

**THE SPORTS PERFORMANCE ENHANCEMENT BY USING THE
SENSORIMOTOR RHYTHM NEUROFEEDBACK TRAINING**

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CHAPTER 1
GENERAL INTRODUCTION

1.1. Neural Efficiency Hypothesis

The connection between neurocognitive activity and the behavioral outcomes can be addressed by the neural efficiency hypothesis. Neural efficiency hypothesis proposes that an efficient neural activity occurs while disengaging the irrelevant brain areas for a given task (Haier et al., 1992). In the sports domain, expert athletes develop a focused and efficient neural networks due to the extensive practice over a long period (Milton, Solodkin, Hluštík, & Small, 2007). This efficient neural network indicates the task-related mental processing, which helps the expert performers reach the superior performance.

Although the neural efficiency hypothesis has been supported by several studies (Babiloni, Marzano, Infarinato, et al., 2010; Del Percio, Babiloni, Marzano, et al., 2009; Guo, Li, & Yu, 2017), this hypothesis may need more replications to adequately account for the cortical processing when performing the sports performance (Poldrack, 2015). For example, a study conducted by Del Percio et al. (2008) showed that several factors could affect the neural efficiency, such as the type of sports, brain hemisphere or region, and even the side of movement (left, right). These concerns have been backed up by previous reports. For instance, Babiloni et al. (2008) showed that athletes showed the more complex integration of visual and motor processing when compared to non-athletes. In the same study, the more complex cortical activity was also observed in the personal best performance compared to the worst performance.

Moreover, an increased cortico-cortical communication between parieto-central and parietal-frontal brain regions was observed during the successful putts of elite golfers compared to the less successful putts in the golf putting task (Babiloni et al., 2011). These results suggest that the successful putts of elite golfers were related to more complicated neural processes. Hence, this evidence points out that the concept of neural efficiency remains in debate.

1.2. Psychomotor Efficiency Hypothesis

Psychomotor efficiency hypothesis describes the resource allocation between the behavioral outcomes and the neurocognitive processes (Hatfield, 2018; Hatfield & Hillman, 2001). The greater psychomotor efficiency refers to a refined set of inputs to the orchestration of neurocognitive processes in the brain to perform the intended action. That is, higher efficiency stands for less complexity in the cognitive processes related to the motor control and the neural networks (Hatfield & Hillman, 2001). Consequently, psychomotor efficiency hypothesis puts forward a more specific perspective to understand the cortical processing during the sports performance.

The understanding of psychomotor efficiency hypothesis could be investigated by the cortical activity in the sensorimotor cortex. A previous study suggested that the higher efficiency, as reflected by the reduced activation in the motor-related cortex, could be the product of improved processing of motor cortical synapses (Picard, Matsuzaka, & Strick, 2013). Similarly, the lowered activation in the sensory and motor cortex has been typified as a sign of the less complicated information processing during the motor tasks, (Naito & Hirose, 2014; Nakata, Yoshie, Miura, & Kudo, 2010). This evidence are in line with the findings in the experts in sports performance, showing that the reduced cortical activity was observed during the action preparation period (Hatfield, Landers, & Ray, 1984; Haufler, Spalding, Santa Maria, & Hatfield, 2000; Kerick, Douglass, & Hatfield, 2004; Landers, Han, Salazar, & Petruzzello, 1994; Loze, Collins, & Holmes, 2001; Salazar et al., 1990). The lower activation of the sensorimotor cortex might reflect a more elaborate psychomotor processing during sports performance. The reduced activity in the sensorimotor area has been associated with more consistency of the motor performance (Baumeister, Reinecke, Liesen, & Weiss, 2008; Gallicchio, Cooke, & Ring, 2017), suggesting that the refined processing in the sensorimotor area is related to the superior state of psychomotor efficiency in the sports performance.

However, the relationship between the specific cortical activity and psychomotor efficiency remains questioned in precision sports performance. For instance, Gallicchio et al. (2017) investigated the practice effects while recording the EEG in golf putting task. The recreational golfers demonstrated that the characteristics of the superior putting performance were associated with lowered activity in the temporal regions. This finding suggests that the superior putting performance was preceded by the reduced cortical activity in the irrelevant areas. However, increased activation in central regions was observed after the putting practices. The controversial findings regarding the significant activation in central regions might be a result of the skill level of the recruited golfers, as the average golf experience was 4.63 years compared with a similar study in learning (elite golfers with averaged 9.35 years experience in golfing). However, these findings raise concerns regarding the adaptive cortical activity of psychomotor efficiency.

To understand the psychomotor efficiency hypothesis in sports performance, the comparisons of the expert-novice and the optimal-suboptimal performance on the cortical activity may lend support to this understudied field. This research direction is in line with recent reports which examined the intra-individual comparisons and showing the subtle differences on cortical processing with athletes (Bertollo et al., 2013; Di Fronso et al., 2016).

1.3. Brain Activity and Sports Performance

The skilled performance is characterized by high levels of automaticity, minimum energy expenditure, and high consistency (Schmidt & Lee, 2014). For instance, the skilled performers are typified with the specialized cortical processing when performing a given task. This specialized cortical processing suggests that the skilled performers can reduce the task-irrelevant cortical activation and reduce the level of attentional control to achieve the skilled performance (Del Percio et al., 2011; Grabner, Neubauer, & Stern, 2006; Hatfield, 2018).

The distinction of the brain activity between experts and novices offers the insights in understanding the adaptive cortical processing. Compared to experts, the novices are typified by several characteristics in the cortical processing, such as more cortical resources flow into the verbal-analytic processing during motor preparation (Hatfield, Haufler, Hung, & Spalding, 2004; Haufler et al., 2000), more extensive spreading of brain activity during the action execution (Chang et al., 2011), and more taxing of the working memory, significantly monitoring on the somatosensory information (Loze et al., 2001; Schröter & Leuthold, 2009). Regarding the cortical activity in response-based tasks, novices were reported to be slower in stimulus detection and weaker in inhibition to the irrelevant target when planning responses (Muraskin, Sherwin, & Sajda, 2015; Nakamoto & Mori, 2008, 2012).

The characteristics of the experts are in line with the notion of the multi-action plan model (MAP model). According to the MAP model, the professional athletes can maintain the high-quality performance while being able to cope with the motor task by efficiently switching between an automated state and a controlled state (Bertollo et al., 2016). In the MAP model, the performance states are divided into four categories which determined by the effort to perform the task and the level of attentional control. Type 1 performance is characterized by a flow and effortless state. The relationship between the Type 1 performance and the cortical activity in experts shed light on the understandings of psychomotor efficiency hypothesis. As for Type 2 performance, the state is typified by high-performance effectiveness yet low processing efficiency, suggesting the level of attentional control is rising to meet the task demands. Type 3 performance reflects the excessive investment in the control processes, which are related to the low-performance effectiveness and low processing efficiency. This state is characterized by an excessive reinvestment in working memory, therefore, leading to reducing the movement fluidity and automaticity (Maxwell, Masters, & Eves, 2000). Type 4 performance is exemplified by both weak performance and inefficient processing. It is a suboptimal-automatic state with minimal reliance on the working memory. Hence, to understand the specific cortical processes of expert performers, MAP model may supplement

to the theoretical support in the understanding of psychomotor efficiency in sports. An insight from the perspective of the electroencephalogram (EEG) may serve as an informative tool to discover the specific links between psychomotor efficiency and the cortical activity in skilled performers.

1.4. Electroencephalography (EEG)

Electroencephalography (EEG) is one of the best tools to investigate the cortical processes in sports performance. From the psychophysiological perspective, EEG is sensitive to the slight changes in the mental processes with the outstanding time-resolution (Hatfield, 2004). The EEG activity has been shown substantial differences between different performance qualities (Etnier & Gapin, 2014). Furthermore, the modern EEG devices are light-weight and portable. That is, recording the EEG signals with skilled performers at its original place is feasible.

Among the EEG indices, the EEG signals generating from the sensorimotor region may reflect the critical cortical processing in the superior sports performance. The sensorimotor cortex is responsible for the information input and output of the actions (Mann et al., 1996). In the sports domain, the reduced activity in the sensorimotor cortex is related to the successful performance (Baumeister et al., 2008). Hence, an EEG index originating from the sensorimotor cortex may be suitable for investigating the key cortical processing in understandings the psychomotor efficiency hypothesis.

1.5. Sensorimotor Rhythm (SMR)

The sensorimotor rhythm (SMR) is a specific index which can reflect the level of the sensorimotor interference. SMR is a specific frequency band ranging from 12 to 15 Hz over the central regions of the cortex. SMR is considered to be most prominent in central scalp regions in sensorimotor cortex (Blankertz et al., 2010; Mann, Serman, & Kaiser, 1996). The first report of SMR activity was identified during the motionless while waking state over the motor cortex of cats (Serman, Howe, & Macdonald, 1970). This alert yet motionless waking behavior, which was reflected by the increased SMR activity was also observed during the quiet sleep state (Howe & Serman, 1972). Following studies suggested that the generation of SMR activity origins from the communication between somatosensory relay nuclei of the thalamus, known as ventrobasal nuclei (Mann et al., 1996; Serman, 2000). That is, the conduction of somatosensory information to the sensorimotor cortex is attenuated or inhibited when SMR activity increases (Quandt & Marshall, 2014).

Higher SMR power during the preparation period has been linked to the superior performance in sports. The increased SMR power was beneficial to the stimulus processing capabilities, leading to an improved cognitive performance (Kober et al., 2015). This evidence is supported by previous findings which proposed the motor performance can be enhanced by reducing the sensorimotor interference during the action execution, implying more automated processing to the performance output (Serman, 2000). However, the missing link between the functional role of SMR activity and psychomotor efficiency has yet to be answered.

1.6. Neurofeedback Training (NFT)

Promising results of neurofeedback training (NFT) have been accumulated recently in the clinical cases (Arns, De Ridder, Strehl, Breteler, & Coenen, 2009), improving performance in health trials (Ballesteros et al., 2016), and in athletes (Xiang, Hou, Liao, Liao, & Hu, 2018). Deriving from the operant learning theory (Skinner, 1963), which proposes rewarding positive reinforcement to the particular behavior, EEG NFT offers insight into the neurocognitive processing to a specific task demand (Thatcher et al., 1999). EEG NFT can reflect the EEG amplitude via the sensory signals, e.g., audible feedback, visual feedback, or combined. Accordingly, athletes can manipulate the EEG activity into a preferred zone which is related to the desired performance in a real-time manner, e.g., preparation period of golf putting, aiming period of the shooting task, or free throw in basketball.

Hence, performing the NFT should be preferably based on the specific EEG index which correlates with the specific task demands (Hung & Cheng, 2018; Mirifar, Beckmann, & Ehrlenspiel, 2017; Xiang et al., 2018). The types of waveform are associated with specific brain states, such as attentional resources allocation (Asada, Fukuda, Tsunoda, Yamaguchi, & Tonoike, 1999), general state of attention, task-specific attention, cortical relaxation or inhibition (Klimesch, 1999), reduction of sensorimotor information processing (Mann et al., 1996).

The use of SMR as the training target in NFT has been backed up by previous studies conducted with the healthy participants in the cognitive tasks. The reports reveal augmented SMR NFT is associated with the cognitive processing enhancement (Egner & Gruzelier, 2002; Gruzelier, Inoue, Smart, Steed, & Steffert, 2010; Kober et al., 2015; Ros et al., 2009), suggesting that the augmented SMR activity is correlated with the adaptive cortical networking. This fine-tuned cortical state is consistent with the notion of psychomotor efficiency hypothesis (Hatfield & Hillman, 2001; Hatfield, 2018).

However, the causal relationship between the beneficial effect of SMR NFT and the

precision sports performance remains an unsolved topic. To answer this question, three fundamental questions should be resolved. Firstly, what are the characteristics of the SMR power in the experts and novices? Secondly, does the SMR power be sensitive enough to distinguish the subtle cortical changes between the optimal performance and the less optimal performance? Thirdly, to address the causal relationship between SMR power and the sports performance, what would happen after the athletes carry out the SMR NFT? Hence, the aims of this dissertation are threefold, and they are listed in the following section.

1.7. Purpose of the Present Work

1.7.1. Aims

This dissertation aims to establish a systematical relationship between SMR activity and its effects on precision sports performance.

Hence, the first study is to identify the characteristics of SMR activity in skilled performers. The second study aims to further investigate the variation of the SMR activity between the personal best and worst performance.

Based on the findings of the first and second studies, the third study intends to find out the effects of SMR NFT on performance enhancement.

1.7.2. Research Questions

The overall purpose of the present work is to investigate the functional role of SMR activity and how the SMR activity can improve the psychomotor performance.

Along these lines, the present work looks for answering three main research questions:

Is the SMR activity related to the psychomotor performance? That is, does the dart-throwing experts and novices show different patterns on SMR activity during the preparation period? (Chapter 2)

Does the SMR activity reflect the changes in neurocognitive processes even in the comparison between personal best and worst performance? Specifically, does the SMR activity differ between the best shooting performance and the worst shooting performance? (Chapter 3)

Is SMR neurofeedback training an effective method to improve the psychomotor performance? That is, can we observe the beneficial effects of SMR NFT on golf putting performance? (Chapter 4)

1.7.3. Predictions

For the first study, we predicted that the expert dart-throwers exhibit a higher SMR power

during the preparation period compared to the novices.

As for the second study, it is predicted that the best shooting performance is related to the higher SMR power during the preparation period compared to the worst performance.

Thirdly, in the SMR NFT study, we predicted the SMR NFT group would demonstrate the better performance after SMR NFT compared to the control group.

CHAPTER 2

THE COMPARISON OF EEG ACTIVITY ON EXPERT AND NOVICES ON PSYCHOMOTOR PERFORMANCE

Abstract Previous evidence suggests that augmented sensorimotor rhythm (SMR) activity is related to the superior regulation of processing cognitive-motor information in motor performance. However, no published studies have examined the relationship between SMR and performance in precision sports; thus, this study examined the relationship between SMR activity and the level of skilled performance in tasks requiring high levels of attention (e.g., dart throwing). We hypothesized that skilled performance would be associated with higher SMR activity. Fourteen dart-throwing experts and eleven novices were recruited. Participants were requested to perform 60 dart throws while EEG was recorded. The 2(Group: Expert, Novice) \times 2(Time window: -2000. ms to -1000. ms, -1000. ms to 0. ms) ANOVA showed that the dart-throwing experts maintained a relatively higher SMR power than the novices before dart release. These results suggest that SMR might reflect the adaptive regulation of cognitive-motor processing during the preparatory period.

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2.1.Introduction

Decreased activation in the sensorimotor cortex may represent adaptive information processing in motor execution. It is generally accepted that skillful performers execute movement with lower conscious processing during execution as reflected by less cognitive involvement, thus resulting in less variation in the routine of movement execution. For example, expert golfers showed a relatively lower overall cortical activation than that of novices (Milton et al., 2007). In the same vein, pianists exhibited lower activation compared to novices in a complex motor sequence task in an fMRI study (Meister et al., 2005). In addition to these cross-sectional studies, learning studies have also shown that lower activity at C3 and C4 are observed in marksmen after practice (Kelly & Garavan, 2005). All these studies point to either structural or functional changes in the motor cortex after long-term practice (Dayan & Cohen, 2011). Lower activation in the sensorimotor cortex may be associated with lesser cognitive involvement during the execution of movement, as a result of being related to decreased control in monitoring the processing of motor performance, which leads to more adaptive motor performance.

Sensorimotor rhythm (SMR), the 12–15 Hz oscillation in the sensorimotor cortex, is an EEG candidate for the investigation of differences in sensorimotor activation in skilled visuo-motor activities. SMR is one of the attention-related indicators (Egner & Gruzelier, 2002, 2004; Hoedlmoser et al., 2008) that is negatively related to the activity of the sensorimotor cortex (Mann et al., 1996). The transmission of somatosensory information through the ventrobasal thalamus was shown to be inhibited during SMR activity in animal studies (Howe & Serman, 1973). In other words, SMR power is positively related to the inhibition of sensorimotor cortex activity. SMR neurofeedback training (SMR NFT) studies have shown that individuals can increase SMR power to reduce somatosensory interference during the information processing phase to maintain perception and attention (Vernon et al., 2003). Moreover, augmented SMR power by NFT has been related to motor inhibition and the facilitation of relaxed attention focusing, increases in working memory capacity, better motor preparation (Gruzelier, Egner, & Vernon, 2006), and calming effects on mood (Gruzelier, 2014a). Therefore, higher SMR power might represent the suppression of irrelevant information input from activities in the sensorimotor cortex, which facilitates the formation of relaxed focus (Gruzelier, 2014) and results in more adaptive preparation for action (Gruzelier et al., 2006).

However, investigations of SMR activity and motor performance are scarce. Gruzelier et al. (2010) used virtual reality to increase SMR activity in a monologue dance. The results demonstrated that greater SMR activity was related to better overall monologue dancing

performance, but they did not record SMR activity during the actual execution of the skill. The present study attempted to extend our understanding of SMR and the relevance of motor performance by comparing SMR activity between dart-throwing experts and novices during the preparation period. It was hypothesized that experts would exhibit higher SMR power than those of novices prior to skill execution.

