Frontal Midline Theta is a Specific Indicator of Optimal Attentional Engagement During Skilled Putting Performance

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The purpose of this study was to determine whether frontal midline theta activity (Fmθ), an indicator of top-down sustained attention, can be used to distinguish an individual's best and worst golf putting performances during the pre-putt period. Eighteen golfers were recruited and asked to perform 100 putts in a self-paced simulated putting task. We then compared the Fmθ power of each individual's 15 best and worst putts. The results indicated that theta power in the frontal brain region significantly increased in both best and worst putts, compared with other midline regions. Moreover, the Fmθ power significantly decreased for the best putts compared with the worst putts. These findings suggest that Fmθ is a manifestation of sustained attention during a skilled performance and that optimal attentional engagement, as characterized by a lower Fmθ power, is beneficial for successful skilled performance rather than a higher Fmθ power reflecting excessive attentional control.

Keywords: Fmθ, attention, golf, psychophysiology

Maintaining an optimal psychological state during the pre-performance period is the key to achieving the ideal performance (Boutcher, 1992). Among several psychological characteristics, attention, sustained attention in particular, is one of the most important features involved in achieving a superior athletic performance, especially in precision sports, such as golf putting. Gould, Eklund, and Jackson (1992) reported that perfect performance was characterized by a focused state that enables athletes to concentrate and block distractions. This condition is a significant feature of the optimal psychological state (Gould, Dieffenbach, & Moffett, 2002; Williams & Krane, 1993; Krane & Williams, 2006). Accordingly, the quality of sports performance significantly depends on the regulation of sustained attention during the execution of a skill.

Although a number of electroencephalogram (EEG) signatures have been used to study the brain processes related to superior athletic performance (Hatfield, Haufler, Hung, & Spalding, 2004), none have directly measured sustained attention per se. For example, the most widely used marker has been the increase of alpha activity in the left temporal cortex before skill execution. This pattern of EEG activity is thought to reflect a reduction in task-unrelated processes, such as self-talk

and verbal-analytical activities that interfere with skilled performance (Haufler, Spalding, Santa Maria, & Hatfield, 2000; Salazar, Landers, Petruzzello, Crews, & Kubitz, 1990). Variation in alpha coherence among the frontal, temporal, and parietal areas is another EEG pattern that has been associated with superior athletic performance (Babiloni et al., 2011; Deeny, Haufler, Saffer, & Hatfield, 2009; Deeny, Hillman, Janelle, & Hatfield, 2003). These patterns were interpreted as reflecting a change in communication or interference among task-relevant or -irrelevant regions of the brain. In addition, there are other performance-related EEG patterns that are not as well studied, such as increased occipital alpha power (Loze, Collins, & Holmes, 2001) and lower high-frequency alpha power in the frontal and sensorimotor brain regions (Babiloni et al., 2008). The findings from these studies were interpreted to suggest either a reduction in the interference of automatic attentional processes or an increase in the investment of attentional resources for motor planning and motor control, both of which are considered beneficial for superior skilled motor performance. By examining these EEG signatures, investigators were able to indirectly investigate the close relationship between sustained attention and athletic performance from a psychophysiological perspective. However, this endeavor can be greatly improved by employing an EEG indicator that is more directly related to sustained attention.

Frontal midline theta activity (Fmθ) is a good candidate to provide a fairly direct measure of sustained attention. Sauseng, Hoppe, Klimesch, Gerloff, and

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Hummel (2007) have proposed that Fmθ is an indicator of the mental effort that is necessary to perform a task requiring sustained attention (Mitchell, McNaughton, Flanagan, & Kirk, 2008). In addition, neurophysiological evidence provides further support for the close relationship between Fmθ and attention and suggests that Fmθ originates either in the anterior cingulate cortex (ACC) or from the alternative activation generated from the prefrontal cortex and anterior cingulate gyrus (Asada, Fukuda, Tsunoda, Yamaguchi, & Tonoike, 1999; Osaka, Komori, Morishita, & Osaka, 2007). These brain regions are responsible for the attentional control that is associated with a top-down process regulated by volitional control (Buschman & Miller, 2007), which, in turn, helps performers reallocate attention to optimally adapt their behavior for the execution of a goal-oriented performance (Kennerley, Walton, Behrens, Buckley, & Rushworth, 2006; Rushworth, Buckley, Behrens, Walton, & Bannerman, 2007). Furthermore, theta activity in these regions plays a role in the interaction between action monitoring and cognitive control. Studies have shown that with the increase of demand of cognitive control and occurrence of response error, theta activity in the medial prefrontal cortex was enhanced, reflecting an engagement of volitional attentional control (Cavanagh, Cohen, & Allen, 2009; Cohen, 2011; Nigbur, Ivanova, & Sturmer, 2011). These studies suggest that Fmθ activity is a relatively direct attentional index that investigators can use to examine the relationship between sustained attention levels and performance.

