were significantly higher in the NFT condition than in the CON condition ($t = 3.354$, $p = 0.002$, $d = 0.52$). The changes in SMR power were $0.45 \pm 0.68\,\mu V^2$ in the NFT condition and $0.08 \pm 0.24\,\mu V^2$ in the CON condition (see Figure 4).

[¶]Regardless of condition sequence (NFT-CON or CON-NFT), the participants exhibited greater improvement in successful putts following the NFT session compared to the CON session (NFT-CON: $t = 2.421$, $p = 0.025$ or CON-NFT: $t = 2.244$, $p = 0.036$.). This finding suggests that carryover effects were unlikely to be the explanation for the observed effect in the present study.

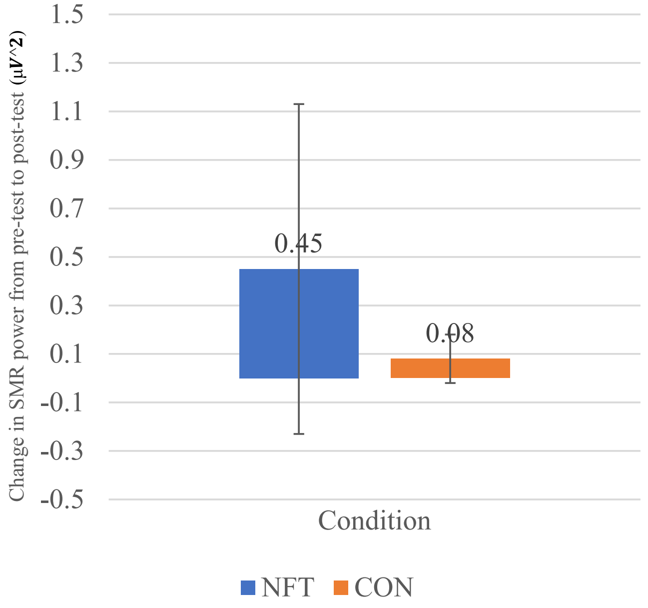

FIGURE 4 Changes in SMR power in the NFT and CON conditions.

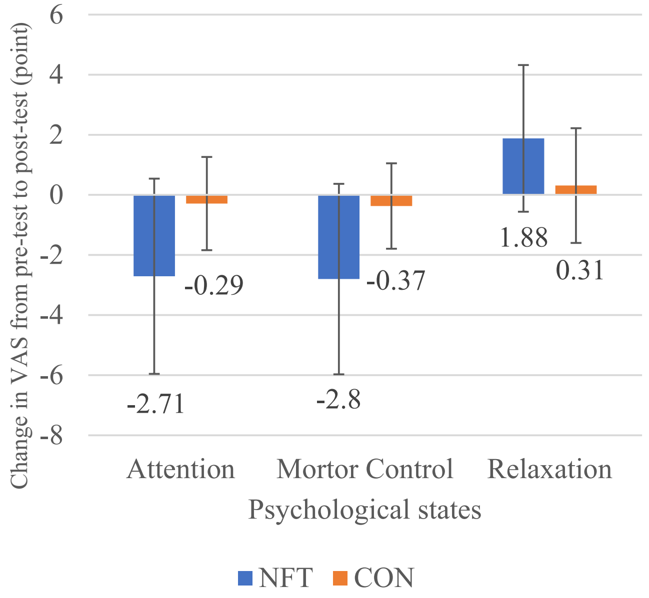

FIGURE 5 Changes in psychological states in the NFT and CON conditions.

3.4 | Psychological states

For the changes in attention engagement, there were statistically significant differences between the NFT and CON conditions ($t=-4.331$, $p<0.000$, $d=-0.65$). The participants' attentional engagement in putting tasks decreased by a larger amount in the NFT condition (decreased by 2.71 ± 3.25 points) than in the CON condition (decreased by 0.29 ± 1.55 points). There were statistically significant differences in the changes in conscious motor control between the two conditions ($t=-4.398$, $p<0.000$, $d=-0.66$). The participants in the NFT condition demonstrated a greater decrease in investment in movement adjustment or movement detail (-2.8 ± 3.17 points) than those in the CON condition (-0.37 ± 1.42 points). There was a statistically significant difference in the changes in physical relaxation between the two conditions ($t=3.074$, $p=0.004$, $d=0.46$). The participants in the NFT condition demonstrated a larger increase in relaxation (1.88 ± 2.44 points) than those in the CON condition (0.31 ± 1.91) (see Figure 5). There was a significant difference in the changes in FS between the NFT and CON conditions ($t=4.581$, $p<0.001$) (NFT $=0.73 \pm 0.97$ points, CON $=-0.13 \pm 0.85$ points).