2.2. Methods

2.2.1. Participants

Fourteen dart-throwing experts (mean age = 41.86, SD = 13.79 years) and eleven novice dart-throwing athletes (mean age = 22.04, SD = 2.09 years) were recruited. The experts had practiced dart throwing for 13.93 years (SD = 10.02). To familiarize participants to the dart-throwing task, novices were allowed to practice before actual testing and EEG recording were conducted. All the participants were right-handed and did not have any nervous system disease. All participants provided their informed consent and were approved by the institutional review board of the University of Taipei for the protection of human subjects. The participants had the right to withdraw from the study at any time.

2.2.2. Procedures

Participants were asked to refrain from having drinks containing alcohol or caffeine for at least 24 hours prior to their arrival at the laboratory.

2.2.3. Task

All participants were asked to perform dart-throwing tasks. The distance from the front of the dartboard to the throwing line was 2.37 m, and the distance from the floor to the center of the bull's-eye was 1.74 m (consistent with international dart rules). The score was calculated based on the actual scores on the dartboard; the red region of the bull's eye was determined to be 11, and the outermost circle and a target-miss were calculated as 0. The dart-throwing task consisted of 60 self-paced dart-throwing trials in 6 separate recording blocks. Participants were asked to commence dart throwing when ready and were instructed to throw as accurately as possible. For analyzing the SMR before the onset of the dart-throwing movement, a steady interval of at least 2 seconds before the EMG trigger was needed for each trial. Therefore, participants were asked to first hold the dart in front of the chest for 2 seconds and use their wrist and elbow for aiming and shooting, with minimum body sway. The standardized instructions were given to each participant to reduce confounding effects on EEG and EMG.

2.2.4. Electrophysiological Recording

A stretchable Lycra electrode cap (Quick-cap, Neuroscan, Charlotte, NC, USA) was fitted to participants to record their EEG signals from 12 scalp electrodes (i.e., Fz, F3, F4, C3, C4, T3, T4, Pz, P3, P4, O1, & O2) based on the international 10–20 system (Jasper, 1958). The reference was located at the mastoids to obtain an ear-averaged reference offline, and the ground electrode was located at FPz. To monitor blinking and eye movements, vertical and horizontal electrooculograms (VEOG and HEOG, respectively) were recorded with bipolar configurations that were located superior and inferior to the right eye and on the left and right orbital canthi. EEG and EOG signals were sampled at 500 Hz and amplified 5000 times using Neuroscan Synamps and NeuroScan 4.3 software (Neuroscan, Charlotte, NC, USA), with a band-pass filter setting from 1 to 100 Hz and a notch filter of 60 Hz. Furthermore, electromyograms (EMGs) were utilized to obtain the timing of the onset of the dart-throwing movement. A pair of Ag/AgCl electrodes was attached to the flexor digitorum superficialis of right hand: one was located at the one-third position from the wrist and the other was located at the one-third position from the elbow, with bipolar recording used to detect the timing of release upon throwing. The impedance at each electrode was kept under 10 kOhm. In addition, an event marker, activated by pressing a function key, was utilized by the experimenter when the dart-throwing movement was initiated. The event markers were used in subsequent analysis with the EMG signals to correctly identify the EMG peaks caused by the initiation of the dart-throwing movement, not a false alarm. After electrode registration, the participants participated in a 10-minute warm-up before commencing the formal test. The whole experiment lasted approximately 2 hours.

2.2.5. Data Reduction

EEG data reduction was conducted offline using Neuroscan Edition 4.5 software (Neuroscan, Charlotte, NC, USA). A band pass of 1–30 Hz with 12db/oct FIR filter was applied to the EEG and EOG channels. EOG correction (Semlitsch, Anderer, Schuster, & Presslich, 1986) was performed on the continuous EEG data to eliminate artifact signals due to blinking. To investigate brain activity prior to the initiation of the dart-throwing movement with a common data structure across trials and participants, EEG data were sampled starting at 2000 ms prior to the dart release. The timing of the initiation of the dart-throwing movement was determined using 20% of the EMG amplitude above baseline. Artifact detection as well as eye inspection by the experimenter were performed to screen for unusable trials. Artifacts were defined by amplitudes exceeding $\pm 100 \mu\text{V}$ from baseline (Männel & Friederici, 2009). The

numbers of artifact-free trials for the –2 s and –1 s epochs before dart throwing were 42 ($SD = 11.17$) and 33 ($SD = 16.34$) for dart-throwing experts and 40 ($SD = 1.91$) and 40 ($SD = 1.91$) for novice dart-throwers, respectively, and were not significantly different, $t(23) = .681$, $p = .601$, $\eta^2 = .012$, in a group comparison. After artifact-free EEG data were acquired, Fast Fourier Transforms (FFT) were calculated on 50% overlapped, 256 sample Hanning windows for all artifact-free segments to transform the C3 and C4 into spectral power (μV^2). To examine the sensorimotor activity, the mean power of C3 and C4 in the frequency band of 12–15 Hz was defined to be SMR (Babiloni et al., 2008).

2.2.6. Data Analysis

For behavioral data, we compared the dart-throwing scores between two groups with an independent t test.

The SMR power was subjected to a 2 (Group: Expert, Novice) x 2 [Time Window: –2000 ms to –1000 ms (T1), –1000 ms to 0 ms (T2)] analysis of variance (ANOVA), with repeated measures on the Time Window factor. The Greenhouse-Geisser procedure was employed to correct the degrees of freedom when the sphericity assumption was violated. Simple main effect tests were employed when the interaction effect was significant. The alpha level was set at $p < .05$, and the eta square (η^2) was utilized for the estimate of effect size.

2.3. Results

2.3.1. Between Group Comparisons of the Performance of Dart Throwing

An independent t test on the dart-throwing scores showed a significant group effect, $t(27) = 8.948$, $p = .001$, $\eta^2 = .748$. As expected, the experts ($M = 9.28$, $SD = 0.68$) performed better than the novices ($M = 6.44$, $SD = 1.01$).

2.3.2. Between-group Comparisons of SMR Power

The SMR power ($\log \mu V^2$) for the expert group for T1 and T2 was 1.335 ($SD = 0.542$) and 1.310 ($SD = 0.654$), respectively. For the novice group, the SMR power for T1 and T2 was 0.374 ($SD = 0.410$) and 0.354 ($SD = 0.351$), respectively. Two-way ANOVA did not show significance for neither interaction, $F(1, 23) = 0.005$, $p = .942$, $\eta^2 = .000$, nor a main effect for the Time factor, $F(1, 23) = 1.030$, $p = .321$, $\eta^2 = .043$. However, the main effect of Group was significant, $F(1, 23) = 21.699$, $p = .001$, $\eta^2 = .485$. An examination of the mean revealed that the experts exhibited a higher SMR power ($M = 1.322$, $SD = 0.137$) than the novices ($M = 0.360$, $SD = 0.155$) prior to dart throwing, $t(23) = 4.658$, $p = .001$ (Table 2.1).

Table 2.1

The SMR power between two groups among T1 (−2000 ms ~ −1000 ms) and T2 (−1000 ms ~ 0 ms) in dart throwing performance.

	T1	T2
Expert Group	1.335 (0.542)	1.310 (0.654)
Novice Group	0.374 (0.410)	0.354 (0.351)

Unit: $\log \mu V^2$

2.3.3. Control Analysis

2.3.3.1. Regional specificity

In this study, the SMR power (a mean power of 12–15 Hz in C3 & C4) of the experts was significantly higher than that of the novices during the 2 seconds prior to dart throwing. It is unknown whether the greater 12–15 Hz EEG power was limited to the sensorimotor cortex and the somatosensory integration regions (parietal lobe) (Fogassi & Luppino, 2005) or if there was fluctuation over the other less relevant regions, such as the occipital cortex and frontal cortex. Accordingly, we expected that a relatively elevated 12–15 Hz power at the sensorimotor and parietal regions compared to the frontal and occipital regions would be found in the experts. Moreover, based on the cortex efficiency hypothesis (Milton et al., 2007), experts exhibited a generally higher 12–15 Hz power than the novices, regardless of the regions being examined. Due to insignificant findings regarding the time effect, the SMR results from the two time windows were pooled together. Thus, a 2 (Group: Expert, Novice) x 4 (Region: Frontal, Central, Parietal, Occipital) two-way ANOVA mixed design was applied to test the differences in all the regions. However, in computing the power variation among these regions, establishing a normalized power comparison was needed. Therefore, relative power (%), defined as the ratio of the mean power of 12–15 Hz divided by the mean power of 1–30 Hz corresponding to a given electrode, was employed, which is a common method to investigate whether a certain frequency band is prominent within the designated background activity to establish a normalized comparison among the regions (Niemarkt et al., 2011). The frontal region was represented by Fz, the parietal region used Pz, and the occipital region applied the mean relative power at O1 and O2.

It was hypothesized that the relative power of 12–15 Hz in the sensorimotor and parietal regions would be higher than that of the frontal and occipital regions in experts and that the experts would have a higher 12–15 Hz power overall than the novices. We found a significant main effect of the Group factor, $F(1, 23) = 12.066, p = .002, \eta^2 = .344$, in which the expert group exhibited a higher relative power with a 12–15 Hz frequency band ($M = 1.025, SD = 0.142$) than that of the novice group ($M = 0.855, SD = 0.087$), $t(23) = 3.474, p = .002$. The results also showed that the effect of the Group x Region interaction was significant, $F(3, 69) = 10.912, p = .000, \eta^2 = .322$; subsequent simple main effect analysis revealed that expert group showed a significantly higher relative power of 12–15 Hz at the frontal, $t(23) = 4.563, p = .001$, central, $t(23) = 2.946, p = .007$, and parietal regions, $t(23) = 2.863, p = .009$ compared to the novice group. In addition, we observed that the novice group exhibited a significantly different relative power within these regions, $F(3, 30) = 25.843, p = .001, \eta^2 = .721$. A

significantly higher relative power was observed in the occipital, $t(10) = 10.655, p = .00$, central, $t(10) = 4.610, p = .001$, and parietal regions, $t(10) = 4.989, p = .001$, relative to that of the frontal region. All the means are presented in Table 2.2.

Table 2.2. The mean relative power of 12–15 Hz at the frontal, central, parietal, and occipital regions for the expert and novice groups before dart throwing.

	Frontal	Central	Parietal	Occipital
Expert group	0.994 (0.185)	1.039 (0.181)	1.054 (0.195)	1.013 (0.062)
Novice group	0.709 (0.144)	0.842 (0.144)	0.851(0.129)	1.001 (0.037)

Unit: %

2.3.3.2. Frequency specificity

Although the above analysis demonstrated a distinct 12–15 Hz power in the sensorimotor region, it is not clear whether the expert-novice difference was only observed on the 12–15 frequency band instead of other EEG markers. Alpha (8–12 Hz) is associated with sensory information processing over the sensorimotor area (Pfurtscheller, Neuper, Ramoser, & Müller-Gerking, 1999). Moreover, the higher alpha power prior to skill execution also predicted a more adaptive golf putting performance in a previous study, which could be interpreted as a sign of fine cognitive-motor performance (Babiloni et al., 2008). In addition, theta (4–7 Hz) and beta1 (15–18 Hz), the other two neighboring frequency bands, were also included in the examination of the frequency specificity of the present study. Theta, alpha, and beta power (a mean power of 4–7, 8–12 and 15–18 Hz, in C3 & C4) were separately subjected to 2 (Group: Expert, Novice) x 2 (Time Window: –2000 ms to –1000 ms, –1000 ms to 0 ms) analyses of variance (ANOVAs). The results showed that there was no difference in alpha power before dart throwing between experts ($M = 1.122$, $SD = 0.121$) and novices ($M = 0.709$, $SD = 0.137$), $F(1, 23) = 0.149$, $p = .703$, $Eta^2 = .006$. Neither an interaction effect, $F(1, 23) = 0.012$, $p = .914$, $Eta^2 = .001$, nor a main effect of the Time factor, $F(1, 23) = 0.082$, $p = .380$, $Eta^2 = .034$, were observed in our analysis. As for theta power, we found no difference prior to dart throwing between the expert ($M = 1.228$, $SD = 0.084$) and novice groups ($M = 1.235$, $SD = 0.094$), $F(1, 23) = 0.003$, $p = .956$, $Eta^2 = .003$. Furthermore, the analysis showed that neither the interaction effect, $F(1, 23) = 0.156$, $p = .696$, $Eta^2 = .007$, nor the main effect of the Time factor, $F(1, 23) = 0.001$, $p = .978$, $Eta^2 = .000$, were significant. However, the expert group showed a higher beta1 power ($M = 1.235$, $SD = 0.126$) than that of the novice group ($M = 0.147$, $SD = 0.142$) before dart throwing, $F(1, 23) = 52.818$, $p = .001$, $Eta^2 = .697$. Neither the interaction effect, $F(1, 23) = 0.318$, $p = .578$, $Eta^2 = .014$, nor the main effect of the Time factor, $F(1, 23) = 2.028$, $p = .168$, $Eta^2 = .081$, for beta1 power were observed. The means for this analysis are presented in Table 2.3.

Table 2.3. The mean power of theta, alpha and beta1 at the C3 and C4 sites for the expert and novice groups before dart throwing.

	Theta	Alpha	Beta1
Expert group	1.228 (0.084)	1.122 (0.121)	1.235 (0.126)
Novice group	1.235 (0.094)	0.709 (0.137)	-0.147 (0.142)

Unit: $\log \mu V^2$

2.3.3.3. *Task specificity*

To determine whether the higher SMR power was task-specific in dart throwing, we extracted the SMR power from the resting condition in which the participants were instructed to stand up in the same position used when dart throwing and to keep their eyes open, staring at the bull's eye for two minutes. The continuous EEG data were segmented by 2 seconds each to obtain the mean SMR power in the resting condition. A 2 (Group: Expert, Novice) x 2 (Condition: Resting, Dart Throwing) x 2 (Electrode: C3, C4) three-way ANOVA with Condition and Electrode as the repeated measures was employed. The three-way ANOVA revealed a 2 (Group) x 2 (Condition) interaction effect, $F(1, 23) = 11.997, p = .002, \eta^2 = .343$. The simple main effect was significant for the resting condition between the two groups, $F(1, 23) = 97.008, p = .001, \eta^2 = .808$, in which the expert group showed higher SMR power than the novice group in the Resting condition. As expected, we also found a significant simple main effect of the Dart Throwing condition, $F(1, 23) = 23.306, p = .001, \eta^2 = .503$, in which the expert group exhibited a higher SMR power than the novice group before dart throwing. In addition, we revealed a significant simple main effect within conditions for the expert group, $F(1, 13) = 6.946, p = .021, \eta^2 = .348$, and the novice group, $F(1, 10) = 5.682, p = .038, \eta^2 = .362$, in which the expert group exhibited lower SMR power in the Dart Throwing condition than in the Resting condition, while the novice group showed higher SMR power in the Dart Throwing condition than in the Resting condition. The group main effect revealed a significant effect, $F(1, 23) = 105.279, p = .001, \eta^2 = .821$, in that the expert group exhibited a generally higher SMR power ($M = 1.621, SD = 0.408$) than the novice group ($M = 0.137, SD = 0.283$), regardless of the condition (see Table 2.4).

Table 2.4. The SMR power for the two groups in the Resting Condition and Dart Throwing Condition.

	Resting Condition		Dart Throwing Condition	
	C3	C4	C3	C4
Expert group	1.933 (0.531)	1.850 (0.509)	1.357 (0.545)	1.346 (0.661)
Novice group	-0.003 (0.476)	-0.174 (0.493)	0.381 (0.399)	0.342 (0.356)

Unit: $\log \mu V^2$

2.3.3.4. The EMG prior to movement between experts and novices

We also compared the mean power frequency (MPF) (Vance, Wulf, Töllner, McNevin, & Mercer, 2004) between the two groups to investigate whether these two groups showed different EMG patterns prior to dart throwing. We computed the EMG signal two seconds before dart throwing and filtered it into 1–100 Hz frequency bands. Then, we performed an independent t test to examine the means. The results showed that the mean power of EMG was 2.849 ($SD = 1.276$) and 0.573 ($SD = 0.306$) in the expert and novice groups, respectively. The expert group revealed a significantly higher EMG power than the novice group, $t(23) = 5.754$, $p = .001$.

2.3.3.5. The ocular activity between experts and novices

To minimize the confounding effect of ocular activity between the two groups during the preparation period in dart-throwing task, we further compared the difference in fixation between the novice and expert groups. As previous studies have suggested, the common structure of fixation was defined as a stable gazing position that is steadily maintained for at least 100 ms (Manor & Gordon, 2003). The first step to extract the gazing position was to segment the EOG signal with time windows of 100 ms each for 60 dart-throwing trials. Second, these segmented epochs underwent an artifact rejection process, as they were required to be within $\pm 100 \mu V$ of baseline to be validated as a stable gazing position. Third, the number of remaining gazing position trials was counted and averaged for every participant. The average number of trials represented the number of fixations. Finally, a t test was performed to compare the number of fixations between the two groups. We hypothesized that both groups shared a similar number of fixations in the preparation period. Results showed that the mean number of fixations in the expert and novice groups was 58.768 ($SD = 6.421$) and 59.636 ($SD = 1.206$), respectively. We found no significant differences between these two groups in the t test, $t(23) = 0.441$, $p = .664$.