Few studies have employed Fmθ to examine its relationship with athletic performance, and all such studies exclusively relied on a between-subject design. The strongest evidence was reported by Doppelmayr, Finkenzeller, and Sauseng (2008). These authors found that Fmθ was significantly higher during the aiming process in expert rifle shooters relative to novices. The increase in Fmθ was interpreted as reflecting the experts' ability to engage in top-down sustained attention and to focus until the skill was executed. Similar findings were reported in a golf-putting task in which experienced golf players exhibited higher Fmθ power compared with their inexperienced counterparts for the duration of the putting process (Baumeister, Reinecke, Liesen, & Weiss, 2008). In addition, Haufler et al. (2000) observed higher overall theta activity in expert shooters relative to novices. All of these studies provided preliminary evidence in support of Fmθ as a relevant measure of sustained attention during the pre-performance period of athletic performance.

Although the aforementioned studies provide evidence of a close relationship between Fmθ and skilled motor performance, examining the discriminative power of Fmθ during skilled performance using a within-subject design can further test the significance of this relationship. Because trial-by-trial performance variation represents minor fluctuations in the fine-tuning of sustained attention during the last moments of a performance, comparing successful and unsuccessful performances by highly skilled performers, a method used in several previous studies (Babiloni et al., 2011, 2008; Loze et al., 2001), provides a powerful test of the relevance and sensitivity of Fmθ for motor performance.

Using a framework of sustained attention that is characterized by an interaction between the dorsal fronto-parietal attentional network (DAN) and the default mode network (DMN), it may be possible to clarify the relationship between Fmθ and motor performance. In general, the DAN is activated by goal-directed attention with active engagement (Ptak & Schnider, 2010), whereas the DMN is deactivated during acts of attentional control, showing greater activity during rest than during goal-directed tasks (Broyd et al., 2009; Raichle et al., 2001). Esterman, Noonan, Rosenberg, and DeGutis (2012) used functional magnetic resonance imaging to measure DAN and DMN activities as a neural fluctuation of sustained attention that was induced by gradually continuous performance tasks, and investigated the relationship between sustained attention and performance in distinct mental states. The mental state was distinguished by response variability, with lower variability and response error termed "in the zone," which is believed to be an optimal performance state. Higher variability and response error was "out of the zone," which is believed to be a poor performance state. The results indicated that when performers were in the zone, the DMN was significantly activated at an intermediate level, which helped to maintain attention in an optimal range. However, when performers were out of the zone the DAN was activated to avoid a subsequent attentional lapse. These findings suggested that poor individual performance could be the result of response variation, leading to further engagement of top-down sustained attention to maintain focus on the task at hand. On the contrary, good performance was characterized by an automatic and effortless state dominated by the DMN. Although these findings are based on continuous tasks with long duration, continuous adjustment of sustained attention is also needed in a short period of time during self-paced pre-performance routine to inhibit irrelevant distractors, suggesting that the sustained attention observed in continuous tasks should be in part applicable during pre-performance routine. In sum, given that DMN activity can be reflected in the assessment of the Fmθ and that increased DMN activity was negatively correlated with resting theta activity in the frontal cortex region (Scheeringa et al., 2008), it is reasonable to hypothesize that Fmθ, an indicator of the top-down control of sustained attention, may be reduced in an individual's best performance in relation to his or her worst.

This hypothesis is also supported by the notion that the excessive engagement of top-down sustained attention, particularly self-monitoring, can be detrimental to performance because too much conscious control can disrupt the automatic processes during a skilled motor performance (Masters, 1992). Studies have found that experts perform worse when asked to explicitly monitor their task execution (Beilock, Carr, MacMahon, & Starkes, 2002). In addition, an internal focus on action monitoring disrupts automatic control mechanisms,

thereby negatively impacting expert athletic performances (Perkins-Ceccato, Passmore, & Lee, 2003). These findings demonstrated that intentionally increasing an individual's focus results in the deterioration of their performance, especially in skilled performers. As such, it is reasonable to expect that skilled performers who have abundant experience with a specific skill will show relatively low engagement of sustained attention, as manifested by reduced Fmθ, when they are performing well. To test this hypothesis, the current study compared golfers' best and worst putting performances.

