

ABSTRACT

Title of Dissertation: THE IMPACT OF MOTOR LEARNING ON MOTOR BEHAVIOR AND CORTICAL DYNAMICS IN A COMPLEX STRESSFUL SOCIAL ENVIRONMENT

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An economy of effort is a core characteristic of highly skilled motor performance often described as being effortless or automatic. Electroencephalographic (EEG) evaluation of cortical activity in elite performers has consistently revealed a reduction in extraneous associative cortical activity and an enhancement of task-relevant cortical processes. However, this has only been demonstrated under what are essentially practice-like conditions. Recently it has been shown that cerebral cortical activity becomes less efficient when performance occurs in a stressful, complex social environment. This dissertation examines the impact of motor skill training or practice on the EEG cortical dynamics that underlie performance in a stressful, complex social environment. Sixteen ROTC cadets participated in head-to-head pistol shooting competitions before and after completing nine sessions of skill training over three weeks. Spectral power increased in the theta frequency band and decreased in the low alpha frequency band after skill training. EEG Coherence increased in the left frontal region and decreased in the left temporal region after the practice intervention. These suggest a refinement of cerebral cortical dynamics with a reduction of task extraneous processing in the left frontal region and an enhancement of task

related processing in the left temporal region consistent with the skill level reached by participants. Partitioning performance into 'best' and 'worst' based on shot score revealed that deliberate practice appears to optimize cerebral cortical activity of 'best' performances which are accompanied by a reduction in task-specific processes reflected by increased high-alpha power, while 'worst' performances are characterized by an inappropriate reduction in task-specific processing resulting in a loss of focus reflected by higher high-alpha power after training when compared to 'best' performances. Together, these studies demonstrate the power of experience afforded by practice, as a controllable factor, to promote resilience of cerebral cortical efficiency in complex environments.

THE IMPACT OF MOTOR LEARNING ON MOTOR BEHAVIOR AND
CORTICAL DYNAMICS IN A COMPLEX STRESSFUL SOCIAL ENVIRONMENT

by

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Overview

An *economy of effort* is a core characteristic of highly skilled motor performance often described as being effortless or automatic. This is consistent with the autonomous stage of Fitts and Posner's (1967) three-stage model of motor learning. This final stage is characterized by accurate, consistent and fluent movement. However, the concept of efficiency appears to go beyond mechanical and physiological adaptation. Sparrow, Hughes, Russell, and Le Rossignol (1999) described muscle activation as being *organized* in such way that energy consumption is minimized with respect to the *constraints* imposed by the task, the environment, and the unique attributes of the performer. Lay, Sparrow, Hughes, and O'Dwyer (2002) provided support for this concept by observing changes in coordination, metabolic activity and the pattern of muscle activation after short-duration and low-intensity skill training in a rowing task. Movement variability, energy consumption, muscle activity, and perceived exertion (the phenomenological experience) all decreased after training relative to the baseline state. Beyond physiological adaptations, Lay and colleagues (2002) primarily attributed the increased efficiency to the control strategy employed by the nervous system. Therefore efficient cerebral cortical activity is a hallmark of highly skilled motor performance.

Electroencephalographic (EEG) evaluation of cortical activity in elite performers has consistently revealed a reduction in extraneous associative cortical activity and an enhancement of task-relevant cortical processes (for review see Hatfield, Haufler, Hung, & Spalding, 2004; Hatfield & Kerick, 2007). This has been observed in local cortical activity as well as networked activity

between regions when comparing experts to novice performers (Haufler, Spalding, Santa Maria and Hatfield, 2000; 2002; Deeny, Haufler, Saffer, & Hatfield, 2009) and when novice performers undergo skill training (motor learning) (Gentili, Bradberry, Oh, Hatfield, & Contreras Vidal, 2011; Gentili, Bradberry, Oh, Costanzo, Kerick, Contreras-Vidal, & Hatfield, 2015; Studer, Koeneke, Blum, & Jäncke, 2010). This refinement of the control strategy, reflected in the cortical dynamics and expressed as an increase in the quality and consistency of motor performance, is referred to as psychomotor efficiency (Hatfield & Hillman, 2001).

The model of constraints invoked by Sparrow and colleagues (1999) was put forth by Karl Newell (1986) and holds that coordinated patterns of movement emerge from constraints related to the structure and function of *the performer*, the requirements of *the task* to be performed, and *the environment* in which the performance takes place. With respect to Newell's model of constraints, motor performance studies employing EEG to explore cortical dynamics have shown changes in the refinement of cerebral cortical activity in predictable directions consistent with the psychomotor efficiency hypothesis when comparing *performer's* experience level (Haufler, Spalding, Santa Maria and Hatfield, 2000; 2002; Deeny, Haufler, Saffer, & Hatfield, 2009), changing *the task* difficulty (Rietschel, Miller, Gentili, Goodman, McDonald, and Hatfield, 2012), and altering the perceived importance of *the performance environment* (Hatfield, Costanzo, Goodman, Lo, Oh, Rietschel, Saffer, Bradberry, Contreras-Vidal, and Haufler, 2013). Often these studies examine EEG alpha power, which reflects synchronous cortical activity in the 8-13 Hz frequency band. High levels of alpha

power have been attributed to a reduction in cortical engagement or “idling” of the cerebral cortex (Pfurtscheller, Stancák, & Neuper, 1996). Efficiency of cortical dynamics has also been revealed by examining the coherence between pairs of EEG electrodes which reflect the level of cooperative network activity or cortico-cortical communication between underlying regions. Increased regional alpha power and/or decreased coherence are common EEG findings in performers with increase psychomotor efficiency. Often these findings are interpreted as a reduction of extraneous cortical processing and an enhancement of task-relevant processes. While expert performers possess higher psychomotor efficiency relative to novices, increased task difficulty and environment complexity have been show to diminish cerebral cortical efficiency relative to task performance.

Performance is fundamentally different from practice. Performance is accompanied by the desire to execute the skill to the best of one’s ability in situations of perceived importance related to a potential positive or negative consequence and/or some sort of social comparison or evaluation, such as competition. Therefore performance inherently is accompanied by pressure or stress. All other attempts to execute a skill, either in part or in its entirety, without consequence should be considered an opportunity to learn or practice, whether deliberate or not. Motor learning is the ability to benefit from experience-dependent improvement in skill performance (Schmidt, 1991). Although perceptible improvement is a fundamental component in this framework of motor learning, it is possible that some beneficial changes may occur from learning that isn’t readily observable. For example, consider the ability to produce an identical performance after practicing a motor skill, relative to a baseline state, but with

increased muscular or cerebral cortical efficiency. In this regard, EGG has been shown to be sensitive to changes in the pattern of underlying cortical activity as a consequence of motor learning, even in the absence of outward changes in performance (Studer, Koeneke, Blum, & Jäncke, 2010). Examination of the effects of motor skill training or practice on cortical dynamics of novice performers have revealed increased regional alpha power (Gentili, Bradberry, Oh, Hatfield, & Contreras Vidal, 2011), particularly in the left temporal region associated with verbal-analytic processes (Landers, Han, Salazar, Petruzzello, Kubitz, and Gannon, 1994; Kerick, Douglass, and Hatfield, 2004) and decreased coherence between regions (Gentili, Bradberry, Oh, Costanzo, Kerick, Contreras-Vidal, & Hatfield, 2015). These studies demonstrate that the acquisition of a motor skill leading to improved performance is accompanied by a reduction of extraneous cerebral cortical activity leading to enhanced psychomotor efficiency. However, this has only been demonstrated under what are essentially 'practice-like' conditions. Currently, it is unknown if motor skill practice can restore or enhance the psychomotor efficiency which is diminished when performance occurs in a stressful, complex social environment (Hatfield, Costanzo, Goodman, Lo, Oh, Rietschel, Saffer, Bradberry, Contreras-Vidal, and Haufler, 2013).

This dissertation takes a programmatic approach to gain insight as to the impact of motor skill training or learning on the cortical dynamics that underlie performance in a stressful environment and is presented here as three separate studies (papers). The first study is published work that examines performance in a complex social environment fostered by 'head-to-head' competition relative to a 'practice-like' condition (Hatfield, Costanzo, Goodman, Lo, Oh, Rietschel, Saffer,

Bradberry, Contreras-Vidal, and Haufler, 2013). This work demonstrates the efficacy of 'head-to-head' competition as a stressful environmental manipulation, and its impact on motor behavior and cerebral cortical dynamics. An identical 'head-to-head' competition scenario was utilized in the remaining two studies to reproduce this complex, stressful social evaluative environment. The second study employed a practice intervention to examine the impact of skill training on cerebral cortical dynamics while performing in a stressful competitive environment. The final study partitions performance outcomes in order to compare the cerebral cortical activity associated with 'best' performances and 'worst' during stressful 'head-to-head' competition.

Study 1 – The influence of social evaluation on cerebral cortical activity and motor performance: A study of “Real-Life” competition

Introduction

Cognitive-motor performance is often executed within social contexts involving observation and judgment of the quality of performance as occurs in sport settings. A fundamental difference between sport and non-sport settings is the element of competition, which essentially implies a process of social comparison and explicit evaluation of performance. In essence, sport is a social-evaluative phenomenon and such competitive situations can increase the level of cognitive demand on the performer beyond that which is required simply to execute the pure motor demands of a task. The increase in such demand may explain, in part, how competition influences the quality of motor performance due to the attendant alterations of the performer's mental state and underlying neural processes. More specifically, the perception of social evaluation may manifest as an increase in cerebral cortical activation and cortico-cortical communication, relative to a non-competitive condition, and translate to the peripheral nervous system as elevated and nonessential skeletal motor unit activity. Such a change in skeletal muscle activity could then degrade the efficiency of motor performance and could negatively impact performance outcome if the changes in motor unit activity were sufficient to significantly alter the kinematics of limb movement (e.g., changing the throwing motion of the upper extremity and altering the trajectory of a pitched ball). Weinberg and Hunt (1976) examined the relationship between state anxiety and electromyographic (EMG) activity of the

upper arm during a throwing motion of a ball at a target and observed an elevation in motor unit activity that was associated with heightened anxiety and degraded performance (i.e., reduced accuracy), but they did not examine concomitant brain activity. Accordingly, the present investigation adopts a social cognitive neuroscience approach, as described by Lieberman (2007), in order to understand how evaluative social settings influence the quality of neuro-motor behavior.

Investigations of brain activity (i.e., cerebral cortical dynamics) during motor performance have typically been conducted in non-competitive laboratory settings. These studies have revealed that skilled motor performance is characterized by psychomotor efficiency during task execution, relying on essential brain networks in an adaptive manner with refinement or suppression of non-essential input to the motor planning region (Deeny et al., 2003, 2009; Hatfield et al., 2004; Hatfield and Hillman, 2001). It is reasonable that such refinement of neural communication facilitates skeletal muscle coordination and congruency between the intended or planned and the actual or executed cognitive-motor action (Baumeister et al., 2008; Del Percio et al., 2007; Hatfield et al., 2004; Hatfield and Hillman, 2001). However, competition would likely perturb these brain processes to some degree depending on the perceived importance of the event. In this manner, elevated cortical activity from the perception of evaluation and social judgment (i.e., beyond that required for motor behavior) would promote non-essential cortical activity resulting in a discordance between intended and executed movements depending on the magnitude of non-essential brain activity.

Precision aiming tasks such as pistol and rifle shooting have been effectively employed to explore the notion of psychomotor efficiency during motor performance, since aiming requires visual-spatial processing, planning, and precise control of the extremities to avoid unnecessary movement (Deeny et al., 2009; Del Percio et al., 2009a; Hatfield et al., 2004). Such tasks hold the advantage of ecological validity relative to novel tasks employed in laboratory settings since the participants in many of these studies (e.g., individuals with varying shooting experience) are challenged with a familiar activity with which they are highly practiced and which they perform while motionless, allowing for minimal artifacts during psychophysiological recording.