2.3.3.6. The contralateral effect on the SMR power within the C3 and C4 sites

It is also arguable whether the activity of SMR power showed a contralateral effect before dart throwing in this study. Therefore, this additional analysis was designed to investigate the difference between the SMR power at the C3 and C4 sites for both groups. We extracted the power of 12–15 Hz from the C3 and C4 sites with a two-second segment before dart throwing. Then, we performed t tests to compare the SMR power at the C3 and C4 sites for the expert and novice groups. The SMR power for the expert group at the C3 and C4 sites

was 1.357 ($SD = 0.545$) and 1.346 ($SD = 0.661$), respectively; the SMR power for the novice group at the C3 and C4 sites was 0.381 ($SD = 0.399$) and 0.342 ($SD = 0.356$), respectively. We found that the expert and novice groups showed no significant difference in SMR power between the C3 and C4 sites [expert group, $t(13) = 1.598, p = .134$; novice group, $t(10) = 1.578, p = .146$].

2.4. Discussion

The aim of this study was to investigate the difference in SMR between experts and novices during a dart-throwing task. The results showed that the performance of dart throwing was preceded by a higher SMR power in the experts than in the novices, lending support for the hypothesis that lower sensorimotor activation, as reflected by higher SMR activity, is a characteristic of superior dart throwing.

The main finding of the present study was consistent with our hypothesis, in which we anticipated that SMR power in experts would be higher than in novices prior to dart release. Mann et al. (1996) suggested that SMR power was negatively correlated with the relay activity in the sensory motor cortex, which represented reduced conduction of somatosensory information during SMR activity. Subsequent studies showed that increasing SMR power was associated with reduced somatosensory and motor interference in an attention-demanding task (Egner & Gruzelier, 2001; Egner & Gruzelier, 2004). Furthermore, augmented SMR NFT was beneficial to declarative memory (Hoedlmoser et al., 2008), mental rotation (Doppelmayr & Weber, 2011), novel music performance in children (Gruzelier, Foks, Steffert, Chen, & Ros, 2014), and acting performance with a greater subjective flow state (Gruzelier et al., 2010). In addition, Ros et al. (2009) observed a significant reduction of simulated cataract surgical time due to the improvement in visuo-motor skills following augmented SMR training, which was accompanied by a reduction in anxiety. Collectively, these findings point to a relationship between augmented SMR activity and adaptive cognitive-attentional processing in attention-demanding tasks. The finding of higher SMR power in skilled participants suggests that their superior dart-throwing performance was preceded by a state of less somatosensory interference. In other words, skilled participants performing a highly coordinated dart throw may depend less on external somatosensory feedback to guide their movement. This adaptive cognitive-motor state results in a chunking execution of a well-practiced skill (Masters, 1992). That is, the dart throwers achieve more adaptive information processing of their motor skill during execution. This interpretation is in line with the characterization of an expert who can perform with high efficiency and refinement after a number of practice sessions (Kelly & Garavan,

2005), which can result in less attention investment during the actual performance (Hikosaka, Nakamura, Sakai, & Nakahara, 2002). This type of mental state is particularly helpful for performance during precision sports (Krane & Williams, 2006).

A conceptualized automatic processing can be useful to explain the relationship between the SMR activity and adaptive mental states. An automatic process is parallel and effortless (Schneider & Shiffrin, 1977). Neurophysiological studies have shown that the automatic pathway includes the bilateral ventral premotor region, the right middle frontal gyrus, the right caudate body, and lateral parts of the basal ganglia (Poldrack, 2005). Furthermore, evidence from a functional magnetic resonance imaging (fMRI) study showed that the weaker activity of the bilateral cerebellum, pre-supplementary motor area, cingulate cortex, left caudate nucleus, premotor cortex, parietal cortex, and prefrontal cortex were characteristics of the automatic process (Wu, Chan, & Hallett, 2008). These findings suggest that the major motor network is involved in processing automatic movements, and reduced activity in the motor region during the execution movement could be related to an automatic process. This conceptualization is consistent with our findings, which showed that higher SMR power was observed in the preparation period of experts than that of novices. Therefore, less activation in the sensorimotor cortex may result in less interference with somatosensory information, which may be the major difference between an expert and a novice.

A generally higher 12–15 Hz power in experts than in novices suggests that skilled dart throwers perform superior dart throwing with lower interference in processing motor-related activity. The 12–15 Hz activity has been associated with the inhibition of motor activity (Mann et al., 1996) and has been shown to compose the dominant “standby” frequency of the integrated thalamocortical, somatosensory, and somatomotor pathways (Serman & Egner, 2006). Our findings suggest that experts performed the dart-throwing task with a globally reduced somatosensory process at the frontal, sensorimotor and parietal regions. This is consistent with previous studies demonstrating that better motor performance was closely related to lower activity among the premotor and primary motor areas (Babiloni et al., 2010; Del Percio et al., 2009) and replicates previous findings that suggest that skilled performers execute specialized tasks with lower cortical processing than novices (Meister et al., 2005). Moreover, the reduced 12–15 Hz power at the frontal region compared with other regions in novices suggests an effortful execution process that is closely related to the controlled process (Schneider & Shiffrin, 1977).

The difference in skill level between dart throwers and novices is mainly reflected by the beta frequency band. Although alpha activity in the central area has been associated with

sensory information processing over the sensorimotor area (Pfurtscheller & Lopes Da Silva, 1999), this was not evidenced by this study. Moreover, we also failed to observe a difference in the theta frequency band between the two groups. However, the expert group exhibited a higher power with a frequency band of 15–18 Hz before dart throwing. The enhancement of 15–18 Hz EEG activity was related to increased cortical arousal and focus mechanisms affecting the sensorimotor cortex (Lubar & Lubar, 1984). Previous findings showed that participants with augmented 15–18 Hz power at the sensorimotor area show reduced error rates (Egner & Gruzelier, 2001). Similarly, participants exhibited a reduction of response time in attentional tasks and an increased P3b amplitude in oddball tasks with augmented SMR and 15–18 Hz power (Egner & Gruzelier, 2004). These results suggest that the beta-related frequency band is closely related to adaptive attentional focus, which is restricted in the sensorimotor area. However, the best way to distinguish the effect of functional specificity in the adherent frequency band has been a controversial question (Gruzelier, 2014c). Our results could lend preliminary support to the legitimacy of using SMR power or a power of 15–18 Hz to examine the relationship between sensorimotor activation and fine motor performance (Gruzelier, 2014b).

Our control analysis on comparing SMR activity between the Resting and Dart Throwing conditions suggest that augmented SMR power is a specific EEG marker that exists in skilled dart throwers. We found that the expert group exhibited a significantly higher SMR power than the novice group in both the Dart Throwing and Resting conditions. SMR is categorized as an influential “standby” frequency, which reflects the activity of the integrated thalamocortical, somatosensory, and somatomotor pathways (Serman & Egner, 2006). Previous studies have revealed that SMR power can be blocked during the planning or simply the imagination of a motor act (Pfurtscheller & Lopes Da Silva, 1999). This finding suggests that the expert group performed both the dart throwing and resting tasks with less motor planning and imagination than the novice group. In addition, the expert group exhibited relatively higher SMR power in the Resting condition than in the Dart Throwing condition, whereas the novice group showed the opposite trend. One speculation regarding these results is that these two groups processed sensorimotor information during these two conditions differently because they perceived the context in a different way. Specifically, it is possible that the expert group maintained lower levels of information processing in the sensorimotor cortex during the dart-throwing task because they perceived the context in a comparably efficient way. On the contrary, the novice group performed the dart-throwing task with a relatively higher sensorimotor activation, which could be characteristic of inexperience and less integration of

motor planning. This speculation is in line with the notion that both motor and visual experiences distinguish how participants proceed with the perception of actions between novices and experts. That is, experts perceive and recognize the specialized task more easily than novices (Hohmann, Troje, Olmos, & Munzert, 2011). Taken together, these findings indicate that the augmented SMR power in expert dart throwers reflects a mental state with less motor planning and less attention-related sensorimotor processing within the two tasks than in novices. However, a more comparable control task with an event-locked segment would be a more advanced way to demonstrate the specificity of the task-specific EEG marker.

The evidence of different SMR power between the two groups can be inferred as a result of the variation of skill level instead of confounding variables before dart throwing, such as EOG and EMG activity. Our control analysis of EOG activity revealed that no difference was found in the fixation between the two groups before dart throwing. This evidence further suggests that the SMR variation between the two groups was due to the difference in sensorimotor information processing in the preparation period of dart throwing instead of the fixation. Moreover, we found that the expert group showed higher EMG power before dart throwing than the novice group. This finding is in line with the psychoneuromuscular theory (Driskell, Copper, & Moran, 1994), which suggests that imagery generates neuromuscular responses similar to those of an actual experience. Specifically, practicing the execution of a movement mentally could lead to the transmission of the impulses to target muscles. This activation of muscular activity has been associated with the improvement of coordination patterns, which then results in the strengthening of motor programs in the motor cortex (Magill, 1998). Thus, the higher EMG power observed in the expert group relative to the novice group in this study could be the result of a large amount of practice, which leads to more integrated control of specific muscular activity. However, interpretations of the EMG results should be made with caution, as the dart-throwing task uses dynamic contraction, which is sensitive to the morphological properties of the muscle (Farina, 2006). Therefore, further investigation of the relationship between EMG activity and SMR power before dart throwing is required.

Caution should be exercised when interpreting this study's findings due to several limitations. Although the antecedent role of SMR provides some support for its causal role, future interventional studies to ascertain this relationship are warranted. The functional meaning of SMR requires further investigation by comparing the best and worst performance within highly skilled performers. Although some studies have found that higher SMR power was related to superior attentional performance (Egner & Gruzelier, 2001; Egner & Gruzelier, 2004; Hoedlmoser et al., 2008), others have indicated that SMR was not essential in musical

performance (Egner & Gruzelier, 2003) or for an audiovisual Go/NoGo cursor movement task (Boulay, Sarnacki, Wolpaw, & McFarland, 2011). Additionally, EEG provides real-time cortical processing information during motor performance (Divekar & John, 2013), but it is limited in its ability to generate information on how the sensorimotor cortex works with the other relevant regions during motor execution (Thompson, Steffert, Ros, Leach, & Gruzelier, 2008). The functional role of SMR requires more specification, and neuroimaging tools, such as fMRI, can be incorporated to generate a more complete understanding of the function of the sensorimotor cortex. Moreover, in a neurofeedback training study, SMR power and subjective measures, such as Flow State Scales (Jackson & Eklund, 2004), were recommended for future studies. Previous research has demonstrated the benefit of neurofeedback in the sports domain (Gruzelier et al., 2010; Kao, Huang, & Hung, 2014; Landers et al., 1991). More neurofeedback training designs are not only useful to examine the causal relationship between SMR activity and motor performance but may also shed light on the practical implications for the regulation of SMR. Furthermore, the electrooculography detected in this study should be examined with more refined tools, although we found that no significant difference was observed for the fixation reflected by the EOG data two seconds before dart throwing. This observation may be refined by using more sophisticated electrooculographic measurements, such as eye trackers. Finally, the limited period of EEG power analysis needs to be extended further to elucidate the fluctuation of EEG power in more detail. We examined the variation of EEG power using only two-second time windows prior to dart throwing. We recommend that future studies explore the time window during the entire skill execution process to further our understanding of the mental process associated with motor skill performance.

In conclusion, as supported by the EEG spectral analysis of SMR in this study, dart-throwing expertise is reflected by a higher SMR power prior to dart release. This finding implies that experts rely less on somatosensory information processing to guide their throwing movement in a relatively more adaptive manner. On the contrary, novices tend to use feedback from kinesthetic information, as reflected by a lower SMR power, to perform the throwing task. These findings advance our understanding of an adaptive mental state in skilled motor performance and shed light on the potential of regulating SMR activity to improve attention during the performance of sports.

CHAPTER 3

THE PSYCHOMOTOR EFFICIENCY AND THE EEG ACTIVITY ON INTRA- INDIVIDUAL PERFORMANCE

Abstract Psychomotor efficiency has been linked with processing efficiency during sport performance. Reduced cortical activity in the sensorimotor area has been related to less variability in the movement preparation that is conducive to skilled motor performance. This study proposes sensorimotor rhythm (SMR), 12–15 Hz of the electroencephalography (EEG) in the sensorimotor area, may be used to investigate psychomotor efficiency in sports performance. Twenty-four skilled air pistol shooters were recruited to fire 40 shots while EEG and shooting accuracy were recorded. The data show that improved performance of skilled shooters is associated with higher SMR power during the last second and lower coherence on high alpha power at Fz-T3 before action initiation. A negative relationship is also exhibited between the SMR power and the shooting performance during the aiming. This finding suggests that reduced interference from sensorimotor processing, as reflected by elevated SMR power, may be related to improve processing efficiency during the aiming period. We conclude that SMR may be used to understand psychomotor efficiency underlying air-pistol shooting performance.

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3.1. Introduction

Understanding cortical processes underlying optimal performance is important for improving athletic performance. Processing efficiency as posited by the neural efficiency hypothesis refers to the general state of nervous system composed with minimal neural activation in a given task (Babiloni et al., 2008; Babiloni, Marzano, Infarinato, et al., 2010). Although neural efficiency can serve as a framework for explaining the cortical processes underlying optimal performance, recent studies of skilled self-paced performance have found that more recruitment of motor programming resources in motor-related areas led to superior putting performance (Cooke et al., 2014; Ring, Cooke, Kavussanu, McIntyre, & Masters, 2015). Similarly, stronger cortical communication in the parieto-central and parieto-frontal has been found for successful putts in elite golfers (Babiloni et al., 2011). This suggests that the cortical processing in elite athletes might be more complex than that predicted solely by the “neural efficiency” hypothesis.

Psychomotor efficiency, a special case of neural efficiency, provides a more specific perspective to further understanding of the cortical processing underlying skilled self-paced performance. The psychomotor efficiency postulates less complexity in the processes associated with motor control and lower neural network activities during cognitive-motor behavior, and thus can be viewed as superior cognitive-motor processing concerning expertise (Hatfield & Hillman, 2001). Decreased cortical activation of the motor planning-related regions (e.g. sensorimotor cortex) might contribute to greater consistency of the motor performance (Baumeister et al., 2008). The relationship between cortical activity and cognitive-motor processing can be investigated by using electroencephalography (EEG) activities in the sensorimotor region and the cortical communication between sensorimotor region and other regions. This direction of research has also been backed up by a general model for the interpretation of cortical activity associated with superior performance, the multi-action plan model (MAP model; Bertollo et al., 2016), which found that a silent sensorimotor area was associated with a more automated shooting performance in elite shooters.

Sensorimotor rhythm (SMR) is an ideal candidate for evaluating psychomotor efficiency in the EEG. SMR is a special category of EEG frequency ranging from 12 to 15 Hz observed in the sensorimotor cortex and is related to activation of this area (Serman, 1996). Specifically, SMR power is inversely related to sensorimotor cortex activity (Serman, 1996), indicating that lower thalamic nucleus activity is associated with less interference of somatosensory processing (Kober et al., 2015). In addition to the low and high alpha frequencies reflecting the attentional processing in general aspects and in semantic tasks,

respectively (Klimesch, 1996), higher SMR power has been characterized as an adaptive state of refined task-related neural processing during psychomotor and attention-related tasks (Gruzelier et al., 2006, 2010; Kober et al., 2015; Ros et al., 2009).

In the context of sports, Cheng et al. (2015) reported higher SMR power during the preparatory period in skilled dart-throwing players compared to novices. Furthermore, neurofeedback training (NFT) aimed at increasing SMR power resulted in improved golf putting performance (Cheng, Huang, et al., 2015). The beneficial effects of less variability in the movement preparation by augmented SMR NFT supports previous findings of lower cortical communication between Fz and T3 at high alpha range (Deeny, Hillman, Janelle, & Hatfield, 2003), suggesting more refined processing regarding motor execution. Taken together, we propose that SMR power is potentially sensitive to complexity during motor execution, and the effect can be compared by examining cortical communication at high alpha range as it has been considered an ideal index for assessment of inter-regional communication (Von Stein & Sarnthein, 2000). Therefore, investigating the cognitive-motor processing by using SMR power could further our understanding of psychomotor efficiency in skilled self-paced motor performance.

In this study, we used air-pistol shooting performance as the motor task because cognitive-motor processing during aiming is fundamental to skilled pistol shooting (Tremayne & Barry, 2001). Previous studies have shown that various EEG activities can distinguish successful air-pistol shooting performance from less successful performance. For example, Loze et al. (2001) found that successful air-pistol shooting performance was preceded by significantly higher occipital alpha power before trigger pulls, whereas less successful performance was preceded by reduced alpha power. Similarly, Del Percio et al. (2011) found that elite air-pistol shooters were characterized by increased cortical communication within the parietal and other posterior areas, compared to non-athletes. These authors suggest that skilled shooting performance is associated with a relatively efficient manner to process visual-spatial information. However, a more relevant EEG index which can reflect cognitive-motor processing has not been investigated in air-pistol shooting performance.