Methods

Participants

Initially, 20 skilled male golfers were recruited in this study; however, two were later excluded due to excessive muscular noise in the EEG data. Thus, the final results were based on the remaining 18 participants, who ranged in age from 19 to 63 years of age (mean age 36.6 ± 14.2 years), were right-handed, and had an average of 10.8 years (SD = 5.4 years) of competitive experience at the national level. The average handicap of all golfers was 7.9 (SD = 6.4). According to United States Golf Association's (USGA) statistics, a handicap range of 7.0 to 7.9 reflects golf skill that is above 83.76% of all golfers in the country (USGA, 2013). None of the participants had neurological disorders, and all participants signed an informed consent form that was approved by the institutional review board of Taipei Medical University.

Procedure

Participants were asked to refrain from consuming any alcohol or caffeine on the day of testing. After reaching the laboratory, the participants were instructed on the requirements of the study and were asked to sign the informed consent. The participants were then fitted with a Lycra electrode cap (Quick-cap, Neuroscan, Charlotte, NC, USA), and the impedances and signals were checked. All participants putted right-handed and were told to keep their bodies static and their eyes open for at least 3 s before the backswing to minimize possible artifacts from body sway and eye blinks. The participants then completed a minimum of 10 putts for practice. Upon initiation of the task, the participants were instructed to do their best and were informed that their individual putting accuracy for 100 self-paced putts would be compared with that of the other participants. In each trial, the EEG and event-marker data sampling, conducted via an infrared sensor that detected the movement of the backswing, were initiated after the participant had adopted a steady pre-performance stance in which the real-time display of EEG recordings was free of artifacts. Each trial terminated with the backswing, which was recorded by the event-marker channel. During the putting test, the participants were allowed to sit after every 10 putts.

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 according to the international 10–20 system. Additional recordings of the left and right mastoids (A1, A2) were obtained to derive an average-ear reference offline. The ground electrode was located at FPz. Scalp recordings were obtained with surface tin electrodes housed in a stretchable Lycra cap. Vertical and horizontal electrooculograms (VEOG and HEOG, respectively) were recorded with bipolar configurations located superior and inferior to the right eye and on the left and right orbital canthi. The impedance at each electrode site was maintained below 5 kΩ. The EEG data were recorded using NeuroScan NuAmps acquisition amplifiers (Neuroscan, Charlotte, NC, USA) with band-pass filter settings of DC - 70 Hz. A 60-Hz notch filter was also employed during the data collection. The data were acquired at a sampling rate of 500 Hz using Neuroscan software 4.3 installed on an IBM R400 notebook computer.

Putting Task

The putting task was measured with a putting green simulator consisting of a start zone (130 cm length × 90 cm width), a slope of 6 degrees (180 cm length × 90 cm width × 20 cm height), and a green (165 cm length × 90 cm width × 20 cm height). The distance between the starting point of the ball and the hole was 4 m. An experimenter scored each putting trial according to the ball's final placement relative to the hole. The experimenter judged putting performance using the nine concentric rings marked on the green. The innermost ring was the hole, which had a diameter of 10 cm. A putt into the hole was scored as a 10. The other eight concentric rings were marked with different diameters (an increase of 10 cm per ring) and different scores depending on the proximity to the target hole; a score of 9 indicated that the ball was closest to the hole, and a score of 1 indicated that the ball was outside of the outermost ring but still on the green. A putt that failed to land upon the green was scored as 0.