Numerous studies employing electroencephalography (EEG) have revealed heightened alpha power in experts across the entire topography of the scalp during the aiming period of target shooting up to the time of the trigger pull indicative of a widespread reduction in cerebral cortical activity. However, the elevation in alpha power is often pronounced in those recording sites over the left temporal region (T3) (Hatfield et al., 1984; Haufler et al., 2000; Kerick et al., 2001; Lawton et al., 1998), which suggests attenuation of verbal-analytical processes during performance. EEG alpha power is also progressively elevated as a function of practice sessions completed over time to improve motor skill (Kerick et al., 2004). In this manner, EEG alpha power is positively related to cortical relaxation, suggesting attenuation of non-essential explicit processes during performance of a motor task and refinement and economy of neural processes while engaged with task-specific demands (Babiloni et al., 2008, 2009, 2010; Del Percio et al., 2008, 2009a,b, 2010; Zhu et al., 2011). The brain

dynamics observed in the left temporal region suggest that skilled performers employ less verbal–analytical processing during the aiming period (possibly due to a shift to reliance on sub-cortical structures and relative engagement of right hemispheric visual-spatial processing) (Hatfield and Brody, 2000; Hatfield et al., 1984; Kerick et al., 2004). This assertion is based on the findings that superior performers exhibit relative synchrony of alpha power (relaxation) in this region compared to other cortical areas (Hatfield et al., 2004) and the convincing evidence provided by Sperry (1974), as well as Springer and Deutsch (1998), that the left temporal region is involved in verbal–analytical processing. Furthermore, the broad EEG alpha band is composed of specific ranges for low-alpha power (8–10 Hz) and high-alpha power (10–13 Hz), which are indicative of general cortical arousal and task specific cortical arousal, respectively (Pfurtscheller and Lopes da Silva, 1999). Power is inversely related to these neural processes such that elevated low-alpha power is indicative of a reduction in general cortical arousal and elevated high-alpha power is indicative of a reduction in task-relevant attentional processes. Accordingly, the demands of competition may result in desynchrony of neuronal activity and reductions in low- and high-alpha power indicative of increased cortical arousal and heightened attentional processes.

The neural efficiency of skilled motor performance can also be assessed via EEG coherence, an EEG-derived metric, which is indicative of cortico-cortical communication or networking. A special case of neural efficiency involving the refinement of non-motor input to the motor planning region during performance was described by Hatfield and Hillman (2001) as psychomotor efficiency, a

cortical state indicative of superior cognitive motor performance during which communication between various areas of the cortex and the motor planning region (i.e., the latter is assessed by recording from site Fz that overlies the mid-frontal cortex) is lower in those who are skilled at a particular cognitive-motor behavior compared to those who are relatively unskilled. Lower cortico-cortical communication or networking between non-motor and motor regions, as reported by Deeny et al. (2003), was specifically noted between the left temporal region (site T3) and the mid-frontal region (Fz) in marksmen with competitive shooting experience relative to those with an absence of competitive experience during the aiming period prior to trigger pull. More generally, Deeny et al. (2009) also noted lower coherence between broad regions cortical activity across the scalp topography and the frontal regions in expert marksmen relative to novices during the aiming period of target shooting. Collectively, the findings suggest that superior visuo-motor performance is associated with attenuation or refinement of non-essential input to the motor regions of the brain.

However, as stated above, a competitive environment may perturb the cerebral cortical activity associated with skilled performance through promotion of heightened regional activation and excessive cortico-cortical communication, which may negatively impact the brain processes essentially related to motor behavior. If practice and a focused effort to improve shooting performance results in attenuation of cerebral cortical activity, then it follows logically that a more complex and cognitively demanding environment involving social comparison (i.e., competition) would promote heightened activation and networking of cerebral cortical activity. In this manner, the neural efficiency of skilled motor

performance reported by Del Percio et al. (2009b) would become disrupted during competition leading to behavioral changes in task performance. That is, degradation of motor behavior would occur in the form of non-essential limb movement owing to elevated central drive and excessive motor unit activity.

It remains to be seen whether an elevation in cerebral cortical activity is promoted by competition-induced social evaluation as no one, to date, has manipulated the social environment via direct competition to assess this possibility. If the possibility is supported, then alterations in motor performance may be caused by the processing of social demand during competition adding non-essential cortical activity and extraneous input to central motor preparatory processes beyond those required to meet the pure motor demands of a task. In this manner, the introduction of non-essential cortical activity would translate to the quality of motor behavior through an introduction of additional activation of the muscle activity of peripheral effectors (e.g., upper and lower extremities) and degradation of stability in the aiming posture and performance accuracy.

Therefore, the present study was conducted to examine concomitant changes in cortical dynamics and motor behavior associated with competition. To achieve this end, participants engaged in a precision aiming task (i.e., target shooting) during which they performed both alone and under the condition of 'head-to-head' competition involving direct comparison of their performance to that of an actual competitor. The social perception and evaluation associated with competition was expected to elevate cerebral cortical activity and introduce heightened cortico-cortical communication between non-motor and motor regions as revealed by EEG spectral and coherence analyses, respectively. More

specifically, both low- and high-alpha EEG power were expected to decrease during competition compared to that observed during the aiming period of a non-competitive condition while EEG coherence was expected to increase during competition. In addition, the increase in regional activity and communication to the motor planning region during competition was expected to be elevated in the left temporal region relative to all other regions, indicative of excessive “self-talk” during the mental stress of the competitive condition. As such, the magnitude of reduction in low-and high-alpha power at T3 and the magnitude of elevation in coherence between sites T3 and Fz due to competition were expected to be highest compared to all other sites. Finally, relative to the non-competitive condition, the elevation in cortical activity was expected to reduce steadiness in the aiming behavior and accuracy of shot placement on the target.

Methods

Participants

Nineteen participants (N = 19, 2 female) were enrolled from the Reserve Officers' Training Corps (ROTC) program located at the University of Maryland. All participants were right-hand dominant (Oldfield, 1971) and right-eye dominant. Participants were between the ages of 18 and 38 years (M = 22, SD = 4.33) and were screened with a health history questionnaire to ensure that they were free of neurological and psychiatric disorders as well as psychotropic medications. None of the volunteers had competitive shooting experience and all participants met a minimum performance level for inclusion in to the study such that each individual had to hit the target 80% of the time during a preliminary practice session consisting of 40 shots. Prior to testing, all participants provided

written informed consent approved by the Institutional Review Board and were informed that they were free to withdraw from the study at any time.

Task

Participants employed their right (dominant) hand to complete a dry-fire pistol shooting task for which the Noptel ST-2000, an optical tracking system, was used to monitor the aiming motion of the pistol barrel and shooting performance (shot placement on the target). Participants stood 5 m from the target to complete the task. Accordingly, the target was scaled to maintain a proportionate diameter consistent with that of an official competitive target (i.e., at a distance of 50 ft, or 15.24 m). Participants assumed a standard shooting posture; feet positioned approximately shoulder-width apart and nearly perpendicular to the shooting lane to minimize sway. Participants extended the shooting arm while aiming and sighted the target with their right eye, while the left eye was occluded. Each condition (i.e., performance-alone (PA) and competition (C)) consisted of 40 shots to minimize fatigue and to ensure stable estimates of the successive intervals (i.e., four 1-s epochs) of the attention state leading to the trigger pull. Such an approach reasonably allowed for detection of dynamic change in attention during this critical period, if present. Visual feedback was provided for each trial (shot) consisting of shot score and the position of the shot on the target. All scoring was consistent with competitive shooting scoring metrics of Bull's eye = 10 and outermost ring = 1 with the magnitude of the proximity to the Bull's-eye being proportional to the score.

Measures

Arousal measures. Electrocardiogram (ECG) was collected using a Thought Technology Procomp2 system, (encoder model #SA7400). ECG was sampled at 256 Hz through a single chest lead.

Saliva samples were collected and analyzed by Salimetrics (State College, PA) for cortisol using a highly sensitive enzyme immunoassay Saliva collection (Saliva Oral Swab). Tubes were labeled in accordance with sample time.

Visual Analog Scales (VASs) were employed to provide unobtrusive self-report measures. The following questions were posed: VAS 1: How competitive do I feel? (0 = not competitive, 100 = ultra competitive); VAS 2: How stressed am I? (0 = no stress, 100 = completely stressed); VAS 3: How confident do I feel? (0 = extremely confident, 100 = no confidence); VAS 4: How relaxed am I? (0 = not relaxed, 100 = completely relaxed). This approach was adapted from that employed by Bixby et al. (2001). In addition, the State Anxiety Inventory (Spielberger et al., 1970) was employed to assess mental stress with scores ranging from 20 to 80 with higher scores reflecting greater anxiety.

Cerebral cortical activity – EEG. Scalp electroencephalographic data were collected using tin electrodes housed within a stretchable lycra cap, (Electro-Cap International, Inc.). Data were acquired from 30 sites (FP1, FP2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, CZ, FZ, PZ, FCZ, CPZ, CP3, CP4, FC3, FC4, TP7, TP8, FT8, OZ, FT7) to generate topographical maps of EEG low and high-alpha power for each successive second during the 4-s final aiming period of the performance-alone and competitive conditions. From these

sites, 10 homologous sites of interest (F3, F4, C3, C4, P3, P4, T3, T4, O1, O2) were subsequently chosen to capture the major regions within each of the cerebral hemispheres for the purpose of spectral and coherence analyses and were referenced to linked earlobes and a common ground (FPz), and impedances were maintained below 10 k Ω . The Fz electrode served as the common site of interest in all electrode pairings for the coherence analysis (e.g., Fz-F3, Fz-F4, Fz-C3, etc.) to enable examination of cortico-cortical communication between all regions with the motor planning region (Fz). All channels were amplified 500 times using Neuroscan Synamps 1, and recorded using Neuroscan software (version 4.3.3). Online bandpass filters were set at 0.01–100 Hz with a sampling rate of 1000 Hz. Electrodes were placed above and below the left eye over the orbicularis oculi muscle to assess VEOG and at the outer canthi of both eyes (HEOG) to record eye blinks and lateral movements. An electronic pulse was generated by the shooting simulator to mark the trigger pull in the continuous EEG recording.

Motor behavior. The Noptel optical shooting simulator system was used to measure shooting score and motor performance as determined by the aiming trajectory sampled at 66 Hz. The shot location in two dimensions was recorded as the position of the aiming point on the target at the time of the trigger pull.

Procedure

The study required participants to complete two testing sessions, (1) performance-alone (PA) and (2) competition (C), in a single day. However, all participants were brought in to the testing environment prior to the testing day to be familiarized with the procedures of the study and to confirm that they all met

the criterion for skill level (i.e., ability to hit the target 80% of the time while executing 40 shots for record). All participants were informed of the requirements of the experiment and provided an opportunity to ask questions before they provided consent. In order to reduce any novelty effect that might be observed on the actual testing day, the EEG and heart rate (HR) monitors were placed on the participants for familiarization during the orientation session. They also completed the psychological assessments (VAS, State Anxiety Questionnaire), and were instructed on the acquisition procedures for salivary cortisol (i.e., oral swab). Participants also viewed a videotape generated by a National Collegiate Athletic Association (NCAA) Division I pistol shooting coach through which instructions about shooting mechanics and safety were provided. Participants were then asked to begin the practice session consisting of three blocks of 20 trials (shots) each. The first block was considered a “warm up” and did not contribute to the study selection criteria. Selection criteria for participation in the study required that 80% of shots during blocks 2 and 3 of the orientation practice sessions be located inside the outermost ring of the target. This performance criterion was established to assure that study participants were relatively similar in their ability and could complete the shooting task successfully. Participants were also informed of the procedures for two testing conditions: performance-alone (PA) and competition (C) that were completed in counterbalanced order during the day of testing.