The aforementioned evidence supports the functional relation of SMR power and skilled motor performance. However, the difference in regulation of psychomotor processing during motor performance between experts and novices can be assumed to be large. The SMR differences between these two highly distinctive skill categories serve as a starting point for the relevance of SMR power in skilled motor performance. In contrast, a comparison of skilled performers' performance fluctuation represents an even more sensitive test because a trial-by-

trial comparison could reveal the fine-tuning of cognitive-motor adjustment in the individual (Bertollo et al., 2013; Di Fronso et al., 2016).

Therefore, our study was designed to examine different levels of SMR power during best and worst skilled air-pistol shooting performances. Based on previous findings, we expected that lower activation of the sensorimotor cortex, as reflected by higher SMR power, would be associated with better performance.

3.2. Methods

3.2.1. Participants

Twenty-four right-handed skilled shooters (14 male; 10 female) were recruited in this study, ranging in age from 14 to 22 years old ($M_{age} = 18.12$, $SD_{age} = 2.39$) with an average of 3.82 years ($SD_{experience} = 2.60$ years) of shooting experience. They practiced shooting regularly at least four times per week. The mean shooting score of the male shooters was 557.93 and for the female shooters, 362.90. The shooters in this study were classified as B-level according to the International Sports Shooting Federation. The study was approved by an institutional review board, National Taiwan Sport University, for the protection of the human subjects. All of the participants provided their informed consent and if a participant was younger than 18 years old, a parent signed a consent form.

3.2.2. Air-pistol Shooting Task

To increase the ecological validity, this study adopted an actual shooting task in accordance with normal competitions instead of using an electrical shooting training system. A 10 m range was constructed in a purpose-built data collection building, following International Shooting Sport Federation regulations. The shooting task lasted approximately 60 minutes. Four 10-shot blocks were built-in and there was a one-minute break between blocks (Deeny et al., 2003). The entire shooting session consisted of 40 self-paced shots to equalize the number of shots, as the required shots in women's shooting regulations are 40. Participants used their own pistols to perform the shooting task to minimize unfamiliarity regarding pistol handling. Shot scores were determined by the terminal location on the target, which was a concentric circle in a 170 mm \times 170 mm square. The bull's eye was scored as 10. The other eight concentric rings were marked with different diameters (an increase of 0.8 cm per ring) and different scores, depending on proximity to the bull's eye; a score of 9 indicated that the shot was closest to the bull's eye, and a score of 0 indicated that the shot was outside of the outermost ring but still on the target. The shot score and position for all of the participants were

reported after each shot.

3.2.3. EEG Recording

The EEGs were recorded from Fp1, Fp2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T3, C3, Cz, C4, T4, TP7, CP3, CPz, CP4, TP8, T5, P3, Pz, P4, T6, O1, Oz, and O2, corresponding to the International 10–10 system (Chatrian, Lettich, & Nelson, 1985). The left and right mastoids (A1, A2) were used as an averaged ear reference for recording and offline analyses. The ground electrode was located at Fpz. For monitoring blinks and eye movements, vertical and horizontal electrooculograms (VEOG and HEOG, respectively) were recorded located superior and inferior to the right eye and on the left and right orbital canthi. EEG and EOG signals were sampled at 500 Hz, using Neuroscan Nuamps and NeuroScan software, version 4.5 (Neuroscan, Charlotte, NC, USA), with a band pass filter setting from 1 to 100 Hz and a notch filter setting of 60 Hz. The impedance at each electrode site was maintained below 5 k Ω . In addition, an event marker via microphone was recorded using Neuroscan software, version 4.5, and was merged to continuous EEG recording when participants fired the shots (Hung, Haufler, Lo, Mayer-Kress, & Hatfield, 2008). The microphone was attached to a table located at the firing line. The event markers were used in subsequent analyses to synchronize the EEG signal and behavior. The total experiment lasted approximately 1.5 hours.

3.2.4. Procedures

The participants were asked to refrain from consuming alcohol- or caffeine-containing drinks for at least 24 hours prior to performing on the shooting field. The participants were instructed on the requirements of the study and then fitted with an electrode cap (Neuroscan, Charlotte, NC, USA). Participants who were near-sighted wore their glasses or contact lens. After electrode registration, the participants were asked to practice ten warm-up shots. Subsequently, resting EEG with eyes open or closed was recorded for 60 seconds each. The participants were asked to stand firmly and to watch the target without aiming. During experimental recordings, all of the participants were asked to keep their bodies static and their eyes open for at least three seconds prior to shooting to minimize possible artifacts from body sway and blinking while shooting.

3.2.5. Data Reduction

EOG correction (Semlitsch et al., 1986) was performed on the continuous EEG data to reduce artifact signals due to blinking. A band pass of 1–30 Hz with a 12 db/oct FIR filter was applied to the EEG and EOG channels. To investigate brain activity prior to initiation of the

shot, EEG data were sampled starting at 3 s prior to the shot, based on the event markers. This segment was selected to replicate previous studies that selected the interest period before rifle, pistol, and archery performance (Del Percio et al., 2011; Doppelmayr, Finkenzeller, & Sauseng, 2008; Hatfield et al., 1984; Haufler et al., 2000; Kerick et al., 2001; Loze et al., 2001). The baseline for each segment was corrected based on the entire sweep. Trials consisting of less than 3 s were excluded from analysis. The 3 s segments were further divided into three time windows, each one of which was 1 s, that is, time window 3 (TW3: $-3s$ to $-2s$), time window 2 (TW2: $-2 s$ to $-1s$), and time window 1 (TW1: $-1s$ to $0s$). Artifact rejection was performed to screen for contaminated trials, which were defined by amplitudes exceeding $\pm 100 \mu V$ from baseline (Baumeister et al., 2013).

To distinguish the best and worst shooting performances, the pool of ten best (scoring 9 or 10) and ten worst (scoring 8 or less) shots were selected for each participant from the remaining artifact-free trials. To preserve overall power and to transform it into spectral power (μV^2), fast Fourier transforms (FFTs) was used together with a Hanning windows taper (10 % taper, 1 Hz bins) to retain the least spectral leakage for all artifact-free segments. A natural log-transform (\ln) was applied to ensure that the data were in normal distribution. To minimize the individual differences in EEG frequency, individual alpha frequency (IAF) and beta frequency (IBF) were performed for each subject (Del Percio, Babiloni, Bertollo, et al., 2009; Klimesch, 1999). The IAF was defined as the frequency band showing the highest power in the 7.5–12.5 Hz spectrum. The frequency bands selected in this study were: theta (IAF-6 Hz to IAF-3 Hz), low alpha (IAF-2 Hz to IAF), high alpha (IAF to IAF+2 Hz), SMR (IAF+2 Hz to IAF+5 Hz). The mean alpha peak of the IAF was 9.9 Hz ($SD = 0.9$). The IBF was defined as the frequency band showing the highest power in the 14–30 Hz spectrum. The frequency bands selected in this study were: low beta (IBF-2 Hz to IBF Hz), and high beta as (IBF to IBF+2 Hz). The mean beta peak of the IBF was 17.7 Hz ($SD = 2.5$ Hz).

3.2.6. Data Analysis

Paired t-tests were conducted to determine whether the mean and standard deviation of shooting performance varied between best and worst shots. The SMR power was subjected to 2 (performance: best, worst) \times 3 (time window: TW3, TW2, TW1) analysis of variance (ANOVA), with repeated measures on both factors. The Greenhouse-Geisser procedure was employed to correct the degrees of freedom when the sphericity assumption was violated. Simple main effect tests were employed when the interaction effect was significant. In addition, to further test the relationship between SMR and movement variability, a correlational analysis

between SMR and distance from the bull's eye was performed. The alpha level was set at .05. Partial eta square (*Eta*²) is reported as a measure of effect size, with values of .02, .12, and .26 indicating relatively small, medium, and large effect sizes, respectively (Cohen, 1992).

Four control analyses were performed to strengthen the interpretations. Age-related alpha power showed distinct patterns in participants approximately 17-18 years old in a previous study (Bresnahan, Anderson, & Barry, 1999). To test whether the age-related factor would show different alpha power before the shooting, participants were separated into two groups. One group contained participants who were younger than 18 years old (N = 10); the other included those older than 18 years old (N = 14). The alpha power was computed with 2 (age: younger than 18 years, older than 18 years) × 4 (site: Fz, Cz, Pz, Oz) × 3 (time window: TW3, TW2, TW1) to test this working hypothesis.

The frequency specificity test was designed to identify whether only the SMR power at Cz could differentiate best shots from the worst, compared to the neighboring frequency bands. The other frequency bands (i.e., theta, low-alpha, high-alpha, low-beta, high-beta) were analyzed for 2 (performance: best performance, worst performance) × 2 (hemisphere: Right, Left) × 5 (region: F3, F4, C3, C4, T3, T4, P3, P4, O1, and O2) × 3 (time window: TW3, TW2, TW1) ANOVAs.

The EEG coherence test was designed to examine whether the best and worst shots were affected by cortico-cortical communication based on Cz. We applied Fisher's Z transformation on 12–15 Hz to normalize the distribution of coherence in the shooting task (Deeny et al., 2003). The coherences of 12–15 Hz for pairs between Cz and Fz, T3, T4, Pz and Oz were subjected to 2 (performance: best, worst) × 3 (time window: TW3, TW2, TW1) × 5 (coherence sites: CZ–Fz, CZ–T3, CZ–T4, Cz–Pz, Cz–Oz) three-way ANOVA.

Cortico-cortical communication in high alpha power has been considered an index of psychomotor efficacy (Zhu, Poolton, Wilson, Maxwell, & Masters, 2011) and characteristic of top-down activities (Von Stein & Sarnthein, 2000) in which lower coherence between the frontal area and left temporal area indicates more efficient motor programming in movement execution. The coherences were evaluated for the high alpha power within the F3, F4, T3, T4, C3, C4, P3, P4, O1, and O2 electrode sites paired with Fz. A 2 (performance: best, worst) × 3 (time window: TW3, TW2, TW1) × 10 (coherence sites: Fz–F3, Fz–F4, Fz–T3, Fz–T4, Fz–C3, Fz–C4, Fz–P3, Fz–P4, Fz–O1, Fz–O2) × 2 (hemisphere: left, right) four-way ANOVA was performed.

3.3. Results

3.3.1. Shooting Performance

Regarding mean shooting score, the overall average score in this study was 8.68 (SD = 0.38). The average score of the 10 best shots was 9.77 (0.22); and 7.61 (0.61) for the 10 worst shots. The paired t test showed that the average score for the 10 best shots was significantly higher than that of the 10 worst shots, $t(23) = 21.5, p < .001, \eta^2 = .950$. In regards to the consistency of shooting scores, the standard deviation of the best shots was less than that of the worst shots, $t(23) = 5.282, p < .001, \eta^2 = .548$.

3.3.2. SMR Power between the Best and the Worst Shots

Two-way ANOVA with the factors of performance (2) and time window (3) revealed a significant interaction effect, $F(2, 46) = 3.224, p = .049, \eta^2 = .123$. Post hoc testing showed that SMR power was significantly higher in the best shots compared to the worst shots only at TW1, $t(23) = 2.217, p = .037, \eta^2 = .176$. Furthermore, the simple main effect on time window comparison in best shots was significant, $F(2, 46) = 7.827, p < .001, \eta^2 = .385$. The post hoc test showed that significantly higher SMR power was observed at TW1 than at TW2, $t(23) = 4.568, p < .001, \eta^2 = .476$ and TW3, $t(23) = 4.407, p < .001, \eta^2 = .458$. The result of this part is illustrated in Figure 3.1.

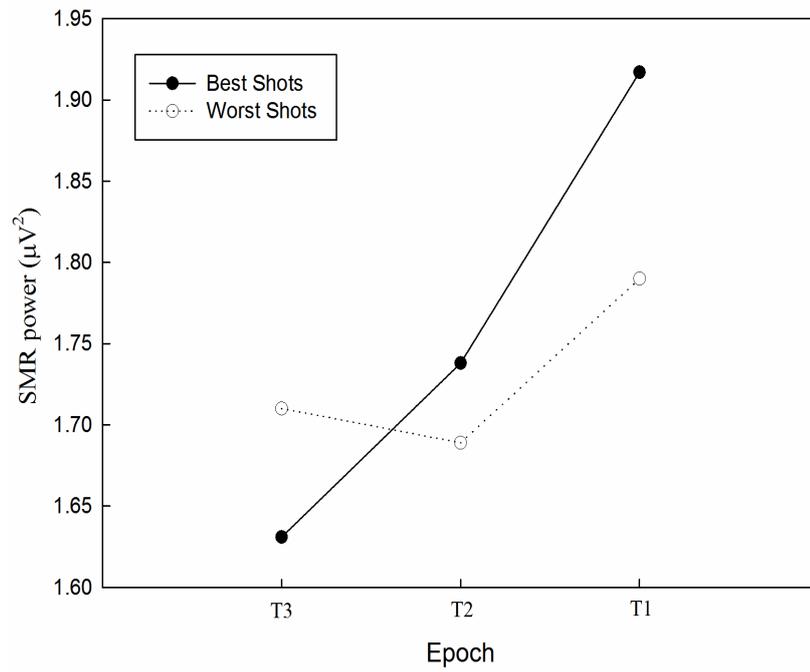


Figure 3.1 The SMR power between the best and worst shots 3 seconds prior to the shot on Cz electrode.

3.3.3. Correlation between SMR and Distance from the Bull's Eye

The average distance from the bull's eye and SMR power were 1.22 (0.19) cm and 0.86 (1.07) μV^2 , respectively. The Pearson's correlation analysis showed that the SMR power during three seconds before shooting was negatively correlated with the average distance from the bull's eye ($r = -.468$, $p = .021$, $N = 24$).

3.3.4. Control Analysis

Age-related alpha power. Age (2) \times site (4) \times time window (3) three-way ANOVA showed neither the interaction effect, $F(6, 132) = 0.173$, $p = .984$, $Eta^2 = .008$, nor a main effect of the age factor, $F(1, 22) = 0.459$, $p = .505$, $Eta^2 = .020$, on alpha power.

Frequency specificity. The separate performance (2) \times hemisphere (2) \times region (5) \times time window (3) ANOVAs showed no interaction effect for theta, $F(8, 184) = .728$, $p = .450$, $Eta^2 = .225$; low alpha, $F(8, 184) = .676$, $p = .488$, $Eta^2 = .142$; high alpha, $F(8, 184) = .423$, $p = .628$, $Eta^2 = .478$; low beta, $F(8, 184) = .308$, $p = .637$, $Eta^2 = .253$, and high beta, $F(8, 184) = .316$, $p = .669$, $Eta^2 = .145$.

SMR coherence between best and worst shot performances. The performance (2) \times time window (3) \times coherence (5) three-way ANOVA showed neither an interaction effect, $F(8, 184) = .655$, $p = .730$, $Eta^2 = .028$ nor an interaction of performance (2) \times time window (3), $F(2, 46) = 1.389$, $p = .260$, $Eta^2 = .057$, or performance (2) \times coherence (5), $F(4, 92) = 0.823$, $p = .514$, $Eta^2 = .035$.

The coherence of high alpha power and shooting performance. The performance (2) \times time window (3) \times coherence (10) \times hemisphere (2) four-way ANOVA showed a significant performance \times coherence site interaction, $F(4, 92) = 2.719$, $p = .034$, $Eta^2 = .106$. Post hoc analysis indicated that the best performance ($M = .396$, $SD = .035$) exhibited significantly lower coherence, $t(23) = 2.378$, $p = .026$, $Eta^2 = .197$, on high alpha power at Fz-T3 than the worst performance ($M = .468$, $SD = .038$).

3.4. Discussion

To our knowledge, this is the first study to empirically investigate the SMR power among intra-individual trials in sports, especially for action execution. Our results showed that best shooting performance was preceded by higher SMR power during the last second before action initiation. Furthermore, SMR power was negatively correlated with shooting performance (distance from the bull's eye). Both findings provide support for the relevance of SMR power in cortical processes underlying superior shooting performance and in support of

the concept of psychomotor efficiency. Notably, the consideration concerning age-related difference on SMR power has been ruled out in our analysis.

The association of lower activation in sensorimotor cortex as reflected by higher SMR power supports psychomotor efficiency in superior shooting performance. Previous studies have suggested that higher SMR power is correlated with lower activity of the sensorimotor cortex (Serman, 1996) and lower activation in this area has been associated with various positive effects on skilled motor performance. For instance, Ros et al. (2009) found that a shortened overall operation duration and lower anxiety score were observed following augmented SMR NFT in microsurgery performance. Gruzelier et al. (2010) also revealed that improved acting performance and a higher subjective flow state were reported with augmented SMR power after NFT. These results suggest that augmented SMR power is related to improved attention-related processes through fine-tuning impulse control, as well as the integration of relevant environmental stimuli. This explanation is supported by previous studies of the positive effects of augmented SMR NFT on cognitive performance. For example, Egner and Gruzelier (2001) observed, after SMR NFT, an increased P300b amplitude at frontal, central, and parietal sites in the auditory oddball task, as well as reductions in commission errors and reaction time variability on the Test of Variables of Attention. Similarly, Doppelmayr and Weber (2011) demonstrated that participants exhibited improved performance on spatial rotation, simple, and choice reaction time tasks, suggesting advanced visuospatial ability after augmented SMR NFT. Augmented SMR NFT also improved the memory and attentional performance, accompanied by increased N1 and P3 event-related potential amplitudes (Kober et al., 2015). In the context of sport performance, higher SMR power in the final phase of preparation was linked with better performance output in dart-throwing (Cheng, Hung, et al., 2015) and golf putting (Cheng, Huang, et al., 2015). Collectively, these results suggest that lower sensorimotor processing decreased interference with visual processing (Serman, 1996), indicating a lower complexity during motor performance, which could strengthen cognitive performance by improving attentional processing (Kober et al., 2015). This adaptive cognitive processing is conducive to natural internal guidance for action execution (Milton et al., 2007) and is associated with the type of optimal-automatic performance from the MAP model (Bertollo et al., 2016; Di Fronso et al., 2016).