Data Analysis

An EEG data reduction was performed offline using the Neuroscan Edition 4.3 software. Sections of continuous EEG data were removed manually when clear eye movements were visually detected. For the purpose of analyzing the pre-putt psychological state, a static interval of at least 3 s before the backswing was needed for each trial. Therefore, putts with a static interval less than 3 s were excluded to achieve a common structure of artifact-free data across trials and participants. The remaining continuous data (M = 90.1, SD = 10.3) were subjected to a band-pass filter set at 1–30 Hz and epoched into 3-s epochs before the backswing. Each 3-s epoch was baseline-corrected based on the entire sweep and was then segmented into three 1-s epochs. The trials pertaining to

each 1-s epoch containing amplitudes exceeding ± 100 μV and abnormal waveforms were excluded so that the available trials in 1-s epoch –3 s, –2 s, –1 s before back-swing were 79.2 (SD = 14.5), 79.3 (SD = 16.4), 81.4 (SD = 15.3), respectively, and were not significantly different (F = .875, p = .426, η^2 = .088). The 15 best and worst putts from each 1-s epoch were selected from remaining artifact-free trials according to each participant's putting performance (Loze et al., 2001). A fast-Fourier transform with hanning window was applied to each 1-s epoch marked with the best or worst putts. The transformed epochs were averaged for each participant such that estimates of power spectral values (μV^2) of theta bands (4–7 Hz) were derived for either the best or the worst putts of the three 1-s epochs. Before entering the statistical analysis, the data were natural log transformed (Davidson, 1988).

Statistical Analysis

The average power for theta frequency band was subjected to a 2 (performance: best, worst) × 3 (epoch: –3 s, –2 s, –1 s) × 4 (electrode: Fz, Cz, Pz, Oz) analysis of variance (ANOVA) with repeated measures on all three factors. The Greenhouse–Geisser correction was employed to control for possible inflation of Type I error whenever the sphericity assumption was violated. Follow-up analyses were conducted using paired t tests and least significant difference. The alpha level was set at $p < .05$ for all analyses. Effect sizes (η^2) were also calculated for any significant contrasts.

Results

Putting Performance

The overall averaged score in this study was 6.48 (SD = 1.03). The mean score of the best 15 putts was 10 (SD = 0) in each 1-s epoch. The mean score of the worst 15 putts was 0.52 (SD = 0.5), 0.51 (SD = 0.49), and 0.5 (SD = 0.44) in each 1-s epoch respectively. A paired t test was conducted to determine whether there was a difference between best and worst putts. The results showed that the average score for the 15 best putts in each 1-s epoch was significantly higher than that of the 15 worst putts –3 s (p = .000), –2 s (p = .000), and –1 s (p = .000) before the backswing.

Theta (4–7 Hz)

The 2 × 3 × 4 (performance × epoch × electrode) ANOVA revealed a significant performance × electrode interaction effect (F = 5.189, p = .019, η^2 = .234). As shown in Figure 1, the post hoc simple main effect analysis showed that the theta power was significantly lower at Fz (T = 9.393, p = .007, η^2 = .356), Cz (T = 9.335, p = .006, η^2 = .369), and Pz (T = 7.334, p = .015, η^2 = .301) during good performances compared with poor performances; however, no difference was found at Oz (T = .378, p = .547, η^2 = .022). An electrode main effect (F = 26.145, p = .000, η^2 = .608) was also observed. Although the aforementioned

Performance × Electrode interaction effect suggested that it is unnecessary to further investigate this main effect, for the purpose of the current study, we conducted a post hoc analysis to show that the theta power was significantly higher at Fz than at Cz, Pz, and Oz (Figure 2).
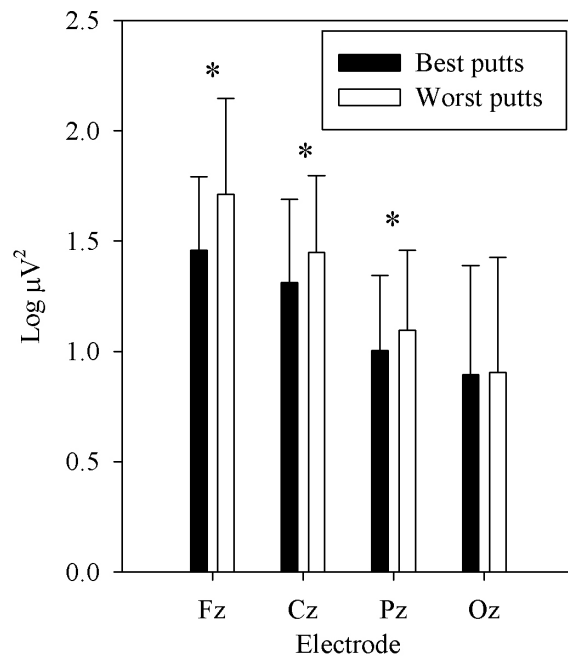