Participants were asked to refrain from consuming any alcoholic or caffeinated beverages on the day of testing and asked to obtain 7–8 h of sleep during the night prior to testing. Upon arrival, the participants were provided with

a brief review of the instructional video that they had viewed during the orientation session and were familiarized with the tasks associated with the test session (see Figure 1.1). The testing conditions (PA and C) were counterbalanced such that half of the participants engaged in PA, followed by C and the other half of the participants completed C first and then PA with rest periods in between. Participants were allowed 10 practice shots prior to each testing condition. Prior to each condition cortisol, VAS, STAI-S behavioral questionnaires and EEG baselines (i.e., 1-min standing in the shooting position with arm extended toward the target without the pistol to match the shooting posture employed during the conditions of interest while avoiding fatigue) were collected prior to session commencement. There was a 15-min rest period between conditions (PA and C). The participants stood continuously during the two conditions and sat during the rest interval.

Performance-alone. PA was executed without evaluation of performance. Participants were instructed to remain focused and relaxed during this period. Following the baseline measures and the practice shots, a second cortisol sample was collected just prior to the first 20 shots for record. Upon completion of the first 20 shots (i.e., block 1), the participants received a 5-min break during which they completed a second battery of VAS and STAI behavioral assessments. The final 20 shots for record (i.e., block 2) were then executed followed by a third cortisol sample.

Competition. C involved the same order of measurements, but included direct comparison of shooting performance to another study participant. Participants took turns shooting at the targeted such that one shot while the other

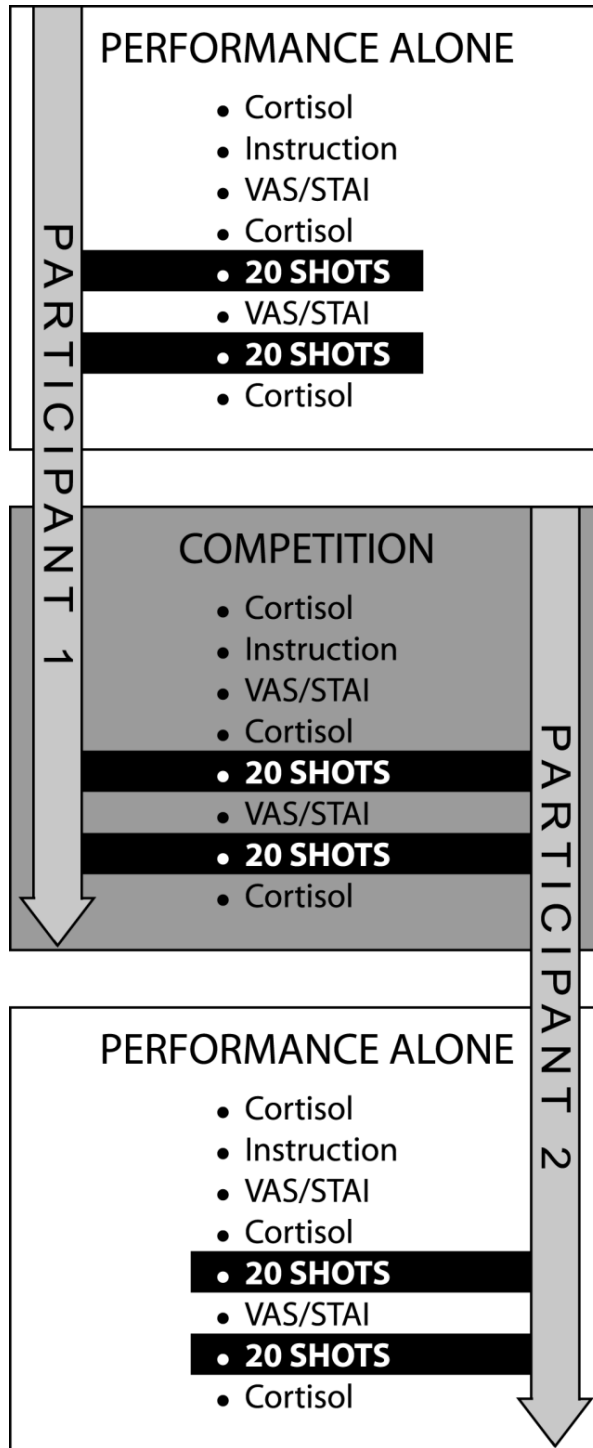


Figure 1.1. Experimental protocol indicating the timing of arousal measures relative to conditions and task. The first participant in the competition completed their performance alone (PA) session prior to the competition (C) whereas the second participant completed their performance alone (PA) session after the competition (C).

observed the opponent's performance. The shooting order was alternated such that in one trial, participant A shot first followed by participant B, but during the next trial participant B shot first, followed by participant A. Participants were instructed to set the pistol down between each shot and to remain standing throughout the respective conditions. Scores were presented to the competitors after each trial and a winner of that trial was declared. The competitive setting included: 1) social evaluation by a superior officer who conspicuously took notes and evaluated the participants' shooting stance and accuracy; 2) financial loss or gain of 50 cents per round, from a starting sum of \$20 (in the case of a tie, the sum at stake (\$1) carried over to the next round), a dollar bonus for a bull's-eye and a dollar loss for missing the target completely; 3) a 30-s time constraint for each shot, beginning when the participant first grasped the pistol to initiate the shooting position; 4) video camera recording; and 5) social responsibility as participants were placed on teams such that their score contributed to overall team score, both of which were displayed outside the ROTC field house. Participants were explicitly informed of all of these pressures during the instructional period prior to task execution and were encouraged to win the competition.

Signal Processing and Data Analysis

All data were co-registered and trials were only included for analysis if simultaneous cardiovascular, motor behavior, and EEG data were available. Of the total number of trials generated by the participants across the two conditions, approximately 10% of the trials failed to achieve this criterion and were discarded from consideration. Cardiovascular activity was analyzed during the PA and C

conditions for each block of trials (first 20 and second 20 shots). The first and last 10% of each ECG time series were discarded in order to remove the transient portion associated with beginning and end of a block. The remaining 80% of ECG recording represented cardiac during task engagement (PA and C).

Arousal measures. The inter-beat-interval (ibi), defined as the time in ms between positive peaks of the R wave of the QRS complex in the ECG signal, was determined using customized software written in a Matlab environment (Mathworks). HR in beats per minute (bpm) was computed from the average ibi.

The salivary cortisol levels were computed for each sample time (1, 2, and 3) for each condition (PA and C). For each participant the pre and post C samples (sample 2 and 3 respectively) were normalized by their baseline sample (subtracted sample 1) to adjust for individual differences in the diurnal cycle of cortisol (Stone et al., 2001).

Cerebral cortical activity – EEG. EEG data reduction was performed using Neuroscan 4.3 edit software. In order to reduce the influence of eye blinks on the EEG data an ocular artifact-correction regression procedure to remove the influence of vertical eye movements and blinks was applied to the EEG recordings (Semlitsch et al., 1986). Next, the data were visually inspected, the correction algorithm for ocular artifact was applied, and the transformed EEG time-series were band-pass filtered from 1 to 50 Hz with a 24 dB/octave rolloff. A 4-s period of continuous EEG data prior to the completion of each shot (i.e., trigger pull) was partitioned into four successive 1-s epochs. The termination of the final epoch was coincident with the trigger pull (i.e., the numbering of epochs was based on a temporal sequence during the aiming period so that Epoch 4

represented the initial 1-s period proceeding successively to Epoch 1 that ended with the trigger pull). The segmented data were then baseline corrected by subtracting the average voltage value of the epoch from each sample in that 1-s time series and linear detrended. A final visual inspection of all sweeps was performed to remove any epochs that still contained significant artifact. These averages were then natural log transformed prior to statistical analysis. Spectral power was calculated using the procedure described by Cooley and Tukey (1965), which is employed in the Neuroscan edit software. More specifically, EEG spectral power was calculated for each 1-sec epoch of the 40 trials of PA and the 40 trials of C (i.e., a total of 80 trials consisting of four separate 1-s epochs). Each epoch was subjected to spline interpolation to generate 1024 points. The first 512 points of the 1024-point series was subjected to the method of Cooley and Tukey as were the second set of 512 points from which an average was created of the two spectra generated for a given epoch. In this manner, a final average for each of the four successive epochs was generated from the values achieved for the 40 PA trials and, separately, for the 40 C trials. Spectral averages were derived by averaging the power over 1-Hz for the bands of interest, low alpha power (8–10 Hz) and high alpha power (10–13 Hz).

The formula employed to calculate EEG coherence was reported earlier by Deeny et al. (2003) and defined as $|C_{xy}(f)|^2$, computed across 1-Hz bins, and averaged for the band of interest, alpha (8–13 Hz), between electrode Fz, which overlies the motor planning region and the following electrodes: F3, F4, C3, C4, T3, T4, P3, P4, O1, and O2. All coherence values were subjected to a Fisher z-transformation prior to statistical analysis to approximate a normal distribution.

Broad band alpha power (i.e., 8–13 Hz) was employed as the band on which to compute EEG coherence in accord with the position of Von Stein and Sarnthein (2000) who articulated that this frequency band was sensitive to medium and long-range cortico-cortical communication, which appeared appropriate given the inter-electrode differences examined herein.

Motor behavior. Mean score was computed based on distance from center target. The aiming point trajectory on the target in mm was sampled at 66 Hz. The tangential displacement with respect to shot was computed for the 3-s period prior to trigger pull. Aiming variability was computed as the standard deviation of the tangential displacement with respect to shot. In addition normalized jerk (NJ) was computed since it is a unit-less measure of the dysfluency based on the third derivative of position (or the rate of change in acceleration). The dynamic change in normalized jerk was computed using a 1-s moving window. The dynamics for each condition were averaged across shots for each subject and fitted with a first order polynomial to determine slope. Normalized jerk was also examined for the final second prior to trigger pull.

$$NJ = \sqrt{T^5 / D^2 \int j^2(t) dt}$$

Where $j(t)$ is the rate of change of acceleration (jerk), T is the movement time, and D is the movement distance.

Statistical Analysis

Separate 2×2 (Condition \times Block) within-subjects ANOVAs were employed to evaluate the effect of stress on self-reported measures (VAS and STAI-S), cardiovascular activity (HR), and the psychoendocrine arousal measure (normalized cortisol sample values).

Separate $2 \times 2 \times 5 \times 4$ (Condition \times Cerebral Hemisphere \times Cortical Region \times Epoch) within-subjects ANOVAs were performed on both spectral power, applied to the low-alpha (8–10 Hz) and high-alpha (10–13 Hz) frequency bands, and coherence, applied to the broad-band alpha frequency (8–13 Hz). The conditions were PA and C, the hemispheres were left and right, the cortical regions were comprised of the frontal, central, temporal, parietal, and occipital regions, and the epochs were the four successive 1-s periods leading to the trigger pull.

In addition, a series of paired one-tailed t-tests were used to examine the differences between conditions on the percentage of negative deflection, performance accuracy, performance variability, the normalized jerk value at the final second prior to trigger pull, and the slope of the normalized jerk dynamics 3 s prior to trigger pull. Cohen's measure of effect size (d) was used to indicate the standardized difference between two means. The Greenhouse-Geisser epsilon (ϵ) was reported when there was the potential to violate sphericity (i.e., more than two levels of a within-subjects variable). Tukey's HSD method was employed for post hoc comparison of means when interactions were observed from the ANOVA. All criterion alpha levels were set to $p < .05$.

Results

Arousal Measures

For the self-report measures, significant effects for Condition were observed with no interaction or main effects revealed for Block. ANOVA applied to the VAS measures revealed an effect of Condition with a robust elevation in competitiveness ($F(1, 16) = 8.87, p = .009, d = 0.67$), and an increase in perceived stress during C ($F(1, 16) = 7.72, p = .013, d = 0.39$). No difference between C and PA was revealed for the confidence or relaxation scales. State anxiety was elevated during C ($M = 34.62$ (SEM \pm 1.9)) relative to PA ($M = 32.35$ (SEM \pm 1.972)) ($F(1, 16) = 4.18, p = .029, d = 0.25$).