The SMR power as a promising EEG component for distinguishing the subtle differences in cognitive processes between the best and worst air-pistol shooting performances was further supported by our control analysis. The results showed that superior shooting performance was related to higher power in 12–15 Hz at the sensorimotor area whereas the

neighboring frequency bands remained indifferent. The frequency specificity of the SMR power in skilled motor performance is in agreement with previous studies (Cheng, Hung, et al., 2015), which suggests a negative relationship between SMR and the variability in the movement preparation and supports the notion that the sensorimotor cortex may serve as a specific brain area for processing the most relevant cognitive information during air-pistol shooting performance. The finding of no significant cortico-cortical communication between Cz and other electrodes along with the notion that the sensorimotor area is a key region for processing motor interference information (Kober et al., 2015; Sterman, 1996) and pure motor information (Hatfield & Hillman, 2001) provide another support for the specific role of SMR in motor performance. The more economical activities in the somatosensory area and premotor area in movement preparation were also discovered in a previous study, which showed that more reduced brain activities were found in top-level shooters than novices in a self-paced finger tapping task (Di Russo, Pitzalis, Aprile, & Spinelli, 2005), suggesting a more refined neural processing. Taken together, higher SMR power, representing inhibition of sensorimotor cortical activation, might lead to fine-tuned neural processing in the sensorimotor area, which results in superior shooting performance. This finding supports the notion of psychomotor efficiency.

Apart from the activity of a single EEG electrode, less irrelevant processing prior to trigger pull might result in better shooting performance. We found that the high alpha coherence was lower in Fz–T3 before trigger pull for the best performance than the worst, suggesting that the communication between the motor planning and the verbal-analytical regions during the motor task was more fine-tuned, with greater attenuation of irrelevant cortical co-activation. Reduced verbal-analytic processing has been associated with expertise but not relevant in novices during the motor performance (Deeny et al., 2003; Hatfield et al., 2004; Haufler et al., 2000). This result was in agreement with previous findings inferring that greater psychomotor efficiency during movement execution is based on reduced co-activation of Fz–T3 coherence (Zhu et al., 2011). The best performance in our study is consistent with the Type 1 performance state construed within the MAP model (Bertollo et al., 2016; Di Fronso et al., 2016), which suggests that less conscious control on performance is related to the optimal-automatic motor performance. Therefore, psychomotor efficiency could be considered as a part of the optimal performance categorized by the MAP model, indicating that the degree of perceived control separates the Type 1 (Efficient processing) performance from the Type 2 (Effortful processing) performance (Robazza, Bertollo, Filho, Hanin, & Bortoli, 2016). As previous studies have shown that alpha coherence is related to top-down processing, which might converge the

sensory input from multiple areas (Von Stein & Sarnthein, 2000), our study indicates that examining SMR power is prospective and influential for understanding the psychomotor processing in precision sports (Cheng, Hung, et al., 2015).

The finding of higher SMR in superior performance assisted in understanding lower variability in the preparation of self-paced performance. Several EEG studies have been suggested relating to this argument in precision sports. For example, previous studies have demonstrated that lower frontal midline theta power was associated with better performance in basketball free throw (Chuang, Huang, & Hung, 2013) and golf putting (Kao, Huang, & Hung, 2013), suggesting a more efficient cortical load during the tasks. Similarly, higher alpha power at the occipital region was associated with better air-pistol shooting performance, suggesting a state of more intentional processing instead of controlled processing (Loze et al., 2001). In addition, lower cortical communication between the frontal and left temporal regions has been found in expert marksmen compared to lesser skilled shooters (Deeny et al., 2003). Higher SMR power in superior shooting performance suggested an adaptive cortical processing with lower interference and complexity from sensorimotor processing.

Taken together, the more efficient cortical processing symbolizes a distinguishing index for superior motor performance, indicating that lesser noise and more task-related cortical processing are the fundamental factors composing peak performance. These findings and interpretation provide convergent evidence supporting the notion of psychomotor efficiency. Furthermore, the more automatic processing in the best performance as reflected by higher SMR power is consistent with the Type 1 performance state of the MAP model, suggesting a superior psychomotor efficiency performed by the shooters. Future studies should work on drawing a more comprehensive picture regarding optimal cortical processing, especially the Type 2 performance state proposed by the MAP model, in self-paced performance by combining these established EEG indices.

The understanding regarding cortical complexity of motor performance, as reflected by SMR power, could be improved by several methodological considerations. First, future studies should include some relevant subjective measurements with mental scales when designing their experiments, e.g. the Activation/Deactivation-Adjectives Checklist (Gruzelier, 2014a) or the flow state scale (Jackson & Eklund, 2004). Second, registration of high-density electrodes and the use of analytical tools with high spatial resolution should be considered to be more precise about the sources of EEG signals. Third, shooting quality could be further classified based on objective measurements, such as the markers of shot 'hold' and triggering 'trace length', as well as subjective measurements, such as self-reported performance (Di Fronso et al., 2016).

Fourth, the examination of functional connectivity concerning SMR activity is still warranted for future studies, especially in relation to cortical communication at the high alpha frequency band, which has been addressed as a sensitive index of inter-region communication (Von Stein & Sarnthein, 2000). Kober et al. (2015) found that augmented SMR power might reflect sensorimotor interference, as reflected by reduced functional connectivity between motor areas and parietal-occipital areas. However, the shooters in this study exhibited identical coherences at the SMR band between best and worst shots before trigger pulls. These incongruent findings might be due to the design of the studies (e.g., between subjects vs. within subjects). The changes in network dynamics regarding SMR activity should be further investigated to close the knowledge gap regarding cortical interaction during the final phase of action execution, especially considering that the connectivity between sensorimotor cortex and parietal cortex on high alpha frequency bandwidth is believed to be functionally related to motor performance (Baumeister et al., 2013).

In summary, skilled air-pistol shooters exhibited higher SMR power during the last second before best shots than before worst shots, suggesting reduced activity in the sensorimotor cortex, possibly reflecting how inhibition of nonessential sensorimotor information input and lower variability in the movement preparation is antecedent for superior task execution. The frequency specificity and coherence analyses provided additional support for the significant activity of SMR power in air-pistol shooting performance. These findings lend support to previous evidence suggesting that fine-tuned activation in the sensorimotor cortex is essential to producing more automatic processing in skilled performance (Baumeister et al., 2008). These observations are in line with the psychomotor efficiency hypothesis and the Type 1 performance state of the MAP model (Robazza et al., 2016), which suggests that optimal performance is constructed by a more automated manner with minimal conscious on performance control.

CHAPTER 4

IMPROVING THE PSYCHOMOTOR EFFICIENCY PERFORMANCE BY USING EEG NEUROFEEDBACK TRAINING

Abstract Sensorimotor rhythm (SMR) activity has been related to automaticity during skilled action execution. However, few studies have bridged the causal link between SMR activity and sports performance. This study investigated the effect of SMR neurofeedback training (SMR NFT) on golf putting performance. We hypothesized that preelite golfers would exhibit enhanced putting performance after SMR NFT. Sixteen preelite golfers were recruited and randomly assigned into either an SMR or a control group. Participants were asked to perform putting while electroencephalogram (EEG) was recorded, both before and after intervention. Our results showed that the SMR group performed more accurately when putting and exhibited greater SMR power than the control group after 8 intervention sessions. This study concludes that SMR NFT is effective for increasing SMR during action preparation and for enhancing golf putting performance. Moreover, greater SMR activity might be an EEG signature of improved attention processing, which induces superior putting performance.

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4.1. Introduction

The quality of mental regulation can differentiate superior from inferior performance in precision sports activities such as golf putting. In golf, the putt is considered one of the most important parts of the game, representing on average 43% of all shots taken during a single round (Pelz & Frank, 2000). From a technical perspective, putting is the simplest skill used in golf. However, mentally, putting is the most stressful and demanding activity in the game (Nicholls, 2007). The mental challenge of putting is reflected by previous psychophysiological studies showing complex brain processes during putting performance (Babiloni et al., 2008). Hence, the maintenance of a mental state conducive to skilled execution is critical for ideal precision sports performance.

Superior performance in precision sports can be characterized as an automatic process as opposed to a controlled process, which is typically observed in less skilled performers (Fitts & Posner, 1967). An automatic process is by nature reflexive, whereas a controlled process is an intentionally initiated sequence of cognitive activity (Schneider & Shiffrin, 1977). Achieving automatic process in action execution is the primary goal of mastery (Logan, 1991). Differences between these two levels of cognitive processing are reflected at the neurophysiological level: participants who were in the automatic stage exhibited weaker activity of the bilateral cerebellum, pre-supplementary motor area, premotor cortex, parietal cortex, and prefrontal cortex compared to novices (Wu et al., 2008). In addition, the somatosensory cortex has been related to conscious perception of somatosensory stimuli (Nierhaus et al., 2015), such that lower activity in the somatosensory cortex might be a signature of reduced conscious involvement in movement execution, as is frequently observed in highly skilled performers.

Although previous studies of the brain function underlying superior golf putting performance have provided insights into adaptive mental states and their cortical processes, few studies have examined the cortical processes that are more directly associated with somatosensory activity. For example, Babiloni et al. (2008) demonstrated that successful putting was preceded by higher high-frequency alpha (10–12 Hz) event-related desynchronization (ERD) over the frontal midline and the right primary sensorimotor area compared to unsuccessful putting performance. Similar studies found that reduced (Kao et al., 2013) and stable (Chuang et al., 2013) frontal midline theta power was the precursor of superior performance in precision sports. Since high-frequency alpha power in these cortical areas reflect only task-related attention (Klimesch, 1997) whereas frontal midline theta power indicates top-down sustained attention (Sauseng, Hoppe, Klimesch, Gerloff, & Hummel, 2007),

these findings support the importance of specialized task-related attention on superior motor performance. However, the information encoded during automatic somatosensory processing during skilled precision sport performance remains unexamined as yet.

Sensorimotor rhythm (SMR), the 12–15 Hz oscillation of the sensorimotor cortex, has shown promising as a link between adaptive mental states (e.g., automatic process-related attention) and skilled visuomotor performance. SMR is considered an indicator of cortical activation, which is inversely related to somatosensory processing (Mann et al., 1996). A recent study showed that skilled dart-throwing players demonstrated higher SMR power prior to dart release than novices in a dart-throwing task (Cheng, Hung, et al., 2015). This result suggests that lower cognitive involvement in processing somatosensory information as reflected by higher SMR power is characteristic of skilled performance. Furthermore, several lines of studies pertaining to SMR power tuning for enhancing adaptive cortical processing in motor performance have shown promising results. Augmented SMR power resulting from neurofeedback training (NFT) has been identified as a relaxed focus state without somatosensory intervention (Gruzelier et al., 2014). Similarly, a reduced trait anxiety score and task-processing time during microsurgery were observed after augmented SMR NFT (Ros et al., 2009). Moreover, a facilitative sense of control, confidence and feeling at-one with a role was demonstrated after augmented SMR NFT prior to acting performance (Gruzelier et al., 2010). Thus, increased SMR activity implies the maintenance of a relaxed, focused state by reducing motor perception (e.g., somatosensory processing) by the sensorimotor cortex (Vernon et al., 2003). This interpretation is similar to the mental characteristics of peak performance in skilled athletes (Krane & Williams, 2006) and is in agreement with the concept of automaticity proposed by Fitts and Posner (1967). Hence, SMR power not only might be a sensitive indicator of the activity of sensorimotor cortex (Mann et al., 1996) but also shows potential for a performance-enhancing intervention.

Although there is no direct evidence to support the effectiveness of SMR NFT on performance enhancement in precision sport, two lines of research lend support to its potential use in sports. First, previous studies have demonstrated the effectiveness of NFT on performance enhancement in precision sports. For example, Landers et al. (1991) demonstrated that "correct" NFT (i.e., augmented slow cortical potential at the left temporal lobe) led to superior performance, whereas "incorrect" NFT (i.e., augmented slow cortical potential at the right temporal lobe) impaired performance in skilled archers. Similarly, Kao et al. (2014) reported that NFT targeting to reduce the frontal midline theta resulted in improved performance in skilled golfers. These findings support the feasibility of tuning EEG to improve

behavioral outcome in precision sports. The second line of evidence is the finding that SMR NFT has a beneficial effect on attention-related performance in various attentional tasks. For example, an increased P300b amplitude at frontal, central, and parietal sites during the auditory oddball task and reduced commission errors, and a reduction in reaction time variability during the Test of Variables of Attention (TOVA) was observed after augmented SMR NFT (Egner, Zech, & Gruzelier, 2004).

These findings suggest that augmenting SMR power might improve attention-related processes by improving impulse control and the ability to integrate relevant environmental stimuli. Similarly, Ros et al. (2009) reported that a shorter operation time and reduced trait anxiety score were observed in surgeons following augmented SMR NFT, suggesting that augmented SMR enhanced the learning of a complex medical specialty by developing sustained attention and a relaxed attentional focus as well as increasing working memory (Vernon et al., 2003). Furthermore, Doppelmayr and Weber (2011) revealed that augmented SMR NFT not only resulted in a significant SMR amplitude increase accompanied by a significant increase in reward threshold but also facilitated the performance of spatial-rotation, simple, and choice-reaction time tasks. These results indicate that visuospatial processing, semantic memory regulation, and the integration of relevant stimuli can be improved following augmented SMR NFT. Collectively, the benefits of augmented SMR NFT can be attributed to an improved regulation of somatosensory and sensorimotor pathways, which in turn leads to more efficient attention allocation (Kober et al., 2015) that results in an improved processing of task-relevant stimuli.

To the best of our knowledge, no study has directly examined the effect of SMR NFT on precision sport performance. Thus, this study investigated the effect of SMR NFT on a golf putting task. We predicted that golfers would be able to increase SMR power prior to putting execution following augmented SMR NFT. More importantly, we predicted that increased SMR power improves putting performance as a result of augmented SMR NFT.

4.2. Methods

4.2.1. Participants

Fourteen male and two female pre-elite and elite golfers were recruited (*Mean handicap* = 0, *SD* = 3.90). Participants were matched based on performance history supplemented by the assessment of a professional coach and then randomly assigned into either an SMR neurofeedback group (SMR NFT) or a control group (seven male and one female for each group). The mean age of the SMR NFT and control group were 20.6 (1.59) and 22.3 (2.07),

respectively. The years of experience in golf were 9.5 (2.67) for the SMR NFT group and 9.2 (1.83) for the control group. An independent t test showed no difference in age [$t(14) = 1.895$, $p = .079$] or years of experience in golf [$t(14) = 0.273$, $p = .789$] between the two groups. None of the participants reported psychiatric and neurological disorders and had never been hospitalized for general brain damage.

4.2.2. Procedures

For the pre-test and post-test, we used the same procedure to collect data. At pre-test, after being informed of the general purpose of the study, all participants were asked to read and sign an informed consent form approved by our institutional review board. They were then given the opportunity to ask questions about the experiment. The participants were individually tested in a sound-proof indoor artificial golf green, where they were initially required to stand 3 m from a hole 10.8 cm in diameter to obtain an individual putting distance (Arns, Kleinnijenhuis, Fallahpour, & Breteler, 2007). Participants performed a series of 10 putts, which were scored as successfully holed or not holed. The percentage of successful putts in a series was determined after each series. This process was repeated until each participant achieved 50% accuracy.

After the individual putting distance was determined, participants were fitted with a Lycra electrode cap (Neuroscan, Charlotte, NC, USA). After a 10 min warm up, participants were first asked to undergo a resting EEG recording, including eye-closed and eye-opened conditions, while assuming a normal putting stance for 1 min each. Then, all participants performed golf putting tasks consisting of 40 self-paced putting trials in 4 separate recording blocks while EEGs were recorded. The participants performed the putting task in the standing position and were allowed to take a brief rest between each putt. They were also allowed to sit briefly after each block of 10 putts. The score was calculated based on the linear distance from the edge of hole to the edge of the ball (cm). Putting into the hole successfully was determined as score 0. Putting trials in which the ball was deflected by contacting the edge of the hole were excluded, and participants were asked to perform extra putting trials to complete the forty trials. The experiment lasted approximately 2 hours in total. After completing the pre-test, all participants were scheduled to go through 8 sessions of neurofeedback training. Then the post-test, which was identical to the pre-test, followed after the neurofeedback intervention.