3.5 | Control analyses

3.5.1 | Frequency specificity

To demonstrate the frequency specificity of our results, we further analyzed different frequency bands in the central regions (Cz and CPz) such as the theta (4–7.5 Hz), low-alpha (8–10 Hz), and high-alpha (10–12 Hz) bands. The statistical analyses were identical to those used to examine the SMR power of putting states. There were no significant differences in the above EEG indices, except for the high-alpha measure, between the experimental conditions. The changes in high-alpha power were significantly higher in the NFT condition than in the CON condition ($t=3.354$, $p=0.002$, $d=0.52$).

3.5.2 | Regional specificity

To demonstrate the regional specificity of our results, we further analyzed the 12–15 Hz band in the frontal (Fz and FCz), central (Cz and CPz), and parietal (Pz) regions. To increase the contribution of local electrical activities and reduce the effect of distal volume-conducted sources,[41,42] the EEG data were transformed using a spherical spline surface Laplacian algorithm[43] via the current source density (CSD) toolbox function[44] (smoothing constant lambda $=10^{-5}$; spherical spline order $=4$). The statistical analyses were identical to those used in the main analysis of SMR power. The results demonstrated the regional specificity of SMR power, indicating that the only significant difference in the changes in SMR power between the NFT and CON condition was identified in the central SMR, which was significantly higher in the NFT condition than in the CON condition (t $(41)=2.147$, $p=0.038$, $d=0.33$). As CSD transforming data changed the unit of measurement from μV to μV/cm^2 (10-cm head radius), the unit of the CSD-transformed alpha power was μV^2/

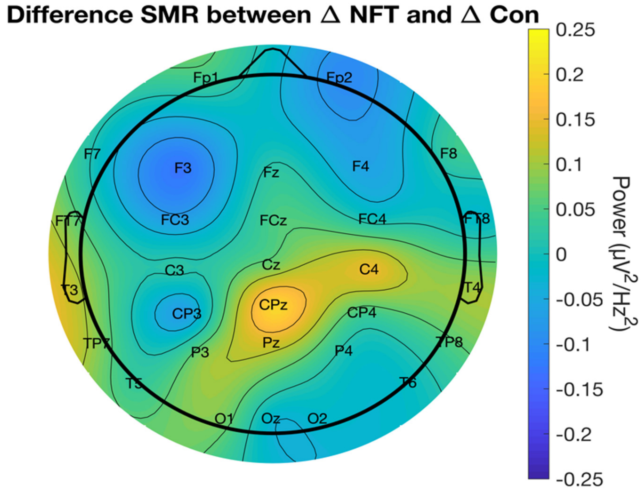

FIGURE 6 Topographic maps of SMR power.

cm^2.[44] The topographic maps of SMR power are presented in Figure 6.

4 | DISCUSSION

This study investigated the effect of a single session of SMR NFT on professional golfers' putting performance. To test the effectiveness of a single session of SMR NFT and the possible underlying mechanism of improved putting performance, SMR power, and various psychological states associated with the functional meaning of SMR in the NFT and CON conditions were examined. A single session of SMR NFT significantly improved professional golfers' putting performance compared with the no-training CON condition. Correspondingly, there was a significant increase in SMR power during motor preparation for the putting task in the NFT condition. In addition, the participants exhibited lower attentional engagement, and less conscious control over motor details and were more relaxed in the NFT condition than in the CON condition. This study provides preliminary evidence that a single session of SMR NFT can improve the putting performance of professional golfers and employs a psychophysiological perspective to identify a possible mechanism for the effect of SMR NFT on putting performance.

4.1 | Putting performance

In support of Hypothesis 1, the results of this study revealed that professional golfers' putting performance improved after a single session of SMR NFT; the participants in this condition exhibited higher success rates and lower absolute distances from the hole than those in the CON conditions. Although previous studies have demonstrated that a single session of NFT is effective in improving precision sports performance in both pre-elite athletes and novices,[17–19,45] none of the studies focused on professional athletes and thus had limited generalizability to those characterized by expert performance. In the present study, all of the recruited participants were professional golfers who had achieved a competitive score in an official examination (e.g., total putts were less than 296 in a 4-day test session on a 72-par golf course for males). Therefore, the results of this study extend current knowledge by providing further evidence of the positive effects of a single session of SMR NFT on shots performance in those at the highest levels of skill (i.e., professional athletes). To provide a persuasive estimation of the effects of a single session of NFT on sports performance, this study adhered to strict randomization procedures and included a task familiarization step before the putting task to minimize undesired biases and reduce measurement errors, respectively. In addition, a sufficient number of participants was recruited to obtain adequate statistical power and assess the levels of motivation and belief in both the NFT and CON conditions using the credibility and expectancy questionnaire to account for possible placebo effects. Therefore, the study results, supported by a rigorous study design, suggest that a single session of SMR NFT can improve precision sports performance in professional golfers.