Figure 1 — Theta power at the frontal midline electrode sites in the best and worst putts. Theta power was significantly lower in the best performance as compared with the worst performance, except for Oz.
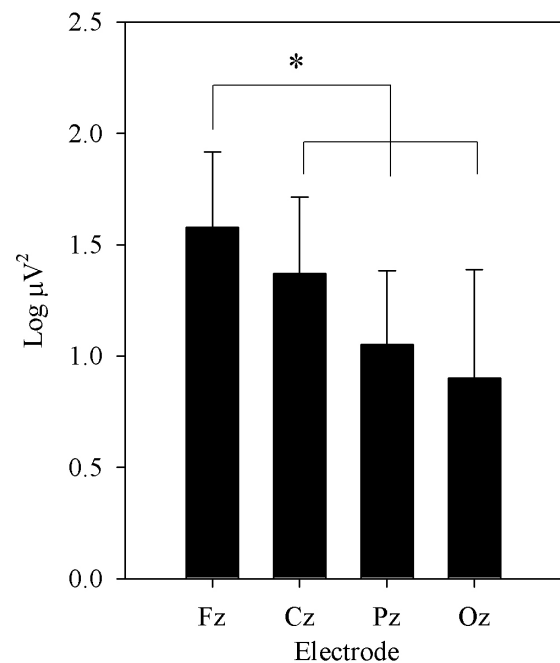

Figure 2 — Theta power at the frontal midline electrode sites. Theta power at Fz was significantly higher than at the other three sites.

Control Analysis

Origin of Frontal Midline Theta. The above results indicate that differences in theta power between the best and worst performances were observed at electrodes other than Fz. It remained unclear, however, whether the observed differences in Fz theta power reflected an ACC-mediated attention process or a general theta fluctuation. One approach to better understand this question was to compare the magnitude of differences between the best and worst performances among the four electrodes. If the magnitude of differences were larger for Fz relative to the other regions, the data would provide support for the claim that the observed Fz theta power possibly reflects ACC activity. A one-way ANOVA was conducted with the electrodes serving as an independent variable and, given that the theta power was higher in worst putts compared with best putts in all electrodes, a difference score as the dependent variable was derived by subtracting theta power for the best performance from theta power for the worst performance (i.e., W – B). The significant effect ($F = 5.195$, $p = .019$, $\eta^2 = .234$) and post hoc analysis revealed that theta power differences at Fz were significantly higher than those at Cz ($p = .049$) or Oz ($p = .010$), whereas the theta power differences at Fz were only marginally higher than those at Pz ($p = .084$) (Figure 3).

Age Effect on Frontal Midline Theta and Putting Performance. Because performance and its related Fmθ may be moderated by age (Cummins & Finnigan, 2007),
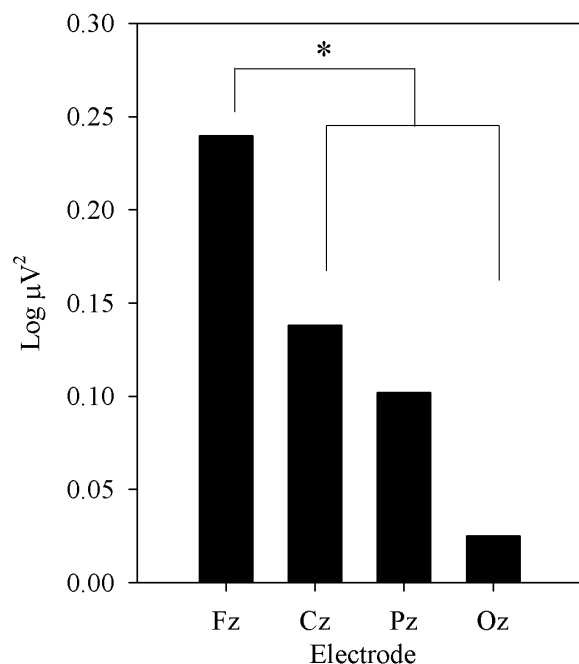

Figure 3 — The W – B theta power at midline electrodes. W – B theta power at Fz was significantly higher than at Cz or Oz and marginally higher than Pz.