4.2.3. Instrumentation

4.2.3.1. EEG

For the pre-test and post-test, EEGs were recorded at 32 electrode sites (FP1, FP2, F7, F8, F3, F4, FZ, FT7, FT8, FC3, FC4, C3, C4, CZ, T3, T4, T5, T6, TP7, TP8, CP3, CP4, CPZ, A1, A2, P3, P4, PZ, O1, O2, OZ) corresponding to the International 10–10 system (Chatrian et al., 1985). In addition, 4 electrodes were attached to acquire horizontal and vertical oculography (HEOL, HEOR, VEOU and VEOL). All sites were initially referenced to A1 and then re-referenced to linked ears offline. A frontal midline site (FPz) served as the ground. EEG data were collected and amplified using a Neuroscan Nuamps amplifier (Neuroscan, Charlotte, NC, USA) with a band-pass filter setting of 1–100 Hz and a 60Hz notch filter. EEG and EOG signals were sampled at 500 Hz recorded online with NeuroScan 4.5 (Neuroscan, Charlotte, NC, USA) software installed on a Lenovo R400 laptop (Lenovo, Taipei City, R.O.C). Vertical and horizontal eye movement artifacts were recorded via bipolar electro-oculographic activity (EOG), in which vertical EOG was assessed by electrodes placed above and below the left eye (VEOU and VEOL), whereas horizontal EOG was assessed by electrodes located at the outer canthi (HEOL, HEOR). Impedance values for all electrode sites were maintained below 5k Ω . An infrared ray sensor was set to detect the swing for each putt. Once the back swing movement was detected, an event mark was sent to the EEG data, which served as the time point for analyzing the EEG activity before putting. Twelve to fifteen hertz of Cz was extracted as the SMR (Babiloni et al., 2008).

4.2.3.2. Neurofeedback

Neurofeedback training was completed with a NeuroTek Peak Achievement Trainer (NeuroTek, Goshen, KY). The EEG data from the assessment were band-pass filtered using the BioReview software (NeuroTek, Goshen, KY). The active scalp electrode was placed at Cz for SMR training, with the reference placed on both mastoids. Signal was acquired at 256 Hz and then A/D converted and band filtered to extract the SMR (12–15 Hz). The amplitude of the SMR was transformed online into graphical feedback representations including the audio-feedback tone by acoustic bass (NO. 33) in the BioReview software.

4.2.4. Neurofeedback Training Procedure

Participants underwent an eight-session training program lasting 5 weeks. Each session was composed of neurofeedback training lasting from 30 to 45 min. On average, a total of 12 training trials were performed in a single session. Each training trial comprised of 30 seconds. The total duration of a single session was approximately 30 minutes. The SMR NFT group aimed to increase absolute SMR amplitude over the designated threshold, which was

individually determined by averaging 1.5 s of each participant's successful putting trials during the pre-test. To enhance the participants' efficacy during NFT, a progressive adjustment of the training threshold difficulty was employed. The standard for adjusting the training threshold was based on the individualized standard deviation which derived from the SMR power of the final three 0.5 s time windows prior to putting during the pre-test. When participants' SMR power was higher than the threshold, the acoustic bass sound was displayed. Participants were instructed to perform based on their own putting routine while receiving the auditory feedback. The successful training ratio, defined as the time spent above threshold divided by the total time of a single training trial (30 s), was reported to participants following every training trial.

In the control group, the training protocol was similar to that used by the previous study (Egner, Strawson, & Gruzelier, 2002) to establish a mock feedback condition. This protocol was designed to prevent study participants from learning to regulate SMR by using the randomly pre-recorded feedback tone during the training trials from SMR NFT group. The total length of this pre-recorded mock feedback tone was 4 min that were derived from a randomly chosen participant in the SMR NFT group during the session 1 training. Researchers played the mock feedback tone from a random starting point to guarantee a randomized feedback tone was received by participants in the control group. On average, a total of 7 training trials were performed in a single session and the total duration of a single session was approximately 30 minutes.

To evaluate the neurofeedback learning effect, the mean successful training ratio of each session was recorded and computed for subsequent analysis. To reduce the number of sessions necessary for statistical evaluation of the learning efficiency between the two groups, we combined two consecutive sessions into one section [e.g., section 1 = (session 1 + session 2) / 2].

4.2.5. Data Reduction

EEG data reduction was conducted offline using the Scan 4.5 software (Neuroscan, Charlotte, NC, USA). EEG data were sampled 1.5s prior to putting execution and were triggered by the event-related marker from infrared ray sensors. Trial preparation periods of less than 1.5 s were excluded to establish the common structure of artifact-free data across trials and participants. EOG correction (Semlitsch et al., 1986) was carried out on continuous EEG data to eliminate blink artifacts. EEG segments with amplitudes exceeding $\pm 100 \mu\text{V}$ from baseline were excluded from subsequent analysis. After artifact-free EEG data were acquired, Fast Fourier Transforms (FFT) were calculated at 50% overlap on 256 sample Hanning

windows for all artifact-free segments to transform to spectral power (μV^2). SMR power was computed as the mean of 12–15 Hz from Cz and then natural log transformed (Davidson, 1988). To compute a normalized EEG power for each golfer, the relative power was utilized, for which the ratio of power at 12–15 Hz to 1–30 Hz was computed (Niemarkt et al., 2011).

4.2.6. Statistical Analyses

The average putting score and standard deviation between the two groups was analyzed by a 2 (Group: SMR NFT, Control) \times 2 (Test: pre-test, post-test) analysis of variance (ANOVA) with repeated measures on the test factor.

The difference score (post-test – pre-test) for the relative power of SMR was subjected to a 2 (Group: SMR NFT, Control) \times 3 [Time window: -1.5s – -1.0 s (T1), -1.0 s – -0.5s (T2), -0.5s – 0 s (T3)] ANOVA with repeated measures on the time window factor.

In addition, we ran several control analyses to provide additional evidence to support our conclusions.

The success of the training ratio was tested by a 2 (Group: SMR NFT, Control) \times 4 (Training section: Section 1: sessions 1–2; Section 2: sessions 3–4; Section 3: sessions 5–6; Section 4: sessions 7–8) ANOVA with repeated measures on the training section.

To characterize the within-session learning effect, we compared the successful training ratio of the first and last trials of each session across all eight sessions. A 2 (Group: SMR NFT, Control) \times 8 (Session: session 1, 2, 3, 4, 5, 6, 7, 8) \times 2 (Trial: first trial, last trial) three-way ANOVA with repeated measures on the session and trial was used to examine this issue.

To ensure control of neurofeedback in the SMR NFT group within the training program, we employed a one-way ANOVA with training section (Training section: Section 1: sessions 1–2; Section 2: sessions 3–4; Section 3: sessions 5–6; Section 4: sessions 7–8) as a variable to detect the threshold fluctuation within the four training sections.

To examine the regional fluctuation of 12–15 Hz power before and after training, we carried out a 2 (Group: SMR NFT, Control) \times 4 (Region: frontal, central, parietal, occipital) two-way ANOVA with repeated measures on the region.

The examination of concurrent changes in neighboring frequency bands was conducted by analyzing the pre-post difference scores for theta (4–7 Hz), alpha (8–12 Hz), low beta (13–20 Hz), high beta (21–30 Hz), and broad beta (13–30 Hz) frequency bands with a 2 (Group: SMR NFT, Control) \times 3 [Time window: -1.5 s – -1.0 s (T1), -1.0 s – -0.5 s (T2), -0.5 s – 0 s (T3)] two-way ANOVA.

Mauchly's test was used to assess the validity of the ANOVA sphericity assumption

whenever necessary. The degrees of freedom were corrected using the Greenhouse-Geisser procedure, and least significant difference (LSD) analysis was used for post hoc comparisons ($p < .05$). The partial eta square (η^2) was used to estimate the effect size, with values of .02, .12, and .26 suggesting relatively small, medium, and large effect sizes, respectively (Cohen, 1992).

4.3. Results

4.3.1. Putting Performance

The mean distance of the SMR group in the pre-test and post-test was 29.62 cm (5.59) and 16.59 cm (8.92), respectively. The control group distance was 20.17 cm (12.07) and 18.80 cm (5.58), respectively. An independent t test showed no difference in the mean distance in the pre-test between two groups [$t(14) = 2.008, p = .073, \eta^2 = .224$]. The 2 (Group: SMR NFT, Control) \times 2 (Test: pre-test, post-test) mixed model ANOVA revealed a significant interaction effect on putting performance [$F(1, 14) = 5.029, p = .042, \eta^2 = .264$]. The SMR neurofeedback group exhibited a shorter distance from the hole in post-test than pre-test [$t(7) = 3.417, p = .011, \eta^2 = .625$]. No significant difference was observed for other comparisons.

4.3.2. Putting Performance in Standard Deviation

A marginal interaction effect was observed in the 2 (Group: SMR NFT, Control) \times 2 (Test: pre-test, post-test) ANOVA [$F(1, 14) = 4.121, p = .062, \eta^2 = .227$]. We did not observe an effect on Group factor [$F(1, 14) = 0.136, p = .717, \eta^2 = .010$]. The SMR group exhibited a significantly lower SD in the post-test (16.11 cm) than in the pre-test (24.70 cm) [$t(7) = 4.408, p = .003, \eta^2 = .735$], whereas the control group showed no significant variation in SD (21.03 cm to 18.38 cm) [$t(7) = 1.208, p = .266, \eta^2 = .173$].

4.3.3. SMR Relative Power

The difference scores of the SMR group members for T1, T2, and T3 was 0.481 (0.588), 0.186 (0.378), and 0.040 (0.268), respectively. For the control group, the difference scores was -0.200 (0.424), -0.143 (0.440), and 0.009 (0.444), respectively. We compared the difference scores with a 2 (Group: SMR NFT, Control) \times 3 [Time window: -1.5 s – -1.0 s (T1), -1.0 s – -0.5 s (T2), -0.5 s – 0 s (T3)] two-way ANOVA and observed a marginally significant two-way interaction effect [$F(2, 28) = 3.315, p = .051, \eta^2 = .191$]. To explore this marginal interaction effect and examine the training effect before and after NFT, a subsequent simple main effect analysis was performed and revealed a marginal Time effect [$F(2, 14) = 3.470, p = .060, \eta^2$

= .331] in the SMR NFT group. Post hoc analysis showed that the SMR power was significantly greater in T1 than in T3 [$t(7) = 2.925, p = .022, \eta^2 = .550$]. No significant simple main effect was observed in the control group [$F(2, 14) = .671, p = .567, \eta^2 = .141$]. In addition, a simple main effect analysis revealed that the SMR NFT group exhibited a relatively higher SMR power than that of the control at T1 [$t(14) = 2.657, p = .019, \eta^2 = .335$]. The significant group main effect revealed that the SMR NFT group had a higher SMR power than that of the control group [$F(1, 14) = 4.665, p = .049, \eta^2 = .250$]. The difference scores between the two groups are depicted in Figure 4.1.

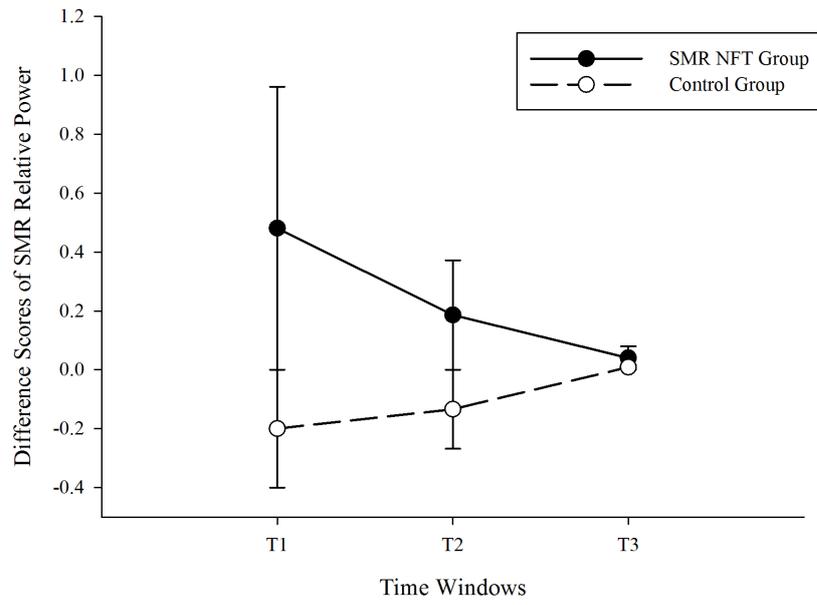


Figure 4.1. The difference scores of SMR relative power between the SMR NFT and control groups at T1 (-1.5 s – -1.0 s), T2 (-1.0 s – -0.5 s) and T3 (-0.5 s – 0 s).

4.3.4. Control Analyses

4.3.4.1. *Successful training ratio*

The overall mean of the golfers' successful training ratio was 62.39 (8.88) % for the SMR training group and 22.27 (22.28) % for the control group. The 2 (Group: SMR NFT, Control) \times 4 (Training section: Section 1: sessions 1–2; Section 2: sessions 3–4; Section 3: sessions 5–6; Section 4: sessions 7–8) ANOVA showed no interaction effect [$F(3,42) = 0.694$, $p = .497$, $Eta^2 = .047$], but a significant group main effect was observed [$F(1,14) = 22.188$, $p = .001$, $Eta^2 = .613$]. The SMR group showed a significantly higher percentage of successful training ratios than did the control group. Table 4.1 lists the successful training ratio for each group during the training sections.

Table 4.1.

The successful training ratios between the SMR NFT and control groups across the four training sections (every two consecutive session was folded resulting in 4 sections).

	Section 1	Section 2	Section 3	Section 4	Total
SMR	53.82 (19.71)	63.85 (12.53)	65.63 (9.52)	66.27 (17.91)	62.39 (5.08)
Control	20.51 (24.11)	23.02 (26.31)	22.94 (21.58)	22.62 (19.61)	22.27 (1.09)

Unit : %. Percentage of increasing time for successfully controlling SMR power

4.3.4.2. *Within-Session Learning*

The results of NFT can be affected by day-to-day fluctuations in arousal level (Gruzelier et al., 2014). Thus, in addition to comparing the average successful training ratios of the eight sessions between these two groups, we compared the successful training ratios of the first and last trials of each session for all eight sessions between the two groups to determine whether participants in the NFT group improved within each training session. We hypothesized that the successful training ratio would be greater in the last trial than in the first trial for the SMR NFT group but not for control group. A 2 (Group: SMR NFT, Control) \times 8 (Session: sessions 1, 2, 3, 4, 5, 6, 7, 8) \times 2 (Trial: first trial, last trial) three-way ANOVA was employed to test this hypothesis. The result showed that although the 3-way interaction effect was not significant [$F(7, 98) = 2.063, p = .082, \eta^2 = .128$], a 2 (Group: SMR NFT, Control) \times 2 (Trial: first trial, last trial) interaction effect [$F(1, 14) = 33.192, p = .001, \eta^2 = .703$] was revealed. Post hoc analysis was consistent with our prediction; only the SMR NFT group demonstrated a greater successful training ratio in the last trial ($M = 77.65, SD = 7.84$) than in the first trial ($M = 50.58, SD = 10.65$) for all sessions [$t(7) = 8.344, p = .001, \eta^2 = .909$]. The control group did not show a significant difference between the first trial ($M = 12.19, SD = 11.86$) and last trial ($M = 16.32, SD = 17.00$) [$t(7) = 1.784, p = .118, \eta^2 = .313$]. In addition, the SMR NFT group demonstrated a significantly higher training ratio on the first trial [$t(7) = 6.810, p = .001, \eta^2 = .768$] and last trial [$t(7) = 9.267, p = .001, \eta^2 = .860$] than did the control group (Figure 4.2).

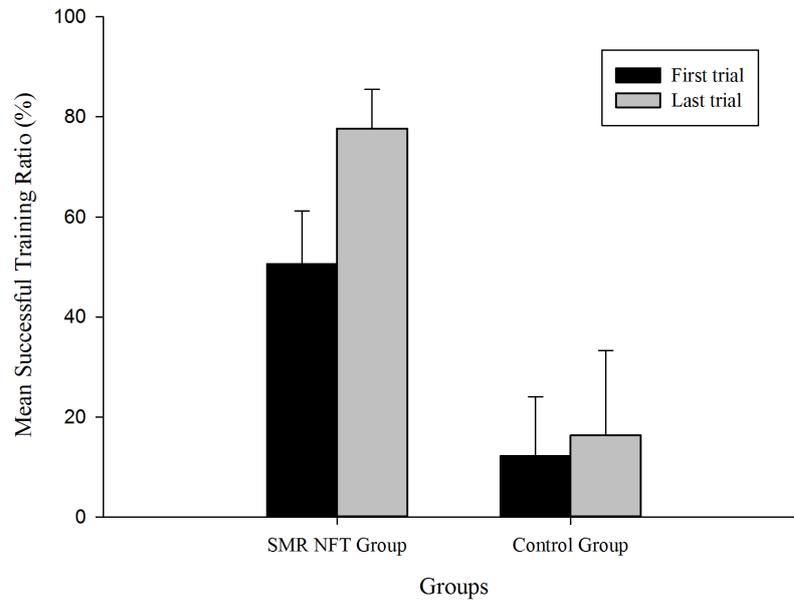


Figure 4.2. The mean successful training ratio for the first and last trial between the SMR NFT and control groups across the eight training sessions.