4.2 | SMR

In support of Hypothesis 2, a single session of SMR NFT significantly increased the SMR power during the preparatory periods before swing initiation in professional golfers. This finding is consistent with a recent NFT study, which demonstrated the effectiveness of a single session of NFT for reducing FMT power in the preparatory period,[17] but is not consistent with another study that did not observe a significant change in FMT power.[18] The discrepancy may be attributed to the training instructions. Specifically, Kao et al. (2014)[18] did not provide the participants with a specific cognitive strategy for regulating FMT power. Furthermore, a single session of NFT may be less effective for inducing changes in FMT power than for inducing changes in SMR power because the participants may be unsure of what to do during the EEG-NFT. In contrast, Chen et al. (2022)[17] offered function-directed instructions for reducing the FMT power and achieving an optimal mental state. Function-related instructions are an appealing way to facilitate the learning efficacy of NFT, allowing researchers to consider the functional significance of the brainwave and avoid interference with target-irrelevant brain activity.[46] This study employed training instruction associated with the functionality of the targeted EEG markers to help the participants effectively modulate SMR power. As an elevation in SMR has been associated with refined mental states, we instructed the participants to gradually decrease their attention on the core activities during motor preparation and to increase their physical relaxation; these activities reduce the SMR power and help the participants achieve the desired mental states. The success of the training instructions was supported by the manipulation, which indicated that participants exhibited greater SMR power and higher adherence to instructions in the NFT condition than in the CON condition. In addition, this study apparently improved on previous study designs by using a crossover randomized controlled trial design that provided better control of biases. According to the advanced psychomotor efficiency hypothesis, experts' superior cognitive-motor performance is characterized by refined cognitive states that decrease neuronal activities in the motoric association areas that underlie the intended act of motor behaviors.[6] Higher SMR power reflects the inhibition of sensorimotor cortex activity[47] (Mann et al., 1996), and the results of this study indicate that the effect of NFT on SMR is central region-specific. Accordingly, our findings verify the causal relationship between SMR power and precision sports performance and support the psychomotor efficiency hypothesis.

Another element of the study worthy of discussion is there was a significantly greater increase in central high-alpha power after the NFT condition than the CON condition. The results from this study differ from previous studies, which associated reduced pre-movement high-alpha power at Cz with superior performance.[48–50] The discrepancies in these results might stem from the distinct cognitive processing underlying superior cognitive-motor performance. EEG alpha power represents an inhibitory function[51] as it controls information through gating by inhibition and guides information to key brain areas by inhibiting the processing of non-key brain areas.[52] In particular, low-alpha is associated with general arousal, while high-alpha pertains to task-specific processing.[53] As such, the significantly reduced high-alpha power before putting in golfers in previous studies[48–50] suggests that the activation of brain regions related to motor planning, such as the force and direction of a putting. In contrast, our finding of increased high-alpha power after NFT implies that these professional golfers allocated fewer neural resources for planning ball control. According to the multi-action plan (MAP) model,[5] superior sports performance can be characterized by two states: an optimal-automatic state (Type 1) and an optimal–controlled state (Type 2). In the Type 1 state, athletes operate in an efficient cognitive state, rendering their movements both effortless and autonomous with minimal cognitive engagement. In contrast, the Type 2 state involves more selective cortical activation due to the cognitive processing required for the action. Bertollo and colleagues also proposed that alpha event-related synchronization (increased alpha power) and desynchronization (decreased alpha power) are linked to Type 1 and Type 2 states, respectively (Bertollo et al., 2016).[5] In the current study, to effectively regulate the neurofeedback tone, participants were instructed to focus less on movement details or movement adjustments and more externally instead, such as on the target hole, before the backswing. This suggests that our instructional strategies seem to promote the Type 1 MAP state by emphasizing minimal conscious control and heightened relaxation, while the golfers in previous studies might relied more on Type 2 to carry out the task. Nonetheless, such an explanation needs follow-up research to verify.