we examined whether putting performance and Fmθ differed between the young ($M = 23.4$ years of age, $SD = 3.2$) and old groups ($M = 49.8$ years of age, $SD = 7.5$) to counter the competing explanation that the observed difference was due to an age effect. An independent t test found no significant difference in the performance ($T = -1.307$, $p = .210$) and Fmθ ($T = 1.469$, $p = .161$) between the young and old groups. Furthermore, no significant difference was found in the magnitude of Fmθ difference ($T = -.365$, $p = .720$) between the best and worst putts of the young and old groups. Moreover, a $2 \times 2 \times 3$ (Age × Performance × Epoch) ANOVA indicated a significant main effect of performance ($F = 9.353$, $p = .008$, $\eta^2 = .369$); however, no significant age-related effects were found.

The Uniqueness of Frontal Midline Theta as a Function of Attention During the Pre-Performance Period. To demonstrate that Fmθ during the pre-performance period is a unique function of sustained attention shifts but not general shifts in spectral power, we examined Fz alpha power (8–12 Hz), which is the most examined spectral component associated with top-down inhibitory control in memory and motor performance, during the pre-performance period (Klimesch, Sauseng, & Hanslmayr, 2007). A paired t test showed that there was no difference in alpha power between the best and worst putts ($T = .571$, $p = .575$), decreasing the possibility that reduced Fmθ was the result of general shifts of spectral power.

Fatigue Effect on Frontal Midline Theta and Putting Performance. To eliminate the possibility that the reduced theta power in the frontal cortex region was the result of fatigue induced by continuous performance (Baumeister, Reinecke, Schubert, Schade, & Weiss, 2012), the time-related changes in Fmθ during the putting task were examined. Artifact-free trials from each subject were evenly divided into four parts and averaged, and then subjected to a repeated one-way ANOVA to determine whether theta power at Fz changes during the putting task. The results indicated that theta power at Fz did not differ during the putting task ($F = 1.033$, $p = .386$, $\eta^2 = .057$). Similarly, a repeated one-way ANOVA was conducted to ensure that the putting performance did not change over time during the putting task. The results showed that the average score was not different from each of the 25 putts in the task ($F = 1.877$, $p = .145$, $\eta^2 = .099$). Taken together, these results suggest that golfers in this study did not reduce theta power at Fz and did not improve their putting performance by accumulating trials, thus eliminating the effects of fatigue and learning.

Discussion

The main purpose of this study was to test the hypothesis that optimal performance by skilled golfers is characterized by reduced top-down control of sustained attention, which is characteristic of effortless and automatic skill execution. Our analysis found that the best putts were executed with a lower Fmθ relative to the worst putts,

supporting the hypothesis that a lower investment in sustaining attention was engaged when skilled golf players performed well.

Regardless of the performance outcome, skilled execution was associated with a clear top-down control of sustained attention. Significant theta activity in the frontal cortex area was observed for both the best and the worst putting performances, suggesting that the appearance of Fmθ before the backswing is a basic component of skilled performance and could represent the successful engagement of top-down sustained attention (Buschman & Miller, 2007; Cavanagh et al., 2009; Cohen, 2011; Kennerley et al., 2006; Rushworth et al., 2007). Similar findings were reported in shooting and putting tasks, in which expert and skilled performers exhibited significant theta activity in the frontal cortex region, indicating their ability to allocate resources toward attentional control during the pre-performance period (Baumeister et al., 2008; Doppelmayr et al., 2008). As such, the engagement of a top-down control of sustained attention, which is manifested by increased Fmθ, can be regarded as a characteristic of skilled execution.

Although enhanced Fmθ was observed in expert performers relative to novice performers (Baumeister et al., 2008; Doppelmayr et al., 2008, Haufler et al., 2000), our study showed that in skilled golfers, a higher Fmθ power was associated with the worst performances, whereas a lower Fmθ power was associated with the best performances. The discrepancy between the current study and other studies might be attributed to differences in the basis of comparison. Compared with experts, who have proficient skills, novices performed with a relatively lower Fmθ because of their lack of experience and knowledge, which makes them less able to focus on the demands of the specific task at hand. The possibility of a novice's failure to elicit significant Fmθ can be observed in the Doppelmayr et al. (2008) study, which found that novices not only exhibited lower theta activity in the frontal cortex region than experts, but also failed to evoke significant theta activity at Fz relative to the other midline electrodes. Similarly, Baumeister et al. (2008) and Haufler et al. (2000) were also unable to find evidence demonstrating that novice performers can evoke predominant frontal theta activity as effectively as skilled performers during a performance. Therefore, it seems that the lower Fmθ in novices relative to expert and skilled performers is caused by their lower skill level because novices have less knowledge and experience to help them focus on or engage in the top-down control of sustained attention toward the demands of the specific task at hand.