4.3.4.3. Threshold increments within SMR training sessions

Although our control analyses provided supportive evidence for the learning progress made by the SMR NFT group, we further analyzed the change in threshold during each session of SMR NFT. In our study, threshold level was used as a difficulty index in the SMR NFT group, in which golfers were instructed to increase the SMR above designated level to meet our training demand. Thus, an improvement in the successful training ratio from the two previous control analysis was meaningful only when the threshold for each session was also examined. Previous studies evaluated the threshold variation within day-to-day sessions and suggested that the increased threshold could serve as a marker for improvement of the controllability due to neurofeedback training (Doppelmayr & Weber, 2011). Thus, we converted the eight training sessions into four sections as described in the methods section and examined the training threshold variation by employing an one-way ANOVA to examine the effect of Training section (Section 1: sessions 1–2; Section 2: sessions 3–4; Section 3: sessions 5–6; Section 4: sessions 7–8) in the SMR group. We hypothesized that the threshold value would increase after the first training section, which supports an improvement in controllability due to SMR neurofeedback training. The average training thresholds for sections one to four in the SMR NFT group were 5.862 (2.781), 7.636 (3.368), 8.214 (3.718), and 7.750 (3.816), respectively. As predicted, a significant difference was detected by the one-way ANOVA [$F(3, 18) = 9.945, p = .001, \eta^2 = .624$]. Post hoc analysis demonstrated that the training thresholds in the second, third, and fourth sections were significantly higher than that of the first section.

4.3.4.4. Electrode specificity

Although the present study demonstrated that the relative SMR power of the SMR NFT group was significantly higher than that of the control group following SMR NFT, it remained unknown whether the greater 12–15 Hz EEG relative power after training was limited to the sensorimotor cortex or there was a spillover to other regions, such as the frontal, parietal and occipital cortices. Thus, we compared the difference scores at 12–15 Hz EEG relative power among Fz, Cz, Pz, and Oz between pre- and post-test sessions. Previous work has shown that the SMR originated in the centro-parietal region (Grosse-Wentrup, Schölkopf, & Hill, 2011). Thus, we hypothesized that the difference score of 12–15 Hz at Cz would be greater than that of the frontal and occipital regions for SMR group participants after training. A 2 (Group: SMR NFT, Control) \times 4 (Region: Frontal, Central, Parietal, Occipital) two-way ANOVA between the two groups was performed to test this hypothesis.

The difference scores at Fz, Cz, Pz, and Oz were 0.035 (0.200), 0.212 (0.178), 0.135

(0.298), and 0.003 (0.241), respectively, for the SMR NFT group. For the control group, the difference scores at Fz, Cz, Pz, and Oz were -0.056 (0.309), -0.438 (0.169), -0.150 (0.268), and -0.168 (0.640), respectively. This result yielded a marginally significant interaction effect [$F(3, 42) = 2.680, p = .089, \eta^2 = .161$]. Because of the exploratory nature of this study, we conducted a follow-up analysis of this interaction effect. The independent t tests of the four regions between the two groups showed that significance was only observed at a difference score of Cz [$t(14) = 5.159, p = .001, \eta^2 = .655$], in which the SMR NFT group exhibited a significantly higher difference score than the control group. Moreover, one-way ANOVA of 4 regions in the SMR NFT group reached marginal significance [$F(3, 21) = 2.644, p = .076, \eta^2 = .274$]. The follow-up pair-wise t tests found that the difference score of Cz was higher than that of Fz [$t(7) = 3.740, p = .007, \eta^2 = .666$] and Oz [$t(7) = 2.530, p = .039, \eta^2 = .478$]. These lines of evidence provide preliminary support for the electrode specificity of SMR NFT in this study.

4.3.4.5. Frequency specificity

Previous studies have shown that neurofeedback training may generate concurrent changes in flanking frequency bands (Enriquez-Geppert et al., 2014). The aim of this analysis was to investigate whether SMR NFT resulted in a change in frequency bands close to SMR. We compared the relative power difference scores of theta (4–7 Hz), alpha (8–12 Hz), low beta (13–20 Hz), high beta (21–30 Hz), and broad beta (13–30 Hz) frequency bands before golf putting from pre-test and post-test between the two groups. The 2 (Group: SMR NFT, Control) \times 3 [Time window: -1.5 s – -1.0 s (T1), -1.0 s – -0.5 s (T2), -0.5 s – 0 s (T3)] two-way ANOVA showed that neither interaction effects on theta power [$F(2, 28) = 0.550, p = .583, \eta^2 = .038$], alpha power [$F(2, 28) = 0.113, p = .802, \eta^2 = .011$], low beta power [$F(2, 28) = 0.052, p = .949, \eta^2 = .004$], high beta power [$F(2, 28) = 0.503, p = .496, \eta^2 = .035$], and broad beta band [$F(2, 28) = 0.883, p = .425, \eta^2 = .059$] nor group main effects on theta power [$F(1, 14) = 0.032, p = .860, \eta^2 = .002$], alpha power [$F(1, 14) = 0.070, p = .795, \eta^2 = .005$], low beta power [$F(1, 14) = 0.764, p = .397, \eta^2 = .052$], high beta power [$F(1, 14) = 0.677, p = .424, \eta^2 = .046$], and broad beta power [$F(1, 14) = 0.023, p = .881, \eta^2 = .002$] were observed. The difference scores among these five frequency bands are listed in Table 4.2.

Table 4.2

The difference scores of relative power for theta, alpha, low beta, high beta, and beta frequency bands in three time windows between the two groups.

	T1		T2		T3	
	(-1.5 s – -1.0 s)		(-1.0 s – -0.5 s)		(-0.5 s – 0 s)	
Group	SMR	Control	SMR	Control	SMR	Control
Theta	.025	.338	-.234	-.186	.311	.085
relative power	(.621)	(.493)	(.172)	(.528)	(1.071)	(.452)
Alpha	.006	.048	.052	.017	-.006	-.058
relative power	(.134)	(.221)	(.177)	(.216)	(.465)	(.223)
Low beta	.035	.014	-.069	-.029	-.097	-.033
relative power	(.258)	(.135)	(.124)	(.164)	(.183)	(.082)
High beta	.014	.015	-.046	.128	-.047	-.030
relative power	(.190)	(.109)	(.085)	(.593)	(.152)	(.070)
Beta	.034	.053	-.064	-.029	-.050	-.082
relative power	(.164)	(.010)	(.094)	(.077)	(.137)	(.112)

Unit: %

4.4. Discussion

The aim of this study was to investigate the effect of SMR neurofeedback training on golf putting performance. Our results showed that golfers receiving SMR neurofeedback training demonstrated enhanced SMR activity during the final 1.5 s prior to golf putting, resulting in better putting performance compared to the control group. This finding lends preliminary support to the hypothesis that SMR NFT is effective for increasing SMR power and leads to superior putting performance.

Increased SMR power by NFT results in better visuomotor performance. For behavioral data, we observed that SMR neurofeedback training improved skilled golfers' putting performance, as indicated by the reduced average distance from the hole and the variability of the score. No significant change in putting performance was observed in the control group. Previous studies have demonstrated that augmenting SMR by NFT improved visual motor performance (Ros et al., 2009) and increased self-rating scores of subjective flow state in dancers (Gruzelier et al., 2010). Furthermore, augmenting SMR by NFT was related to an improved attention-related mental state (Vernon et al., 2003) and memory performance (Hoedlmoser et al., 2008). In addition, converging lines of evidence support the effectiveness of NFT based on non-SMR variables enhancing performance in the sport domain (Arns et al., 2007; Gruzelier et al., 2010; Kao et al., 2014; Landers et al., 1991; Raymond, Sajid, Parkinson, & Gruzelier, 2005). Nevertheless, the present study is the first, to our best knowledge, to use the SMR protocol to investigate the effectiveness of NFT on sport performance. Our results support the finding of the augmented SMR power which is linked with more adaptive fine-motor performance (Cheng, Hung, et al., 2015) and extend the potential facilitation effects of SMR training to the sport domain.

Less task-irrelevant interference of somatosensory and sensorimotor processing, as reflected in augmented SMR power after training, leads to improved putting performance. A previous study has indicated that participants in the automatic stage showed weaker activity in the pre-supplementary motor area, premotor cortex, parietal cortex, and prefrontal cortex compared to novices in a self-paced sequential finger movement task (Wu et al., 2008). A negative relationship between SMR power and sensorimotor activity has been suggested (Mann et al., 1996). The drop in sensorimotor activity, as reflected by increased SMR power, may indicate a greater adaptive task-related attention allocation that facilitates the execution of sport performance (Gruzelier et al., 2010). Increasing SMR power through NFT is also related to more efficient and modulated visuomotor performance (Gruzelier et al., 2010; Ros et al., 2009). These results suggest that augmenting SMR power led to an improved adjustment of

somatosensory and sensorimotor pathways (Kober et al., 2015), which resulted in increased task-related attention toward specific tasks (Egner & Gruzelier, 2001). Moreover, previous studies have suggested that enhanced SMR power leads to a relatively higher flow state (Gruzelier et al., 2010) and calming mood (Gruzelier, 2014a). Based on the functional role of SMR, these findings imply that a reduction in sensorimotor activity may lessen the conscious processing involved in motor execution, which would lead to a more conceptual automatic process (Cheng, Hung, et al., 2015). This interpretation is in line with converging evidence supporting a beneficial effect of augmented SMR on focusing and sustaining attention, working memory, and psychomotor skills (Egner & Gruzelier, 2001; Ros et al., 2009). Collectively, the superior golf putting performance observed in the present SMR NFT group might be the result of reduced somatosensory information processing prior to the back swing, which leads to refined golf putting performance. The interpretation that a reduction in conscious interference facilitates motor operation is in line with the concept of automatic processing proposed by Fitts and Posner (1967). However, given the relatively small sample size, future research should verify the causal relationship between augmented SMR power and fine-motor performance.

Reduced cortical activity in the sensorimotor area, as reflected by the higher power of 12–15 Hz, is sensitive to superior putting performance. First, the electrode specificity of SMR NFT was demonstrated. Although electrode specificity has been suggested to be an important step in support of the NFT training effect on the corresponding EEG component at a specific brain region (Gruzelier, 2014d), this is the first study in the area of NFT and sport performance to provide such preliminary evidence for the localized training effects. The lack of difference between Cz and Pz might suggest that this region is also part of a network associated with SMR activity in motor performance. This speculation is in line with the evidence that the parietal region is involved in processing visual-spatial information during motor performance (Del Percio et al., 2011).

Second, frequency specificity was analyzed. One might argue that enhanced putting performance was caused by variation in another frequency band at the Cz site, but this explanation is inconsistent with the lack of significant changes on difference scores in the theta, alpha, low beta and high beta frequency bands. These results suggest that it is primarily SMR power that accounts for the facilitating effect of SMR NFT on putting performance rather than other neighboring frequency bands. Our demonstration of electrode and frequency specificity strengthens the hypothesis that improved putting performance was the result of reduced sensorimotor activity prior to putting execution.

The SMR NFT group improved the putting performance through the refined strategy

for controlling the SMR power and reached the training goal as a result of the training program. First, our data showed that the SMR group demonstrated a higher successful training ratio than did the control group. Second, previous studies proposed that the training effect would emphasize daily training improvement (Gruzelier et al., 2014). In our control analysis, we compared the successful training ratio of the first and the last trial within eight sessions. A significantly higher successful training ratio for the last trial than for the first trial was observed, suggesting that golfers in the SMR NFT group learned the tuning strategy successfully after the initial trials and that the strategies were effective in the subsequent trials of the remaining sessions. This result lends support to the concept of neurofeedback trainability and further confirms the possibility of EEG tuning within a single training session (Escolano, Oliven, Lopez-Del-Hoyo, Garcia-Campayo, & Minguez, 2012; Kao et al., 2014). Furthermore, we found a significant threshold increase after the first session only in SMR NFT group, suggesting that our training protocol is facilitative to golfers. This evidence was in line with previous work in which the SMR amplitude increased above the daily adjusted threshold (Weber, Köberl, Frank, & Doppelmayr, 2011).

We have several suggestions with regard to future neurofeedback studies. First, combining these studies with neuroimaging tools is necessary. Although we have provided evidence that the regulation of SMR power can enhance putting performance, this result would benefit from the experiments conducted with high-spatial-resolution neuroimaging tools, such as fMRI, to provide a more precise anatomical description of the NFT effect. Second, the phenomenological report of neurofeedback learning and its effects is often overlooked (Gruzelier, 2014b). A sophisticated measurement of subjective mental state, such as an in-depth questionnaire or scale, is needed to further elucidate the mental state associated with NFT (Gruzelier, 2014a). Third, the retention of learning driven by NFT must be examined. Thus far, this issue has received little attention, but it is critical from a practical viewpoint to determine how long the performance enhancement due to NFT lasts. Fourth, to explore the effect of SMR NFT on anticipative motor planning is needed. Future study should investigate the link between neurophysiological and cognitive processes by using the priming tests to further understand the neurocognitive architecture of golf performance. Last but not least, the changes in network dynamics after NFT should be further examined to fill the knowledge gap of cortical interaction caused by NFT. For example, the parietal and sensorimotor cortex networks are thought to be functionally relevant during motor performance (Baumeister et al., 2013).

Our findings should be interpreted with caution due to the limitations of the study. First, the sample size was limited. Some of our statistical analyses reached only marginal significance,

likely due to the small sample size. Furthermore, given the exploratory nature of the study, it is reasonable to speculate implications regarding the the marginally significant effects. Second, although the neurophysiological source of the SMR could not be precisely located due to limited spatial resolution by surface EEG, the finding of a marginally significant larger SMR difference score at the Cz site compared with the Fz and Oz sites as well as the finding that the largest magnitude of 12–15 Hz differences occurred at the Cz site rather than other frequency bands in the SMR group provide indirect evidence to support the impact of somatosensory activity on superior putting performance after SMR NFT. Third, putting is only one of many fundamental motor skills involved in golf performance. Our results may be difficult to generalize to other golf motor skills (e.g., the drive shot and tee shot). Future studies should, therefore, examine different skills involved in golf performance to determine the generalizability of the present findings. Fourth, the skill levels of the participants may impact the effect of NFT, and caution should be exercised when generalizing these findings to golfers at other skill levels.

In conclusion, an eight-session SMR NFT exhibited a putting performance enhancement and increased SMR power in SMR NFT group compared to control group, suggesting that SMR NFT is an effective protocol for enhancing putting performance through fine-tuning somatosensory interference, as reflected by augmented SMR.

CHAPTER 5

GENERAL DISCUSSION

5.1. Key Findings

The first study aimed to examine whether the expert dart-throwers exhibited a superior psychomotor efficiency during the preparation period of dart throwing when compared with the novices. The results showed that the expert dart-throwers showed higher SMR power during the preparation period compared to the novices. These results suggest that the superior performance is characterized by the lower activation of the sensorimotor cortex. The goal of the second study was to discover the neurocognitive processes of psychomotor efficiency between the personal best and worst performance in the air-pistol shooting task. The results showed that the personal best performance was associated with significantly higher SMR power than the personal worst performance during the final second before releasing the trigger.

In addition, the correlation analysis revealed that the SMR power was negatively related to the distance of shot from the bull's eye. That is, higher SMR power was related to better shooting performance.

Furthermore, the EEG coherence analysis revealed that the best performance exhibited significantly lower cortico-cortical communication on the high alpha power between Fz and T3 electrodes compared to the worst performance.

The third study was focusing on the beneficial effects of SMR NFT on golf putting performance. The behavioral results demonstrated that the SMR NFT group showed a significant improvement in golf putting performance after eight sessions of SMR NFT compared to the putting performance before the intervention.

The control analyses revealed that the SMR NFT group showed a progressive improvement on the controllability of the SMR power. The improved controllability was not observed in the control group.

5.2. Implications

5.2.1. EEG and Psychomotor Efficiency Hypothesis

The skilled performance is accompanied by higher SMR power during the preparation period. The first study examined the expert-novice difference on the SMR power during the dart-throwing preparation period. The finding reported that the significantly higher SMR power was preceded by the preparation period in the expert dart-throwers when compared with the novices. This finding suggests that the expert dart-throwers performed the dart-throwing task with an adaptive neurocognitive processes at the sensorimotor areas, indicating a specialized information processing with less sensorimotor interference compared to the novices. This implication is in line with previous study carried out in the cognitive task (Kober et al., 2015),

which suggests the reduced sensorimotor activity was related to improved stimuli recognition. The reduced sensorimotor activity in the expert dart-throwers can be interpreted as the Type 1 performance in the MAP model, which denotes the fluent performance with a high level of automaticity (Bertollo et al., 2016).

In the second study, the results showed that the more precise shooting performance is associated with higher SMR power during the preparation period in skilled performers. Likewise, the higher SMR power was observed during the preparation period in the best shots compared to the worst shots in the skilled performers. That is, the best shooting performance was associated with the reduced activity in the sensorimotor area in the skilled performers. These results support the superior psychomotor processing of the skilled performers. Hence, this finding extends our knowledge of the specific functional role of the SMR power, which served as a sensitive EEG index for examining the psychomotor efficiency.

Same in the second study, the result showed that the personal best shooting performance was accompanied by the lower cortical communication between the central region and the left temporal region. The cortical communication was done by the EEG coherence, a method to reflect the information exchange between two given brain regions. The higher coherence suggests more substantial information exchange and functional bridging between two given areas. As the neurocognitive processing in the skilled performers is more specialized, a lower EEG coherence was expected in the more superior performance when compared with the less successful performance. The finding of the second study suggests that the superior psychomotor performance is characterized by the adaptive cortical activation in the central regions. This result is in line with previous studies, which suggest the superior psychomotor performance is related to the reduced activities of the irrelevant brain regions, such as the left temporal regions where is considered to be responsible for the verbal analytic processing (Hatfield et al., 1984; Haufler et al., 2000; Kerick et al., 2004).