HR during C ($M = 89.61$ (SEM \pm 3.24)) was significantly higher ($F(1, 17) = 6.55, p = .020, d = 0.69$) than that observed during PA ($M = 85.81$ (SEM \pm 2.53)). The cortisol response ANOVA revealed a significant main effect of Condition ($F(1, 16) = 12.02, p = .003, d = 1.05$) such that cortisol was higher during C compared to PA. Figure 1.2 illustrates the psychological and physiological variables measured during PA and C.

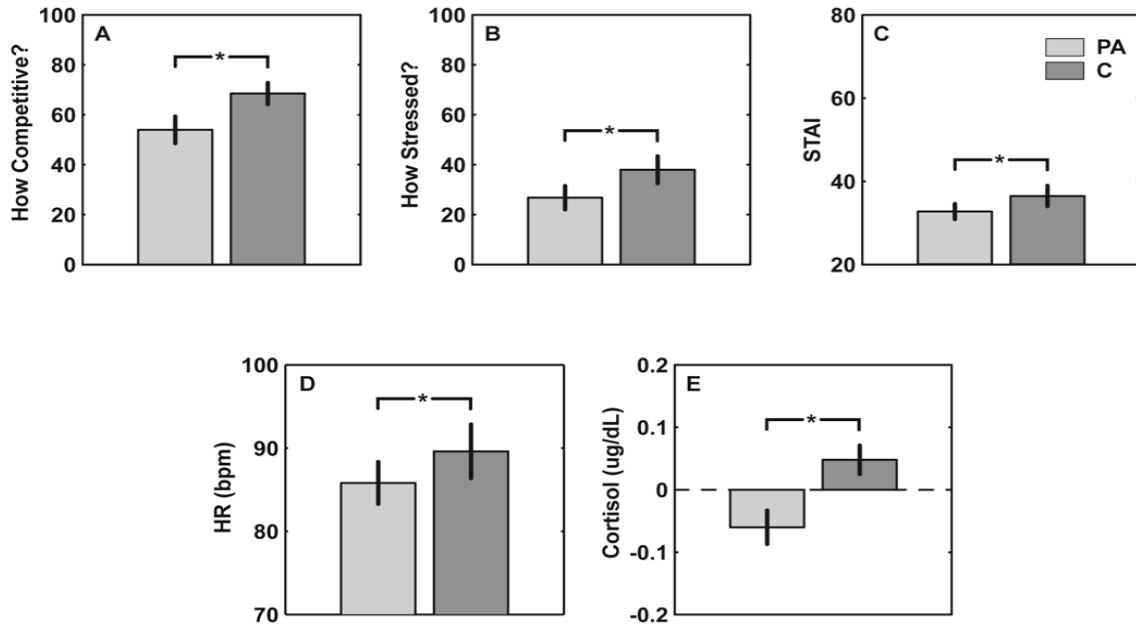


Figure 1.2. Self-reported and physiologic arousal measures during performance alone (PA) and competition (C). Visual analog scale for A) “How competitive do I feel?” (between 0=not competitive and 100=ultra competitive); and B) How stressed am I? (between 0=no stress and 100=completely stressed). C) State-Trait Anxiety Inventory-State scored from 20 to 80, higher scores reflect greater anxiety. D) Heart rate. E) Salivary cortisol levels. Asterisk (★) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

Cerebral Cortical Activity - EEG

Spectral power. The spectral band power during each condition is shown in Figure 1.3. Note that the power illustrated at each site in Figure 1.3 was averaged across the four successive epochs leading to the trigger pull. Figure 1.4 provides topographical maps of the low- and high-alpha band power observed across the topography for each of the four epochs leading to the trigger pull in the PA and C conditions. A significant Condition \times Second interaction ($F(3, 54) = 4.59, p = 0.006, \epsilon = 0.91$) was noted for the high-alpha frequency band (10–13 Hz) such that the power across the scalp topography during C was lower than that observed during PA at each epoch. The interaction can be explained by

the varying degree of the magnitude of difference between the conditions during each epoch (see Figure 1.5). Low-alpha band power (8–10 Hz) was undifferentiated between conditions.

Coherence. A significant effect of Condition ($F(1, 18) = 6.824, p = 0.018, d = 0.61$) was revealed for alpha coherence (8–13 Hz). Coherence was elevated during C, compared to PA, for all 10 regions examined and across all four successive time periods to the trigger pull (see Figure 1.6).

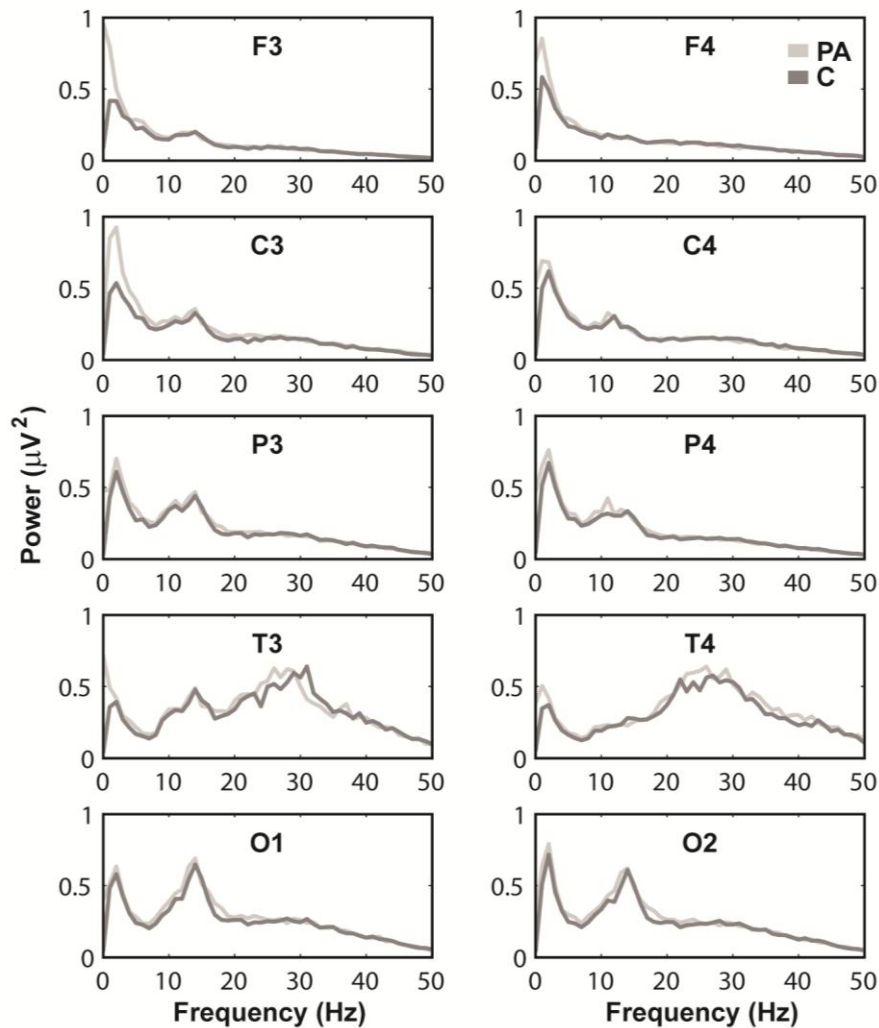


Figure 1.3. Spectral power during the 4-s prior to trigger pull averaged across trails and subject during performance alone (PA) and competition (C).

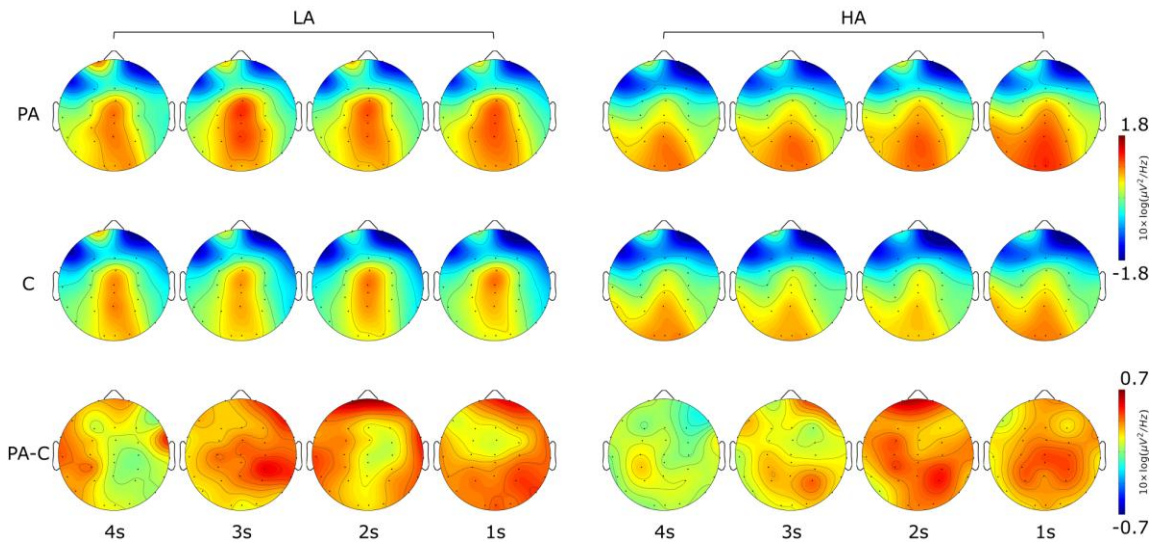


Figure 1.4. Low alpha (LA, 8-10 Hz) and High alpha (HA, 10-13 Hz) power during performance alone (PA) and competition (C) averaged across trials and subjects from four seconds before trigger pull (4s) to the final second before trigger pull (1s). PA-C represents the difference between condition topographic scalp maps (PA minus C).

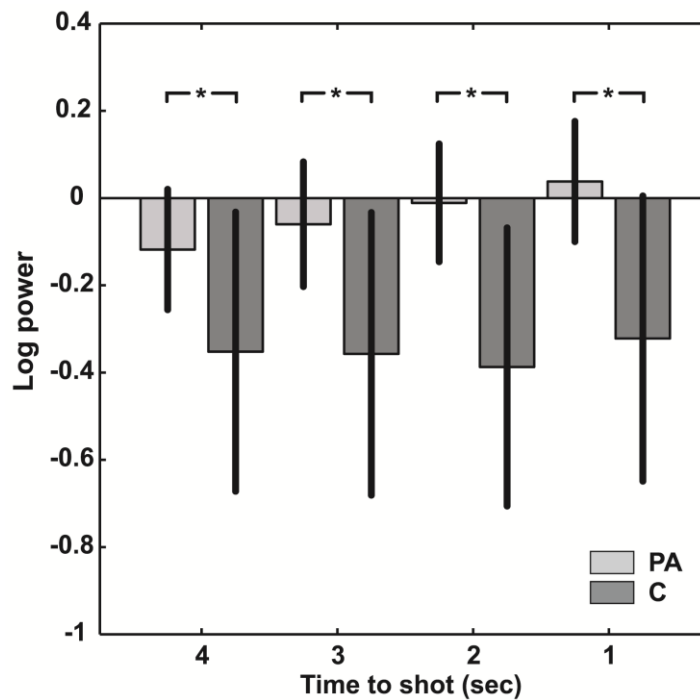


Figure 1.5. High alpha power (10-13 Hz) during performance alone (PA) and competition (C). Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

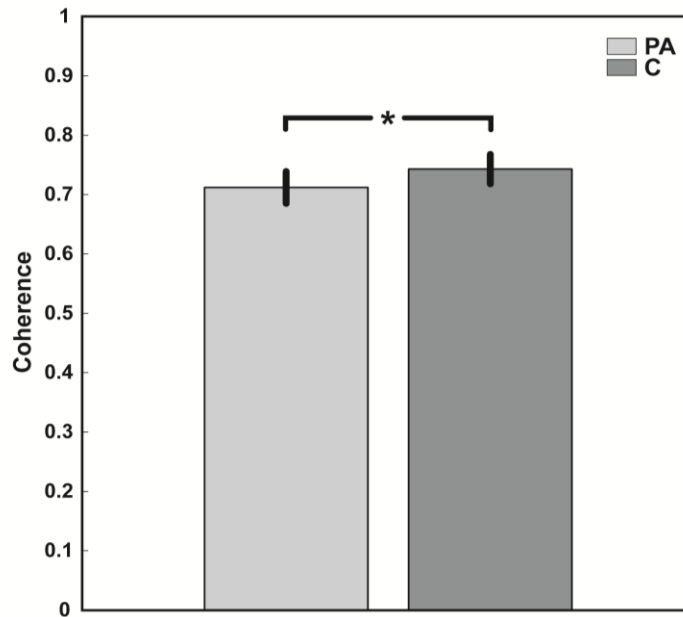


Figure 1.6. Averaged EEG alpha (8-13 Hz) coherence between Fz (representing the motor planning region) and all other recording sites during performance alone (PA) and competition (C). Asterisk (★) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

Motor Behavior

Examination of score and variability of the shot placement on the target revealed no differences between PA and C. The mean score for PA was 6.83 (SEM \pm 0.214) and for C was 6.86 (SEM \pm 0.230), $t(18) = -.183$, $p = .857$.