However, when comparing individual skilled performers' best and worst performances, the association of lower Fmθ power with optimal performance may indicate adequate engagement of top-down control of sustained attention. As mentioned above, well-trained performers who have sufficient experience and knowledge of a specific task can successfully engage themselves in top-down attentional control during skill execution, thus they exhibit prominent Fmθ. As an indicator of top-down con-

trol of sustained attention, higher Fmθ power in skilled golfers might reflect an excessive amount of attentional engagement, which elevates volitional control and thus damages the automatic performance. In contrast, lower Fmθ power may reflect relatively optimal attentional allocation, which prepares the golfer for continuous attention tuning before the backswing. Moreover, given the negative association between Fmθ and the DMN (Scheeringa et al., 2008), a reduced Fmθ before the best performance revealed that performer's attention was dominated by the DMN, suggesting a performance state associated with automatic and effortless attentional processing and optimal performance (Esterman et al., 2012). Such an ideal performance state has also been reported in descriptive reports suggesting that peak golf performance is characterized by automatic, effortless focus (Cohn, 1991). Furthermore, according to the framework of reinvestment theory (Masters, 1992), excessive attentional control, including both execution monitoring and internal focus, are detrimental to experienced performers because the overly conscious mental effort disrupts the automatic skill execution (Beilock et al., 2002; Perkins-Ceccato et al., 2003). Similarly, from a psychophysiological perspective, excessive engagement in attentional control could lead to cortical noise that disturbs the automatic motor program, contributing to the impaired performance (Hung, Haufler, Lo, Mayer-Kress, & Hatfield, 2008; Salazar et al., 1990). An optimal performance state should be characterized by effective and efficient psychomotor operation that is reflected by the attenuation of task-irrelevant cognitive activities, such as verbal-analytical processes (Hatfield & Hillman, 2001).

While it is possible to argue that the change in Fmθ is caused by general theta fluctuations, this explanation is inconsistent with the significant decrease in the theta amplitude from the frontal to the occipital regions. The results indicated that theta activity was most prominent at Fz and then attenuated in proportion to the distance from the frontal cortex region, which suggest the frontal origin of the theta measured in the current study. Moreover, the results of the control analysis of the magnitude of the differences in theta power between the best and worst putts showed a decreasing trend from the frontal to the occipital regions, which further strengthens the frontal origin of theta and indirectly suggests that the ACC-mediated theta activity may contribute to the difference in theta power between the best and the worst putting performances. These results are similar to previous findings that the performance-induced Fmθ originates from the ACC (Asada et al. 1999; Osaka et al., 2007). In addition, this significantly increased theta power at ACC was observed in motor tasks requiring higher demand of sustained attention relative to other less demanding conditions (Sauseng et al., 2007). Accordingly, this ACC-mediated theta activity, which is believed to be an indicator of sustained attention due to its association with the monitoring and controlling the execution of goal-oriented performance (Cavanagh et al., 2009; Cohen, 2011; Rushworth et al., 2007; Ken-

nerley et al., 2006), provides a plausible basis for our interpretation of the present results; for instance, the idea that lower frontal theta power reflects the optimal engagement of top-down control in sustained attention, whereas higher frontal theta power represents excessive attentional control that likely led to a worse performance.

Given that Fmθ is reduced with age and this age-related decline is more significant in a demanding task (Cummins & Finnigan, 2007), the possible moderating effect of age on Fmθ should be examined in this study. However, the explanation that the observed differences in Fmθ between individual best and worst performance were due to age is not plausible because a within-subject design was employed for the current study. Furthermore, in our control analysis, which was inconsistent with the report by Cummins and Finnigan (2007) that performance and Fmθ were reduced in older golfers compared with younger golfers, we found putting performance, frontal midline theta power, and the Worst – Best difference score of frontal midline theta power were not different between young and old golfers. Moreover, the unlikelihood of age as a moderator is further supported by the fact that no age-related effects were found. These results suggested that Fmθ during the pre-performance period is a specific indicator of sustained attention associated with the expertise of putting skill regardless of the performer's age.