5.2.2. SMR Neurofeedback Training on Sport Performance

Augmented SMR NFT sheds lights on the sports performance enhancement. The primary results of the third study demonstrated that the improved putting performance followed by eight times of augmented SMR NFT. The augmented SMR power is connected to the reduced activity in the sensorimotor area. The reduced activation in the sensorimotor area reflects the adaptive processing regarding the complex psychomotor information during the action execution (Mann et al., 1996; Gruzelier, 2014). Accordingly, the results of the third study infer that the golfers were benefited with the augmented SMR NFT.

The results of the third study lend support to the efficacy of using the sham feedback to minimize the placebo effects. The sham feedback group showed no change on the putting performance and the SMR power after receiving the sham feedbacks. However, more evidence is required to re-examine the efficacy of sham feedback of the NFT, as concerns have been raised on the reliability of the sham feedback signals, which could be recognized as the false feedback signals (Kotchoubey et al., 2001).

The learnability of SMR NFT shed light on the application in the actual situation. The third study reported that the golfers in the SMR NFT group showed a noticeable increment on the SMR threshold as the training went forward. Reporting the session-to-session training threshold in the NFT studies on sports performance is a crucial information when addressing the trainability (Hung & Cheng, 2018). This result put forward that the trainability of augmented SMR NFT on sports performance is feasible.

The augmented SMR NFT improved the putting performance by reducing the conscious control over the action monitoring during the putting preparation period. In the third study, the finding exhibited that the SMR power during the preparation period in the post-test was higher than the pre-test in SMR NFT group. The superior putting performance after SMR NFT is in line with the proposal of the MAP model (Bertollo et al., 2016). According to the MAP model, the highly skilled performance is characterized by less perceived control during the preparation period of an action, which is the Type 1 performance in the MAP model. This implication is also consistent with previous studies conducted with skilled performers which reported that the refined neural activity was observed in the relevant cortical areas in the expert performers (Milton et al., 2007; Baumeister et al., 2008).

In sum, the specialized cortical processing is associated with the augmented SMR activity in psychomotor performance. These findings bring up the motivating topic on investigating the further evidence between SMR activity and psychomotor efficiency hypothesis in sports (Hung & Cheng, 2018).

5.3. Limitations and Future Direction

5.3.1. Neural Efficiency & Psychomotor Efficiency Hypothesis

The occurrence of neural efficiency can be altered subjectively by the task difficulty. A previous study has shown that individuals who were confronted in the very complex tasks exhibited a positive correlation between brain activation and cognitive ability. This finding suggests an excessive investment on the cortical resources toward the task demands (Neubauer & Fink, 2009). Accordingly, the similar demands on the task difficulty of the participants

should be maintained in the experiments. For study 1, the difficulty of the task demand was assumed to be equal for the skilled dart-throwers. However, the difficulty of the task demand might be varied for the novices as they might perceive differently by the movement execution. This issue can be investigated by examining the frontal activities. In a simulated archery task, the experiment reported that the novices demonstrated more significant activity in the frontal area, including the superior frontal gyrus, inferior frontal gyrus, and ventral prefrontal cortex compared to the activation of the expert and elite archers (Kim et al., 2014). As the frontal cortex is responsible for the executive functions, it would recruit fewer resources to meet the task demands when the task processing in an automated manner. The further understandings on the frontal cortex are needed, as it can reflect the level of difficulty, when addressing the relationship between neural activity and the neural efficiency hypothesis.

More elaborations on the occurrence of the efficiency are needed, especially the evidence supporting the task-related cortical processing. In a recent study investigating the cortical processes of the elite karate athletes when performing a mental subtraction task (Duru & Assem, 2018), the results revealed that higher power in the alpha frequency band in the posterior brain region was found in the karate players compared to the non-athletes under both the resting and mental subtraction tasks. The authors suggest the elite karate athletes were benefited with the increased recruitment of synchronized neurons in the posterior brain region to meet the task demands. These results indicated that the increased synchronized neurons in the elite karate athletes were not characterized only during the performance execution. Future studies are recommended to investigate the pathway related to the neural efficiency hypothesis, especially the direction of neural information processing under the given tasks (Poldrack, 2015).

5.3.2. EEG

Reporting the rationale of positioning the reference on EEG recording is recommended. The positioning of the reference electrode can impact the dimension of EEG amplitudes across the scalp (Nunez & Srinivasan, 2009). Studies that implemented the link-ear reference claimed to balance the active electrodes in both hemispheres (Luck, 2005). One might use the common average reference to provide a quality estimate of reference-independent potentials (Nunez & Srinivasan, 2009). Although the selection of reference electrode depends on the purpose of how to present the EEG signals, the inconsistency may shade the compatibility of the EEG study in sports performance, especially defining an optimal EEG index for neurofeedback training. Consequently, future EEG study in sports performance is recommended to explicitly report the rationale of positioning the types of reference location.

Several studies investigating the resting-state EEG have emerged recently. The findings showed that predicting the cognitive or motor performance from the resting-state EEG is feasible (Babiloni et al., 2011; Blankertz et al., 2010; Gong et al., 2017). A previous study reported that the karate athletes demonstrated higher power on the alpha frequency band in the resting-state EEG when compared with the novices and amateur athletes (Babiloni, Marzano, Iaconi, et al., 2010). Similarly, Gong et al. (2017) analyzed the resting-state EEG in 35 shooters and found a strong correlation between performance and coherence at C3 and T3 electrode in beta 1 frequency band (12-20 Hz). The authors suggested the information exchange between the left temporal area and the central area was more efficient for better shooting performance. Therefore, more reports to investigate the connection between resting-state EEG and superior motor performance are warranted. As the resting-state EEG might provide the informative prediction on the efficacy of the EEG neurofeedback training (Reichert, Kober, Neuper, & Wood, 2015), such as filtering the capable participants from the less capable participants when carrying out the EEG neurofeedback training.

A reduction of EEG coherence between temporal and frontal regions shed light on the investigation of psychomotor efficiency hypothesis in skilled performers. Gallicchio et al. (2017) found that the improved putting performance was mediated by the lower alpha coherence between left temporal and frontal regions before the initiation of the backswing. This finding is in line with the current findings, the significantly lower cortico-cortical communication between the frontal site and the left temporal site in the best shooting performance when compared with the worst shooting performance. As this reduced EEG coherence is considered to be the signature of psychomotor efficiency (Cheng et al., 2017; Hatfield, 2018), future studies are recommended to replicate this neural activity in the skilled performers.

Last but not least, it is worth to mention that several factors are considered to impact the power and prevalence of baseline levels of alpha in the EEG, such as the genetic, anatomical, physiological and psychological factors (Bazanov & Vernon, 2014). The merits of a more theoretically sound EEG study would be achieved by controlling these factors.

5.3.3. Neurofeedback Training

The rationale of the EEG training target should be theoretically and empirically connected to a task-relevant behaviors (Hammond, 2011; Hung & Cheng, 2018; Mirifar et al., 2017; Xiang et al., 2018). In this sense, a pre-post test comparison regarding the changes on EEG activity, behavioral outcomes, and subjective mental states are recommended to be

reported in the NFT study in sports performance (Hung & Cheng, 2018; Orndorff-Plunkett, Singh, Aragón, & Pineda, 2017).

Furthermore, several critical factors have been mentioned to be related to the effectiveness of the NFT, including excessive electrical artifacts generated by incorrect montage or movement (Allison & Neuper, 2010), difference of the anatomical morphology of the brain (Kropotov, 2010), type of audio-visual feedback (Gruzelier et al., 2010), strategies (Kober, Witte, Ninaus, Neuper, & Wood, 2013), mood (Nijboer et al., 2008), and training length (Arns et al., 2009). Future studies are recommended to take these factors into account.

The issue of identifying the responders and non-responders in the EEG NFT has been raised recently. Previous studies suggested that around 15 to 30 percent of participants were reported to be unable to modulate their EEG signal in the NFT or the brain-computer interface experiments (Allison & Neuper, 2010; Enriquez-Geppert et al., 2014; Zoefel, Huster, & Herrmann, 2011). In this sense, an examination on the EEG activity before the EEG NFT would serve as a fundamental method on ruling out the non-responders. A recent study reported that the responding ability could be predicted by the resting SMR power recorded under the eyes-open condition (Reichert et al., 2015). Therefore, from the practical perspective, the future studies are recommended to filter the non-responders out by using the resting SMR power before entering the NFT. However, more evidence is needed to frame the filtering protocol.

Moreover, the length of the NFT training must be investigated on a greater scale. From the applicable perspective, to formulate the right combination of the training protocol is fundamentally essential, such as the number of training sessions, the duration of each training session, and the interval between training session (Cheng, 2017; Hung & Cheng, 2018). According to the previous review, the positive effects of NFT training lays between 20 to 30 minutes for a single session (Mirifar et al., 2017). As for the ideal number of training sessions, eight sessions of training are considered as a promising number for substantial changes in the EEG and the behavioral results (Hung & Cheng, 2018). Hence, the future studies are recommended to investigate the effects of these variables and congregate the evidence to form an ideal EEG NFT protocol for sports performance enhancement.

The interval of each training session is recommended to set up between one or two days. Although it remains unclear at present whether massed or spaced NFT is more effective (Vernon et al., 2009), a study conducted with microsurgeons when adapting the SMR ratio training may provide the basic idea regarding the ideal training interval. The results exhibited that the microsurgeons showed less improved on the surgical skills in the second half (between-session interval: 8.5 days) compared to the first half (between-session interval: 4.8 days) of an

eight-session training course (Ros et al., 2009). This result implies that the longer the intersession interval, the poorer the learning on the training goals. However, more evidence on this issue is needed to paint a clearer picture of the ideal interval in EEG NFT.

As the tight relationship between superior performance and the psychomotor efficiency, the missing link regarding how the beneficial effect of NFT contributing the psychomotor efficiency remains questions. The third study reported that the greater SMR power was observed after augmented SMR NFT, which resulted in the superior putting performance. This finding suggests that the refinement of task-related cortical regions, reflected by higher SMR power before action execution, could improve the psychomotor performance. However, the observation of economic processing in cortical activity could be much improved by implementing the neural imaging methods, as the combination of video-based tasks and neural imaging tools may promote the ecological validity with active tasks (Smith, 2016). Hence, future study is recommended to cooperate the NFT with the advanced tools, which equip with excellent spatial resolution, to systematically validate the interconnection between target EEG and the projected behavior (Gruzelier, 2014b; Hung & Cheng, 2018).

In sum, establishing a training protocol is exceptionally important as the character of sports performance is complex. To broaden our scopes of the beneficial effects of NFT, a more measurable and comparable training protocol is needed to compare the results from study to study. Furthermore, the NFT protocol can be further implemented with multi-action plan model (MAP model) to identify the optimal training combination for athletes (Bertollo et al., 2016). Hence, bridging the gap between the laboratory-based EEG NFT and the real-world circumstances is the ultimate goal of the EEG NFT in sports performance enhancement.

5.4. Conclusions

The current study aims to examine the EEG activities which could be related to the psychomotor efficiency hypothesis. The assumption of higher psychomotor efficiency is characterized by less interference in the neural processes during the motor performance (Hatfield, 2018). The sensorimotor rhythm (SMR) was used to investigate this process, as SMR can reflect the interference of the sensorimotor information processing.

The current findings conclude that the SMR activity is sensitive to the quality of the sports performance. These results provide the evidence regarding the link between the SMR activity and the quality of the precision sports performance. Furthermore, the results confine the direction of the SMR power, which denote that the increased SMR power might be related to the superior performance.

The best performance of the superior performers was constructed by a more elaborate and refined neural processing during the preparation period when compared with the less successful performance. This finding further supports the psychomotor efficiency hypothesis, as the less complex neural networks were shown by the higher SMR power (Hatfield & Hillman, 2001).

The superior performance is typified by the less verbal-analytic processes during the performance (Zhu et al., 2011). Besides, the lower coherence on frontal cortex and the left-temporal cortex is in line with the notion of psychomotor efficiency hypothesis (Hatfield, 2018). That is, a superior psychomotor performance is typified by the more refined neurocognitive process during the preparation period.

The cortical interference in information processing is reduced during the preparation period. The reduced motor interference, reflected by the augmented SMR power, serves as a key to the superior performance. This adaptive neurocognitive processing is in line with the Type 1 performance in the MAP model (Bertollo et al., 2016).

To sum up, the adaptive cortical activity in experts is closely related to the SMR power. The findings of this study provide further supports on the neurocognitive evidence on the psychomotor efficiency hypothesis. The SMR power may play a crucial role in explaining the adaptive cortical activity behind the psychomotor efficiency.

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DECLARATION

Candidate's Declaration

I hereby declare that this thesis is my own original work unless otherwise referenced or acknowledged. The document has not been submitted for degree in this institution or any other professional qualifications at elsewhere.

Candidate's Signature: Date:

Name: Ming-Yang Cheng

Supervisors' Declaration

We hereby declare that the preparation and presentation of this thesis were supervised in accordance with the guidelines on supervision of thesis laid down by Bielefeld University.

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SUMMARY

The brain and the behavior are interconnected. To study the superior performance, a fundamental approach is to get the insight into what happens in the brain during the performance. In this dissertation, the focus is to investigate the missing link between the psychomotor efficiency hypothesis and the electroencephalography (EEG) activity.

Psychomotor efficiency hypothesis denotes that the adaptive cortical processes, developed by the expertise, leads to superior performance. The primary goal of this dissertation is to find out the specific EEG index, which reflects the crucial cortical processing in the psychomotor performance, to provide the evidence on establishing an ideal neurofeedback training for sports performance enhancement.

Chapter 1 provides an overview of the theoretical backgrounds regarding the relationship between cortical activities and superior sports performance. An introduction of the relevant theories is given to address the unresolved questions between the cortical activities and psychomotor efficiency hypothesis in the superior performance. Then, further missing links are pointed out to explain the rationale of the following studies, especially the candidate EEG index, the sensorimotor rhythm (SMR), and the expected outcomes when applying the SMR for the neurofeedback training.

Chapter 2 explores the first evidence on the missing link between the sensorimotor rhythm and superior performance in sports. An overall introduction and discussion on a cross-sectional study between expert dart-throwers and novices on dart-throwing performance are provided. The expert dart-throwers demonstrated a higher activity on the SMR power before releasing the dart when compared to the novices. This main result shed light on the connection of SMR and the psychomotor efficiency hypothesis in precision sports performance.

Chapter 3 provides further insights into the detailed accounts of the intra-individual difference in SMR power in air-pistol shooting performance. A study was conducted to investigate the SMR power between the personal best and worst air-pistol shooting performance during the preparation period in pre-elite shooters. The results exhibited that the best shooting performance was related to significant higher SMR power compared to the worst shooting performance during the preparation period. Also, the connectivity of the cortical information processing was reduced during the preparation period of the best shooting performance compared to the worst shooting performance. This study suggests that the activity of the SMR is sensitive on psychomotor performance. Hence, the SMR may serve as the training target for the EEG neurofeedback training on sports performance enhancement.

Chapter 4 further investigated the potential application of the EEG neurofeedback

training on golf putting performance. An EEG neurofeedback intervention with pre-elite golfers was carried out to investigate the beneficial effects of the augmentation on SMR power. The pre-elite golfers received eight sessions of training, and they demonstrated an improved putting performance after the neurofeedback training. In contrast, the pre-elite golfers in the control group did not show the improvement after a pseudo neurofeedback training. The results indicate the positive effects of augmented SMR neurofeedback training on precision sports performance.

Chapter 5 summarizes the key findings of the studies and several recommendations for future studies are provided. In particular, the suggestions for establishing a general EEG neurofeedback training protocol in sports performance enhancement are provided.

In sum, the theoretical contributions of the present work elaborated the link between the signature cortical activities and its indication to the psychomotor efficiency hypothesis. From an applied perspective, the current work calls for establishing an ideal protocol for future EEG neurofeedback training research in sports performance enhancement.

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Ming-Yang Cheng

Bielefeld, 10.10.2018

Dedication

To my Mother (deceased), father, brother and our family

The present work is based on the following manuscripts that have been published:

Chapter

- 2** Cheng, M. Y., Hung, C. L., Huang, C. J., Chang, Y. K., Lo, L. C., Shen, C., & Hung, T. M. (2015). Expert-novice differences in SMR activity during dart throwing. *Biological Psychology, 110*, 212–218.

- 3** Cheng, M. Y., Wang, K. P., Hung, C. L., Tu, Y. L., Huang, C. J., Koester, D., Schack, T., & Hung, T. M. (2017). Higher power of sensorimotor rhythm associated with better performance in skilled air-pistol shooters. *Psychology of Sport and Exercise, 32*, 47–53.

- 4** Cheng, M. Y., Huang, C. J., Chang, Y. K., Koester, D., Schack, T., & Hung, T. M. (2015). Sensorimotor rhythm neurofeedback enhances golf putting performance. *Journal of Sport & Exercise Psychology, 37*(6), 626–636.

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