Aiming variability during PA was 0.014 (SEM \pm 0.001) and during C was 0.013 (SEM \pm 0.001), $t(18) = 1.27$, $p = .22$.

However, an increase in dysfluency of the aiming trajectory was seen during the final s before trigger pull in competition compared to performance alone ($t(18) = 2.36$, $p = .015$, $d = 1.02$). In addition, analysis of the slope prior to trigger pull revealed a significantly steeper slope in C compared to that observed during PA ($t(18) = 3.69$, $p = .001$, $d = 1.23$) (see Figure 1.7).

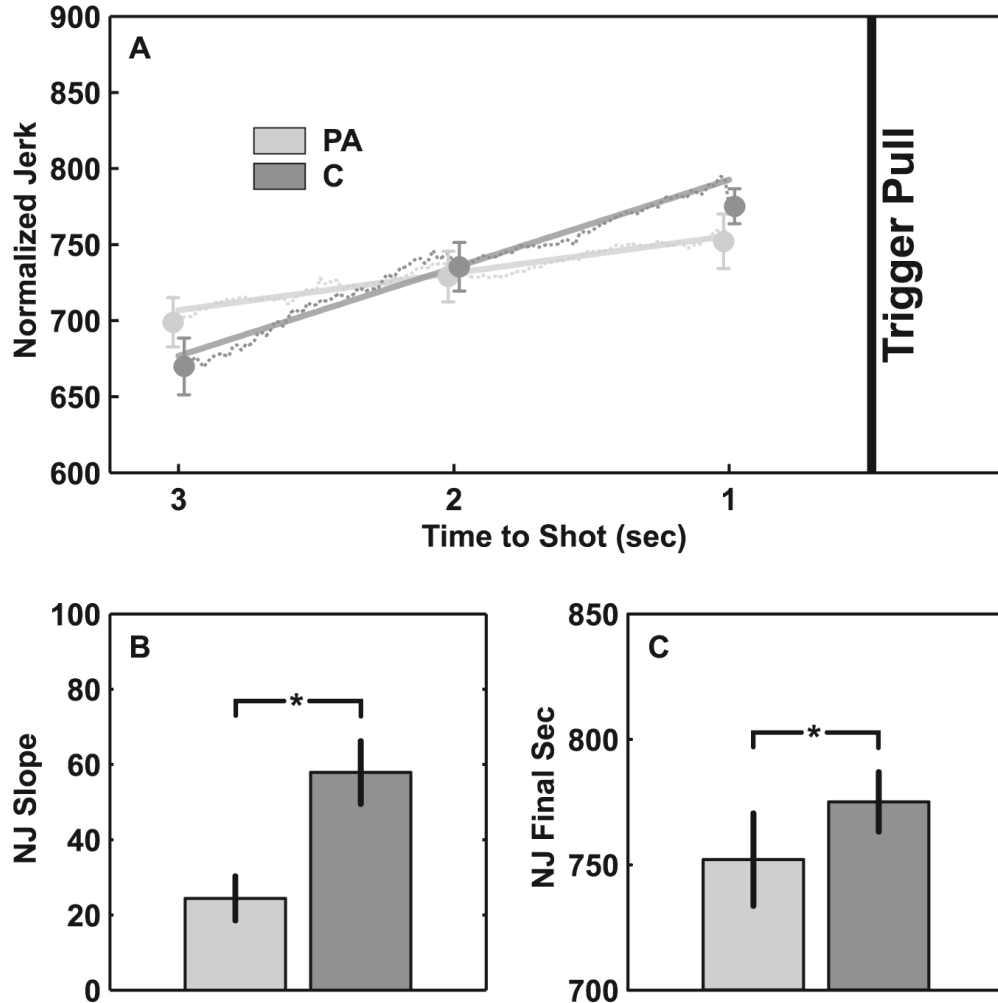


Figure 1.7. A) Dynamics of normalized jerk (dotted line) during the 3s prior to trigger pull (computed with a 1-s window) fitted with a first order polynomial (solid line). B) Slope of the dynamics of normalized jerk (NJ) determine from the first order polynomial. C) Normalize jerk (NJ) of the final second prior to trigger pull. Asterisk (\star) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

Discussion

The present investigation offers a multi-level examination of motor performance, cortical dynamics and physiological responses under the unique, but prevalent social setting of competition. Previous investigations of skilled performance revealed an economy of expert task execution (Hatfield and Brody,

2000; Hatfield and Hillman, 2001). Efficiency is not only reflected in the biomechanical and metabolic processes of skilled performers, but also in the cerebral cortical processes, which mediate the action of the motor effectors. During circumstances of low mental stress, EEG alpha power during expert marksmanship is positively related to performance and has been interpreted as quiescence of cognitive analysis, particularly when present in the left temporal region (Hatfield et al., 2004; Kerick et al., 2004; Zhu et al., 2011). However, few studies have examined the impact of social stress on cortical dynamics during goal-oriented motor behavior. In the present study we examined how direct competition, accompanied by a modest increase in mental stress (based on a moderate elevation of arousal and state anxiety), perturbs cerebral cortical processes and influences the quality of motor performance. In essence, the stress of competition was expected to heighten the activity of the brain due to the additional workload of processing the social demand.

As expected, the processing load associated with the competitive condition did result in heightened cortical activity, as measured by high-alpha EEG power, across all of the topographical regions examined. As such, competition did impose an increase in cognitive load. In addition, the elevation in cortico-cortical communication was robust, involving heightened communication between all non-motor regions with the motor planning region (i.e., Fz) and the input to the motor region was temporally stable across the 4-s aiming period just prior to the trigger pull. More specifically, the heightened frontal input may be explained by elevated executive effort to inhibit task-irrelevant stimuli, while the additional central and parietal communication could be explained by additional

effort in the motor and visual-spatial domains. Such a possibility appears tenable in light of the increased pressure to perform well under the condition of social evaluation.

The findings for EEG coherence are similar to those of Rietschel et al. (2011) who also examined the effect of social evaluation on cortical dynamics and motor performance. They observed elevated communication from the central and parietal regions to the motor planning region during an evaluative condition relative to a non-evaluative condition, but they observed no elevation in frontal and temporal communication with the motor planning processes. In fact, they observed a decrease in cortico-cortical communication between the right temporal and motor planning region, which was interpreted as a refinement of cortical communication and was accompanied by improvement in performance. These apparently contradictory findings may be explained by the different conditions of the competitive challenges employed in the two studies. More specifically, Rietschel et al. imposed a form of evaluation without direct interaction with a competitor, while a central feature of the present study was direct 'head-to-head' competition, which likely imposed a heightened cognitive load on the participants in the present study. In addition, Reitschel et al. found an increase in arousal, but failed to see an elevation in state anxiety during social evaluation, which was observed in the present study.

Although the participants reported a remarkable increase in perceived competitiveness relative to performing alone, the results indicate that state anxiety was only modestly elevated as revealed by self-report in conjunction with HR, SC and salivary cortisol. This finding is consistent with recent work from

Cerin and Barnett (2009) who reported that competition can be an anxiogenic event and affects the performer's emotional state. They reported that competition-related concerns resulted in high self-reported fear that can be characterized as a threatening and challenging event (Cerin and Barnett, 2009). Such a negative affective state is consistent with the general notion of neuromotor noise described by van Galen and van Huygevoort (2000). Their model identifies neuromotor noise as the primary source of human error under workload and time pressure conditions. They argued that such noise reflects a mismatch between an intended movement and the outcome of that movement and suggested that motor performance is inherently noisy due to the degrees of freedom in behavioral repertoires. Van Galen and van Huygevoort argued that psychological and physical stress result in, "...non-specific neural activation spreading" (p. 155). They found that increased neuromotor noise resulted in heightened probability of action error thus not only disturbing the refinement of skilled action, but also resulting in performance decline under pressure (van Galen and van Huygevoort, 2000).

Beyond the alteration in cortical dynamics, our results also indicate that competition, accompanied by a modest increase in anxiety, produced behavioral changes in the fluency of motor performance, but no difference in aiming variability and score. Thus, the performance outcome was constant across conditions, but the quality of the aiming trajectory was compromised under the social evaluation of competition suggesting that the loss of neural efficiency indicated by the spectral and coherence results translated into compromised smoothness and a loss in economy of motion (Smith et al., 2000). This finding

suggests that a noisy (i.e., more complex) central system produces greater activation of skeletal muscle (i.e., heightened motor unit recruitment) and compromises of reciprocal inhibition resulting in co-contraction of agonistic and antagonistic muscles leading to dysfluency of the aiming trajectory. The findings also suggest elevated influence of brain networks that relate to non-motor neural processes interacting with the network associated with perceptual-motor performance thus increasing the opportunity for non-essential activity, beyond that required essentially for motor planning, in the central nervous system. Such a state altered the motor preparatory processes and the quality of the motor behavior. While the reduction in efficiency did not result in a change in performance outcome (as measure by score) in the short run, it is possible that such attenuated efficiency could translate to performance decline (decreased accuracy and a lower score) if mental stress is sustained over time, consistent with the neural processing efficiency hypothesis (Eysenck and Calvo, 1992).

Correlational analyses between the three EEG measures (low-, high alpha spectral power and coherence) and the measures of shooting performance were conducted during the last second prior to the trigger pull during both PA and C separately. However, a significant relationship was noted only during the PA condition in which a positive correlation between high-alpha power at sites F3 and F4 and the magnitude of jerk was observed ($r(df, 18) = .469, p = .043$ and $r(df, 18) = .520, p = .023$, respectively), which implies that a reduction in task-relevant attentional focus was associated with greater aiming variability.

Although the EEG results indicate heightened cortical activity across all scalp regions during competition, the specific elevation of activity in the left

temporal region, as indicated by the reduction in high-alpha power at site T3, implies the presence of self-talk during social evaluation. Such an interpretation is consistent with the reinvestment hypothesis described by Masters (1992) and is indicative of regression to an earlier stage of skilled motor behavior (Fitts and Posner, 1967) under conditions of mental stress that could explain the degradation in the efficiency of the aiming trajectory as noted present study. Such a form of explicit monitoring may be frequent in complex motor tasks since the training is typically centered on substantial explicit technical instruction (Kinrade et al., 2010). In the present study both left temporal regional activity, as estimated from EEG spectral analysis, as well as communication from this region to the motor planning region, as estimated by EEG coherence analysis, was elevated, as predicted, but to no greater extent than all of the other cortical regions examined. Although the prediction of a pronounced effect of social stress on the left temporal region was not supported, the observed change in this region during competition may have introduced non-essential neural activity into the motor control processes underlying the aiming task, thus altering the quality of motor behavior (i.e., the dysfluency of the aiming trajectory).