Although alpha activity has been found to be associated with cognitive and motor performance (Klimesch et al., 2007), Fmθ is a unique index of attentional shifts that distinguish golfer performance and reflect the underlying attentional control. Although Fmθ differed significantly between the best and worst putts during the pre-performance period, our results of control analyses show that no difference was observed in the alpha band. These results suggested that theta activity at Fz before execution is an indicator of the top-down control of sustained attention independent of alpha activity. Moreover, although postresponse theta and alpha activities have both been associated with performance error, which indicates attentional monitoring and adaptation mechanisms (Van Driel, Ridderinkhof, & Cohen, 2012), the task-relevant power change during pre-performance period was only observed in theta band, suggesting that theta activity, especially in the frontal cortex region, reflects not only posterror monitoring and adaptation but also sustained attention during the pre-performance period.

To address the issue that fatigue is a factor that should be taken into consideration when examining the relationship between Fmθ and motor performance (Baumeister et al., 2012), a control analysis was conducted to examine whether putting performance and Fmθ changed over time throughout the putting task. While Baumeister et al. (2012) found that Fmθ decreased with an increase in fatigue, which most likely also causes a decrease in performance, the results of our control analysis indicate that the putting performance and Fz theta power did not differ during the putting task, thus eliminating not only the fatigue effect on putting performance and Fmθ but also the learning effect.

Future studies should take several suggestions into account. First, although Fmθ was negatively correlated with individual performance, the nature of this relationship requires further investigation. Some studies have shown a positive relationship between cortical activation and individual sports performance in proficient performers (Hung et al., 2008; Loze et al., 2001), whereas others suggest a negative relationship (Landers et al., 1994; Salazar et al., 1990). Notably, previous findings showed that an intermediate level of DMN activity was associated with optimal performance, suggesting that a certain degree of volitional attentional control is still needed to prevent attentional lapses (Esterman et al., 2012) and mind wandering (Mason et al., 2007). Accordingly, in an attempt to explain these divergent findings, an inverted-U relationship was proposed to correlate the optimal performance state with moderate cortical activation (Esterman et al., 2012; Hatfield & Hillman, 2001; Loze et al., 2001). To substantiate this hypothesis, further studies are needed to clarify whether the association between Fmθ and performance follows a linear or an inverted-U relationship. Second, a higher density electrode array and a source localization algorithm that will improve the spatial resolution of the EEG analysis are suggested to confirm the origin of Fmθ in future studies. Although several control analysis in present study suggest that the theta power and the difference in theta power between the best and worst performances originated from ACC-mediated activity, the magnitude of theta power difference between the best and worst putts was only marginally larger at Fz relative to Pz. Thus, a high-resolution EEG approach will help to determine with greater confidence whether the observed difference in Fmθ between the best and worst putting performance is associated with ACC activity and top-down control of sustained attention. Third, although the possibility of age as a moderator on neural and behavioral data was unlikely to explain our results given that Fmθ may be varied as function of age (Cummins & Finnigan, 2007), future research that restricts range of age should be considered when investigating the relationship between frontal midline theta and performance to replicate findings from the current study. Finally, the manipulation of Fmθ using neurofeedback is a promising avenue to further examine the effects of Fmθ on athletic performance. As some preliminary studies have demonstrated the effectiveness of neurofeedback training on enhancing athletic performance (Arns, Kleinnijenhuis, Fallahpour, & Breteler, 2008; Landers et al., 1991), this line of research will provide greater insight into the relationship between cortical activity and athletic performance with clear, practical implications.

In conclusion, the results of this study support the hypothesis that a skilled golfer's ideal performance state is associated with a relatively low engagement of the top-down control of sustained attention that is reflected by a low Fmθ. Although the source of Fmθ could not be precisely located due to the limits of measurement of the surface EEG, the gradual decrease in theta power from the frontal to the occipital regions and finding the

largest magnitude of differences between best and worst performance in the frontal midline site provide indirect evidence in support of a frontal origin, likely in the ACC. Furthermore, the possibility of age and fatigue effects on Fmθ were almost eliminated. Based on these results, we conclude that the decreased top-down control of sustained attention helps skilled golfers to optimize their pre-performance state by sustaining attentional tuning until the backswing.

Acknowledgments

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