4.3 | Psychological states

Another contribution of this study was the investigation of the three psychological states associated with the functional meanings of SMR. Our findings support Hypothesis 3. Specifically, after a single session of SMR NFT, the participants exhibited effortless attention engagement and less involvement in motor control and their bodies were more relaxed when they executed the intended actions. The results extend the finding of previous studies, which were not conducted in sports contexts, of the association between psychological states and SMR.[11,25–27] Although previous studies have considered psychological states as possible mechanisms underlying the link between SMR and superior sports performance, few studies have directly measured the combination of psychological states employed here. This study examined the rating scale of Fronso et al. (2016)[7] to query participants about their psychological states including attentional engagement, conscious motor control, and physical relaxation during the preparatory periods of the putting task. After one NFT session for elevating SMR during motor preparation, professional golfers improved their putting performance by allocating attention efficiently, reducing the intention to monitor movements, and increasing physical relaxation. In the theoretical framework of sports psychology, the psychological states underlying optimal sports performance are associated with effortless attention and automatic/effortless experience.[54,55] The present findings are consistent with the role of an optimal-automatic state proposed by the neural proficiency hypothesis developed by sports neuroscientists.[5] In an optimal-automatic state, athletes are in an efficient cognitive state in which movement is effortless. Thus, this study supports existing theoretical perspectives on stabilizing the psychological states that support superior sports performance in professional athletes through changes in SMR.

In addition, the purpose of FS measurement was to control the possible confounding effect of the affective state as a result of NFT. Although results showed an unexpectedly higher FS score in the NFT condition than in the CON condition, additional analysis revealed that there was no significant association between changes in FS scores and putting performance in the NFT condition ($r = 0.111$, $p = 0.494$). This finding suggests that even though golfers had better mood scores in the NFT condition, it was not related to their putting performance. Nonetheless, we suggest that in future studies, FS measurements could be paired with physiological measures such as heart rate variability to better understand the association between NFTs and emotional valence.

4.4 | Limitations and suggestions for future research

Some limitations should be acknowledged. First, as optimal psychological processes may vary between types of motor tasks and levels of skill development,[12,56–58] the training effect observed in this study may not be fully generalized to other sports or to players of different skill levels. Second, as the purpose of this study was to employ NFT to enhance SMR power, other EEG markers related to performance were not considered in the intervention and training. Third, long-term training, which leads to neuroplasticity and learning, is a different process than single-session training.[59] Therefore, the retention effect of a single session of NFT was not examined in this study. Fourth, EEG has a millisecond scale of temporal resolution but is limited by its spatial resolution[37] because scalp electrodes are distal from the source of the current and are likely to be affected by individual differences in scalp, skull, and cerebrospinal fluid. Nevertheless, this study employed a CSD analysis, which improved topographical localization and minimized volume conduction effects[42] to improve spatial inferences. Future studies are encouraged to develop methods to improve EEG spatial resolution, such as performing source imaging or combining EEG and functional magnetic resonance imaging for NFT in the motor domain.[60] Finally, several golf-related motor skills, such as driving, swinging, iron play, and chipping, are involved in typical performances and each skill has specific physical and psychological demands. Whether this study's findings on putting can be applied to other golf skills should be tested.

5 | CONCLUSIONS

The present study extends previous research by demonstrating the effectiveness of a single session of SMR NFT in regulating SMR during putting and revealing that such regulation improves putting performance in professional skill-level golfers. Furthermore, we found that the SMR NFT reduced attention engagement and investment in movement adjustment and increased physical relaxation, which may shed light on the psychophysiological mechanisms underlying the effect of SMR NFT on putting performance. These findings not only advance the understanding of how SMR NFT improves motor performance but also have important practical implications for the use of single-session NFT for top-tier athletes.

6 | PERSPECTIVE

Our results illustrated that a single NFT session effectively increased SMR power and improved putting performance compared to control conditions. The results of the subjective psychological assessment revealed that the participants exhibited lower attentional engagement, decreased conscious control of motor details during the putting task, and were more relaxed than after a control session. The psychophysiological perspective of this study provides initial evidence for possible underlying mechanisms driving the effects of SMR NFTs on putting performance. Providing more insight into the impact of NFTs on putting performance, the current findings have greater implications for shaping the putting ability of professional golfers. In addition, the study holds significant implications for the application of biofeedback and neurofeedback to highly skilled athletes in multiple sports disciplines that challenge concentration and precision movement.

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CONFLICT OF INTEREST STATEMENT

All authors declare that they have no conflicts of interest relevant to the content of this article.

DATA AVAILABILITY STATEMENT

Data available on request due to privacy/ethical restrictions.

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