It is noteworthy that there are circumstances when self-talk may promote rather than interfere with motor performance. For example, St. Clair Gibson and Foster (2007) reported that motivational thoughts can sustain effort during exertion acute exercise. Global cue words that represent a gestalt of explicit skills can reduce reinvestment under mental stress and instead produce self-regulatory approaches that do not require reliance on explicit cues (Gucciardi and Dimmock, 2008; Jackson and Wilson, 1999). In addition, an emotion regulatory

strategy, known as cognitive reappraisal, changes the emotional responses to stressful challenges by verbally reformulating the meaning of a situation (Goldin et al., 2008; Wager et al., 2008). As such, the nature and influence of cognitive regulation on motor processes evoked by competition can vary, but it would seem that the underlying cognitive processes indexed by the change in cortical dynamics during competition were sub-optimal as indicated by the change in the aiming trajectory. It cannot be determined from the present results whether the participants were engaged in negative or positive self-talk, but our results support the notion of a loss of efficiency of cortical dynamics during stressful challenge. However, it is clear from the results that both the condition of performing alone and that of competition were engaging and challenging to the participants as both conditions were marked by considerable cortical activation compared to the baseline periods prior to shooting at the target when they simply stood and pointed at the target in the aiming posture. Although some showed a pattern of change that was opposite to that of the group (i.e., they showed elevated high-alpha power during competition), the magnitude of change was not great and was not reliably related to the performance outcome either in terms of dysfluency of the aiming movement or accuracy. As such, the influence of individual differences was not large in terms of the cortical response to the social manipulation. In essence, it appears that there is a need to examine the impact of social conditions on the processes underlying the quality of motor behavior with a more robust imposition of evaluative stress while employing additional process measures such as EMG to determine whether, in fact, the “noise” introduced in the cerebral cortex via such stress then translates directly in a

perturbation of motor unit activity in the relevant peripheral effectors involved in the performance. Such a relationship could underlie the commonly observed notion of “choking” whereby some individuals perform more poorly than expected under highly competitive conditions. Furthermore, under such conditions, it may be that robust individual differences do occur that help to explain why some are affected differently in terms of the quality of their motor performance under stress.

In summary, the results revealed that competition introduced an increase in activity in the central nervous system, which translated to the quality of motor behavior during the performance of a precision aiming task. In this manner the spectral and coherence derivatives of the EEG recorded during competition suggest the introduction of nonessential neural activity to the visuo-motor processes. Relative to performing alone, the loss of psychomotor efficiency during stress translated to the quality of motor behavior such that it resulted in dysfluency of the aiming movement during competition. The observed changes in cortical dynamics during competition underscore the importance of consideration of the social context and the employment of psychophysiological measures to better understand the processes underlying and accounting for motor performance in such a social setting. Typically, the assessment of performance-relevant neural and physiological processes is devoid of such consideration (i.e., the social context). Recent work by Miller et al. (2013) further underscores the influence of the social environment on brain processes during cognitive-motor performance not only during competition as examined in the present study, but in the case of cooperation (i.e., teamwork). Specifically, Miller et al. observed

reduction in cognitive load, as indexed by event-related responses to attentional probes, when executing a visual-spatial challenge with a teammate perceived as competent, relative to performing the task with a teammate perceived as incompetent. Motor performance typically occurs in a social context so it appears useful to manipulate critical elements of the social environment in ways that are informative to account for the neural processes associated with motor behavior.

Study 2 - The Impact of Motor Skill Training on Motor Performance and Cortical Dynamics in a Stressful Social Environment

Introduction

Motor learning is the ability to benefit from experience-dependent improvement in skill performance (Schmidt, 1991). It is important to note that this definition excludes enhancements in performance that may be attributed to factors other than experience or practice, for instance physical or cognitive maturation. Although perceptible improvement is a fundamental component in this framework of motor learning, it is possible that some beneficial changes may occur from learning or experience that is not readily observable. Studer, Koeneke, Blum, & Jäncke (2010) examined the effect of different training regimens on visuo-motor task performance. While no differences in performance were observed between types of training, examination of regional cortical activation revealed an increase in cerebral cortical activity over the sensorimotor cortex in participants that trained under one particular regime relative to the other. This indicates that one type of training was able to match the level of performance of the other, but with less cognitive resources (i.e., a reduction of extraneous cortical processing). Psychomotor learning is characterized by a refinement of cognitive processes that underlie motor skill acquisition and is often explained in the context of Fitts and Posner (1967) three stage model of skill learning. This progressive and sequential process begins with a cognitive phase involving the identification and development of the component parts of the skill, moves through an associative phase characterized by linking the component

parts into a smooth action, to finally reach the autonomous phase in which skill performance requires little or no conscious thought or attention. As we acquire a motor skill, moving through the three stages of motor learning, the amount of cognitive resources required to perform decreases (Hatfield, Haufler, Hung, & Spalding, 2004; Hatfield & Kerick, 2007).

The term psychomotor efficiency, first invoked by Hatfield and Hillman (2001), has been used to describe the reduction of extraneous associative cortical activity and the enhancement of task-relevant cortical processes that accompanies proficient motor skill performance. These alterations in cortical networks reflect a refined control strategy capable of producing more consistent motor performance. The pattern of electrical activity across the cerebral cortex as measured by electroencephalography (EEG) and how it changes over the course of learning and during performance are referred to as cortical dynamics. One approach to understanding the impact of motor learning on cortical dynamics is to examine the pattern of cerebral cortical activity associated with motor performance of the highly experienced or expert performer (for review see Hatfield, Haufler, Hung, & Spalding, 2004; Hatfield & Kerick, 2007). Highly skilled performance is consistently accompanied by a reduction in extraneous associative cerebral cortical activity and an enhancement of task-relevant cortical processes. These findings have been demonstrated in expert performers (Hatfield, Landers, Ray, & Daniels, 1982; Hatfield, Landers, & Ray, 1984), expert/novice contrasts (Del Percio et al., 2009; Haufler, Spalding, Santa Maria, & Hatfield, 2000; 2002), in pre/post motor learning comparisons (Landers, Han, Salazar, Petruzzello, Kubitz, & Gannon, 1994; Kerick, Douglass, & Hatfield,

2004), and over the course of motor skill acquisition (Studer, Koeneke, Blum, & Jäncke, 2010; Gentili, Bradberry, Oh, Hatfield, & Contreras Vidal, 2011; Gentili, Bradberry, Oh, Costanzo, Kerick, Contreras-Vidal, & Hatfield, 2015) as an alteration in the pattern of EEG alpha frequency band activity across the scalp. These studies, primarily conducted during visuo-spatial aiming tasks such as rifle and pistol marksmanship, have revealed an increase in EEG alpha power over the left temporal region and relative stability of EEG alpha power over the right temporal region during motor performance and motor planning (just prior to performance). Alpha power reflects synchronous cortical activity of the EEG signal in the 8-13 Hz frequency band. High levels of alpha power are attributed to a reduction in cortical engagement or “idling” of the cerebral cortex (Pfurtscheller, Stancák, & Neuper, 1996). As such, the observed synchrony in the left temporal region has been interpreted as quiescence of verbal-analytical processes while the stability of homologous right temporal region reflected a maintenance of visual-spatial processing, which would facilitate such aiming tasks. Although there are other interpretations of alpha band activity, for instance Jensen and Mazaheri (2010) have proposed that alpha band activity functionally inhibits task-irrelevant areas allowing task-relevant regions to become active, the current study consistent with the previous literature in the field (for review see Hatfield et al., 2004; Hatfield & Kerick, 2007) relies on Pfurtscheller and colleagues (1996) explanation of synchronous alpha activity as reflecting cortical disengagement or “idling”.

Refinement of cortical dynamics has also been revealed by examining the coherence between pairs of EEG electrodes, which reflect the level of

cooperative network activity or cortico-cortical communication between regions. Busk and Galbraith (1975) first observed that EEG coherence decreased between regions associated with motor planning and motor cortex as performance of a visuo-motor tracking task improved, which they interpreted as a decreased dependence on networks related to motor planning. More recently, decreased EEG coherence has been observed between the motor planning region and the region associated with verbal-analytic processing (left temporal region) during the aiming period of skilled marksmen with superior competitive histories, relative to a skill matched group with poorer competitive performance history (Deeny, Hillman, Janelle, & Hatfield 2003). Decrease EEG coherence has also been observed between the motor planning region and multiple association regions in expert marksmen when compared to novices (Deeny, Haufler, Saffer, & Hatfield, 2009). The reduction in coherence that accompanies improved motor skill performance suggests that the elimination of cortical networks may be related to the production of successful motor performance. This notion was supported by Deeny and colleagues (2009) who observed that EEG coherence was positively correlated with variability of movement during skilled performance. That is a decrease in network activity between regional recording sites and the motor planning region was associated with lower variability in the aiming trajectory or better quality of movement. Considered together, these studies indicate that motor skill training or practice promote the refinement of local cortical and cooperative network activity which accompanies skilled motor performance.

Another factor that requires consideration is performance pressure.

Performance pressure or stress is defined as the desire to perform to the best of one's ability in situations of perceived importance. When someone performs sub-optimally with respect to their ability, worse than their skill level would predict, they are said to have choked. Suboptimal performance is not related to a random variation in skill quality but instead occurs in reaction to high levels of performance pressure. A lengthy period of sub-par performance is associated with slumps, but choking is a finite performance condition which abates when the source of pressure diminishes. Although choking here is defined at the behavioral level (i.e. performance outcomes), this is not meant to suggest that the effects of pressure aren't reflected in the performers physiologic or cognitive processes. The use of EEG to examine cerebral cortical dynamics associated with performance under pressure has provided useful information concerning the nexus between motor performance and the cognitive/affective states brought about by stressful situations.

A recent investigation compared the cerebral cortical dynamics that underlie motor skill performance during a stressful 'head-to-head' competition to performance in a 'practice-like' environment (Hatfield, Costanzo, Goodman, Lo, Oh, Rietschel, Saffer, Bradberry, Contreras-Vidal, and Haufler, 2013). Relative to the practice condition, the competition condition was accompanied by changes in both physiological and psychological state consistent with an increase in stress. Although the increase in stress produced by competition didn't affect the outcome of performance, movement quality was observed to diminish. This reduction in the quality of movement was thought to be related to an increase in

'neuromotor noise' induced by the competitive environment which was reflected in the electro-cortical activity as a significant decrease in alpha power across the scalp and a significant increase in coherence between the motor planning region and multiple associative areas. This suggests that the stress produced by competition diminished psychomotor efficiency and was expressed as a reduction in the quality of motor performance. It is important to note that while the participants did have time to become familiar with the equipment (the pistol) and the task (competitive shooting technique), they were essentially inexperienced performers. In a separate study Rietschel, Goodman, King, Lo, Contreras-Vidal, & Hatfield (2011) investigated the influence of stress on cerebral cortico-cortical communication and motor behavior during a visual-spatial aiming task performed alone and under social evaluation. Unlike the previous study, participants had the opportunity to substantially practice the task prior to testing. And unlike the previous study, subjects demonstrate improved quality of movement during social evaluation which was observed along with a decrease in EEG coherence between the motor planning (Fz) and temporal regions (T3 & T4). This increase in psychomotor efficiency during the social evaluative condition was interpreted with respect to an inverted-U dose/response curve between arousal and performance suggesting that moderate arousal induces a refinement in nonessential cortical networking, which is exhibited as an increase in the quality of motor performance.

These conflicting results may be related to the experience level of the performer. A stressful performance environment may adversely impact cortical dynamics which maybe expressed in movement quality of inexperienced

performers, while for experienced performers moderate amounts of stress encourage optimal cortical dynamics. Together these studies, both involving a social evaluative stressor, suggest that motor skill training or practice may mitigate the impact a stressful performance environment has on psychomotor efficiency, however further research is needed to establish support for this notion. This study employs a within-subjects design to examine the impact of skill training or practice on motor performance in a stressful social evaluative environment. A 'head-to-head' competitive setting, identical to the one employed by Hatfield et al. (2013), was utilized to produce a stressful performance environment. It was expected that after undergoing skill training subjects would demonstrate improved motor performance during a post-training competition, relative to the pre-training competition. The cerebral cortical dynamics were predicted to reveal an increase in psychomotor efficiency during the post-training competition as indexed by local regional and network cortical EEG activity. Specifically, an increase in alpha power in the left temporal region (T3) and a decreased coherence between the left temporal region (T3) and the motor planning region (Fz) were anticipated, consistent with previous studies examining psychomotor efficiency.

Methods

Participants

Participants were recruited from the University of Maryland's Reserve Officers' Training Corps (ROTC) program. Sixteen right-hand dominant (Oldfield, 1971) and right-eye dominant male cadets ages 19 to 30 years ($M = 22.88$, $SD = 3.69$) voluntarily enrolled in the study. All participants completed a health history

questionnaire to ensure that they were free of neurological and psychiatric disorders. No participants had previous history of competitive shooting but all met a minimum performance level during a preliminary practice session for inclusion in to the study. Prior to testing, all participants were provided written informed consent approved by the Institutional Review Board and were informed that they were free to withdraw from the study at any time.

Task

Participants completed a dry-fire pistol shooting task using their right (dominant) hand at a target 5m away. The target was scaled to maintain a proportionate diameter consistent with that of an official competitive target (i.e., at a distance of 50 ft, or 15.24 m). Participants received instruction regarding a standard shooting posture; feet positioned approximately shoulder-width apart and nearly perpendicular to the shooting lane to minimize sway, extended the shooting arm while aiming and sighted the target with their right eye (the left eye was occluded). Participants received visual feedback after each trial (shot) consisting of the score and the position of the shot on the target. Scoring was consistent with the rules of competitive shooting with the center ring or Bull's eye worth a score of 10 and the outermost ring a score of 1. The pistol was equipped with the Noptel ST-2000 optical tracking system to monitor the aiming motion of the pistol barrel and shooting performance (shot placement on the target).

Measures

Arousal measures. Electrocardiogram (ECG) was collected using a Thought Technology Procomp2 system, (encoder model #SA7400). ECG was sampled at 256 Hz through a single chest lead.

Saliva samples were collected and analyzed by Salimetrics (State College, PA) for cortisol levels using an enzyme immunoassay (Saliva Oral Swab). Samples were labeled in accordance with their collections time with respect to the test session.

The State Anxiety Inventory (Spielberger et al., 1970) was used to assess mental stress. Scores on this measure range from 20 to 80 with higher scores reflecting greater anxiety. Visual Analog Scales (VASs) were employed as a course self-report measure of participant's mental state similar to an approach used by Bixby et al. (2001). The following questions were posed: VAS 1: How competitive do I feel? (0 = not competitive, 100 = ultra competitive); VAS 2: How stressed am I? (0 = no stress, 100 = completely stressed); VAS 3: How confident do I feel? (0 = extremely confident, 100 = no confidence); VAS 4: How relaxed am I? (0 = not relaxed, 100 = completely relaxed).

Cerebral cortical activity – EEG. Scalp electroencephalographic (EEG) data were collected using tin electrodes housed within a stretchable lycra cap, (Electro-Cap International, Inc.). EEG signals were referenced to linked earlobes and a common ground (FPz), and impedances were maintained below 10 k Ω . All channels were amplified 500 times using Neuroscan Synamps 1, and recorded using Neuroscan software (version 4.3.3). Online bandpass filters were set at 0.01–100 Hz with a sampling rate of 1000 Hz. Electrodes were placed above and below the left eye over the orbicularis oculi muscle to assess VEOG and at the outer canthi of both eyes (HEOG) to record eye blinks and lateral movements. An electronic pulse was generated by the shooting simulator to mark the trigger pull in the continuous EEG recording. Data were acquired from 30 sites (FP1, FP2,

F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, CZ, FZ, PZ, FCZ, CPZ, CP3, CP4, FC3, FC4, TP7, TP8, FT8, OZ, FT7). From these sites, 10 homologous sites of interest (F3, F4, C3, C4, P3, P4, T3, T4, O1, O2) were subsequently chosen to capture the major regions within each of the cerebral hemispheres for the purpose of spectral and coherence analyses. The Fz electrode served as the common site of interest in all electrode pairings for the coherence analysis (e.g., Fz-F3, Fz-F4, Fz-C3, etc.) to enable examination of cortico-cortical communication between all regions with the motor planning region (Fz).

Motor behavior. The Noptel optical shooting simulator system was used to record the aiming trajectory of the pistol in two dimensions and its position on the target at the time the trigger was pulled (shooting score). The aiming point trajectory on the target in mm was sampled at 66 Hz.

Procedure

This study required participants to complete two competition testing sessions ('Pre' and 'Post' training) and nine skill training session (practice) falling between competitions over three weeks. Prior to the initial test session all participants were brought in to the testing environment to become familiar with the study procedures and to demonstrate that they could perform to the criterion skill level (i.e., ability to hit the target 80% of the time while executing 40 shots). All participants were informed of the requirements of the experiment and provided an opportunity to ask questions before they provided consent. In order to reduce any novelty effect that might be observed on the actual testing day, the EEG and heart rate (HR) monitors were placed on the participants for

familiarization during the orientation session. They also completed the psychological assessments (VAS, State Anxiety Questionnaire), and were instructed on the acquisition procedures for salivary cortisol (i.e., oral swab). Participants also viewed a videotape generated by a National Collegiate Athletic Association (NCAA) Division I pistol shooting coach through which instructions about shooting mechanics and safety were provided. Participants were then asked to begin the practice session consisting of three blocks of 20 trials (shots) each. The first block was considered a “warm up” and did not contribute to the study selection criteria. Selection criteria for participation in the study required that 80% of shots during blocks 2 and 3 of the orientation practice sessions be located inside the outermost ring of the target. This performance criterion was established to assure that study participants were relatively similar in their ability and could complete the shooting task successfully.

Participants were asked to be well rested and refrain from consuming any alcoholic or caffeinated beverages on the day of testing. Upon arrival, the participants were provided with a brief review of the instructional video that they had viewed during the orientation session and were familiarized with the tasks associated with the test session (see Figure 2.1). Prior to commencement of the competition participants were allowed 10 practice shots and a 1-min EEG baseline was recorded in the shooting position (standing with arm extended toward the target without the pistol).

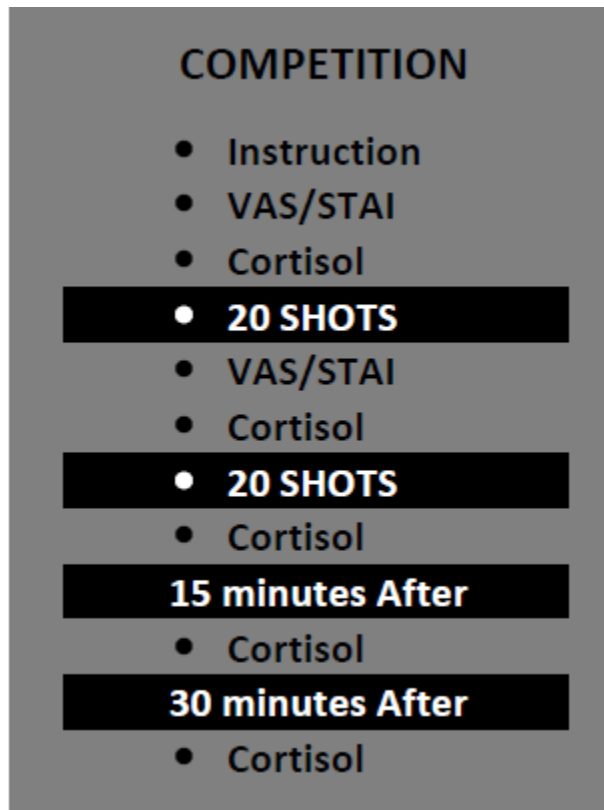


Figure 2.1. Competition protocol indicating the timing of arousal measures relative to task performance.

Competition. Competition involved a direct comparison of shooting performance to another study participant. Participants took turns shooting at the targeted such that one shot while the other observed the opponent's performance. The shooting order was alternated such that in one trial, participant A shot first followed by participant B, but during the next trial participant B shot first, followed by participant A. Participants were instructed to set the pistol down between each shot and to remain standing throughout the competition. Scores were presented to the competitors after each trial and a winner of that trial was declared. The competitive setting included: 1) social evaluation by a superior officer who conspicuously took notes and evaluated the participants' shooting

technique and accuracy; 2) financial loss or gain of 50 cents per round, from a starting sum of \$20 (in the case of a tie, the sum at stake (\$1) carried over to the next round), a dollar bonus for a bull's-eye and a dollar loss for missing the target completely; 3) a 30-s time constraint for each shot, beginning when the participant first grasped the pistol to initiate the shot; 4) video camera recording; and 5) social responsibility as participants were placed on teams and their score contributed to the team's overall score, both of which were displayed outside the ROTC field house. Participants were explicitly informed of all of these pressures during the instructional period prior to task execution and were encouraged to win the competition.

Skill Practice. Practice was executed without evaluation of performance. Participants were instructed to remain focused and relaxed during this period. Detailed shooting technique guidelines were posted in the practice area for review. Participants completed 40 self-paced shots during each of nine practice sessions between the competitions (Pre-training and Post-training competitions).

Signal Processing and Data Analysis

All data were co-registered and trials were only included for analysis if simultaneous cardiovascular, motor behavior, and EEG data were available. Of the total number of trials generated by the participants across the two competitions, approximately 10% of the trials failed to achieve this criterion and were discarded from consideration.

Arousal measures. Cardiovascular activity was analyzed for each block of trials (first 20 and second 20 shots). The first and last 10% of each ECG time series were discarded in order to remove the transient portion associated with

beginning and end of a block. The inter-beat-interval (ibi), defined as the time in ms between positive peaks of the R wave of the QRS complex in the ECG signal, was determined using customized software written (Matlab, Mathworks Inc.). Heart rate (HR) in beats per minute (bpm) was computed from the average ibi.

The salivary cortisol levels were obtained from each sample time for each competition. Five cortisol samples were collected during each competition as follows: 1) just prior to the first shot; 2) just before the start of the second block (shot 21); 3) just after the final shot; 4) 15 minutes after the final shot; 5) and again at 30 minutes after the final shot.

Cerebral cortical activity – EEG. EEG data were analyzed using Neuroscan 4.3 edit software. In order to reduce the influence of eye blinks an ocular artifact-correction regression procedure to remove vertical eye movements and blinks was applied to the EEG recordings (Semlitsch et al., 1986). After visual inspection, the EEG time-series were band-pass filtered from 1 to 50 Hz with a 24 dB/octave rolloff. A 4-s period of continuous EEG data prior to the completion of each shot (i.e., trigger pull) was partitioned into four successive 1-s epochs. The segmented data were then baseline corrected by subtracting the average voltage value of the epoch from each sample in that 1-s time series and linear detrended. A final visual inspection of all sweeps was performed to remove any epochs that still contained significant artifact. These averages were then natural log transformed prior to statistical analysis. Spectral power was calculated using the procedure described by Cooley and Tukey (1965), which is employed in the Neuroscan edit software. More specifically, EEG spectral power was calculated for each 1-sec epoch of the 40 trials from each competition (i.e., a

total of 80 trials consisting of four separate 1-s epochs). Each epoch was subjected to spline interpolation to generate 1024 points. The first 512 points of the 1024-point series was subjected to the method of Cooley and Tukey as were the second set of 512 points from which an average was created of the two spectra generated for a given epoch. Spectral averages were derived by averaging the power over 1-Hz for the bands of interest, theta (3–8 Hz), low alpha (8–10 Hz), high-alpha (10–13 Hz), and broad band alpha (8-13 Hz)

EEG coherence was defined as $|C_{xy}(f)|^2$. Coherence was computed across 1-Hz bins, and averaged for the frequency bands of interest between electrode Fz, which overlies the motor planning region and the following electrodes: F3, F4, C3, C4, T3, T4, P3, P4, O1, and O2. All coherence values were subjected to a Fisher z-transformation prior to statistical analysis to approximate a normal distribution. Coherence was computed for the theta (3–8 Hz), alpha (8–13 Hz), low-beta (13–20 Hz), and high-beta (20–30 Hz) frequency bands in order to examine intermediate and long range cortico-cortical communication (von Stein and Sarnthein; 2000).

Motor behavior. Mean score and variability of score were computed based on the distance from target center (Bull's eye). The aiming point trajectory on the target in mm was sampled at 66 Hz. The tangential displacement with respect to shot location on the target was computed for the 3-s period prior to trigger pull. Aiming variability was computed as the standard deviation of the tangential displacement.

Statistical Analysis

Separate 2×2 (Competition \times Block) within-subjects ANOVAs were employed to evaluate the effect of stress on self-reported measures (VAS and STAI-S), cardiovascular activity (HR), and the psychoendocrine arousal measure (cortisol levels).

Separate $2 \times 2 \times 5 \times 4$ (Competition \times Cerebral Hemisphere \times Cortical Region \times Epoch) within-subjects ANOVAs were performed on both spectral power and coherence to the respective frequency bands of interest. The competitions were 'pre' and 'post' training, the hemispheres were left and right, the cortical regions were comprised of the frontal, central, temporal, parietal, and occipital regions, and the epochs were the four successive 1-s periods leading to the trigger pull.

The Greenhouse-Geisser epsilon (ϵ) was reported when there was the potential to violate sphericity (i.e., more than two levels of a within-subjects variable). Tukey's HSD method was employed for post hoc comparison of means when interactions were observed from spectral and coherence ANOVAs. Paired one-tailed t-tests were used to examine interactions related to arousal measures and performance measures. All criterion alpha levels were set to $p < .05$.

Results

Arousal Measures

Heart rate was significantly higher during competition ($M=85.72$, $se=2.72$) when compared to a baseline heart rate measured prior to competition ($M=81.03$, $se=2.17$) ($F(13,1)=11.67$, $p=0.005$). A significant Time \times Activity interaction was revealed for heart rate ($F(13,1)=5.67$, $p=0.033$). Paired samples t-test revealed a

significant difference ($t(15)=-3.88$, $p=.001$) between the baseline HR ($M=78.0$, $se=2.18$) and competition HR ($M=84.61$, $se=2.43$) during the pre-training competition, but not during the post-training competition ($t(13)=-1.8$, $p=.095$).

No significant differences in cortisol levels were revealed between pre-training and post-training. There was a significant difference between samples ($F(29.01,2.23)=20.61$, $p<0.001$). Cortisol levels were significantly higher in samples taken during competition ('Start' and 'Middle') when compared to after competition samples ('End', 'End+15', and 'End+30'). Figure 2.2 illustrates the physiological variables measured during the 'Pre' training and 'Post' training competition.

No significant differences were revealed between pre-training and post-training competition in subjects perceived relaxation, confidence, stress levels, and competitiveness. There was no significant difference in anxiety levels as measured by the Spielberger state inventory between 'pre' and 'post' training competitions.

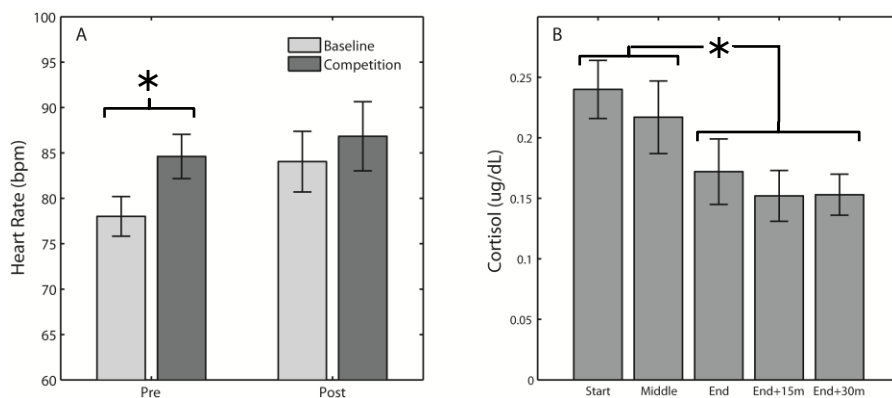


Figure 2.2. Physiologic arousal measures during 'Pre' and 'Post' skill training competition. A) Heart rate. B) Salivary cortisol levels. Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

Motor Behavior

Shooting performance outcomes or scores were significantly higher after training (M=7.5, se=0.19) when compared to pre-training performance (M=6.13, se=0.29) ($F(13,1)=42.66$, $p=0.00$). Variability of shooting performance was significantly lower after training (M=1.53, se=0.10) when compared to pre-training performance (M=2.23, se=0.12) ($F(13,1)=40.78$, $p=0.00$). Variability of aiming trajectory was significantly lower after training (M=.014, se=0.00035) when compared to pre-training performance (M=.018, se=0.00077) ($F(13,1)=37.31$, $p=0.00$) (see Figure 2.3).

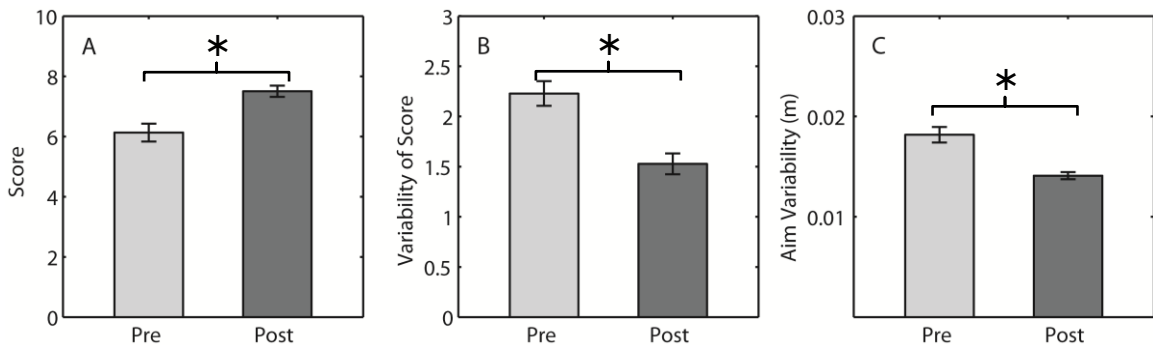


Figure 2.3. Performance measures during 'Pre' and 'Post' skill training competition. A) Score. B) Variability of score. C) Variability of aiming trajectory. Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

Cerebral Cortical Activity – EEG

Spectral power. A main effect was revealed in the theta frequency band ($F(1,15)=11.83, p=.004$) such that significantly higher theta power was seen during the post-training competition ($M=.69, se=.40$) compared to the pre-training competition ($M=-.28, se=.50$).

A main effect was also revealed in the low-alpha frequency band ($F(1,15)=6.03, p=.027$) with higher alpha power observed during the post-training competition ($M=.47, se=.19$) compared to the pre-training competition ($M=.08, se=.24$). Additionally, a main effect in the same direction was seen in broad band alpha ($F(1,15)=4.62, p=.048$), higher power during post-training competition ($M=1.35, se = .46$) compared to pre-training competition ($M=.34, se=.60$) (see Figure 2.4).

Coherence. A significant Time x Hemisphere ($F(1,15)=7.85, p=.013$ driven by Hemisphere differences during pre-training competition) and Time x Hemisphere x Region ($F(2.08, 31.13)=4.17, p=.024$) interactions were revealed. Tukey's HSD post-hoc on the higher order interaction revealed only a significant difference between pre and post training theta coherence in the left frontal region ($p=.00018$) with higher coherence observed during pre-training competition ($M=.86, se=.079$) compared to post-training competition ($M=.76, se=.10$) (see Figure 2.5).

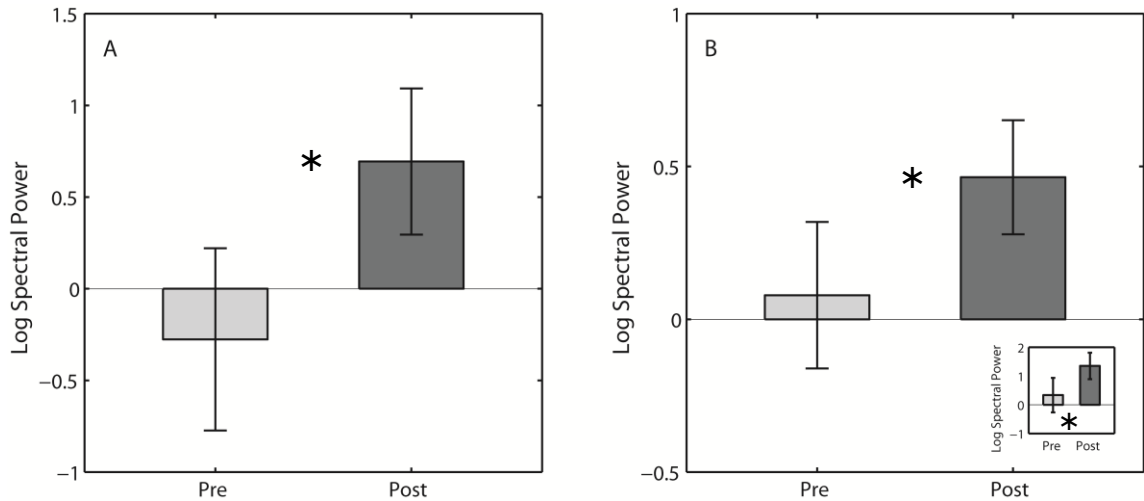


Figure 2.4. EEG Spectral power during 'Pre' and 'Post' skill training competition. A) theta band spectral power. B) low-alpha band spectral power (broad band alpha spectral power inset). Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

A significant Time x Hemisphere x Region ($F(2.04, 30.61)=4.65, p=.017$) interactions was revealed in the alpha frequency band. Tukey's HSD post-hoc revealed only a significant difference between pre and post training alpha coherence in the left frontal region ($p=.033$) with higher coherence observed during pre-training competition ($M=.9, se=.094$) compared to post-training competition ($M=.84, se=.095$) (see Figure 2.6).

A Time x Second interaction was revealed in the low-beta frequency band ($F(3,45)=3.25, p=.03$). Tukey's HSD post-hoc revealed only a significant difference between pre and post training low-beta coherence at 3 seconds prior to trigger pull ($p=.00029$) with lower coherence observed during pre-training competition ($M=.46, se=.063$) compared to post-training competition ($M=.48, se=.066$). Additionally, a significant Time x Hemisphere x Region ($F(2.65, 39.75)=5.31, p=.005$) interactions was revealed in the low-beta frequency band.

Tukey's HSD post-hoc revealed only a significant difference between pre and post training low-beta coherence in the left temporal region ($p=.0018$) with lower coherence observed during pre-training competition ($M=.24$, $se=.043$) compared to post-training competition ($M=.33$, $se=.066$) (see Figure 2.7).

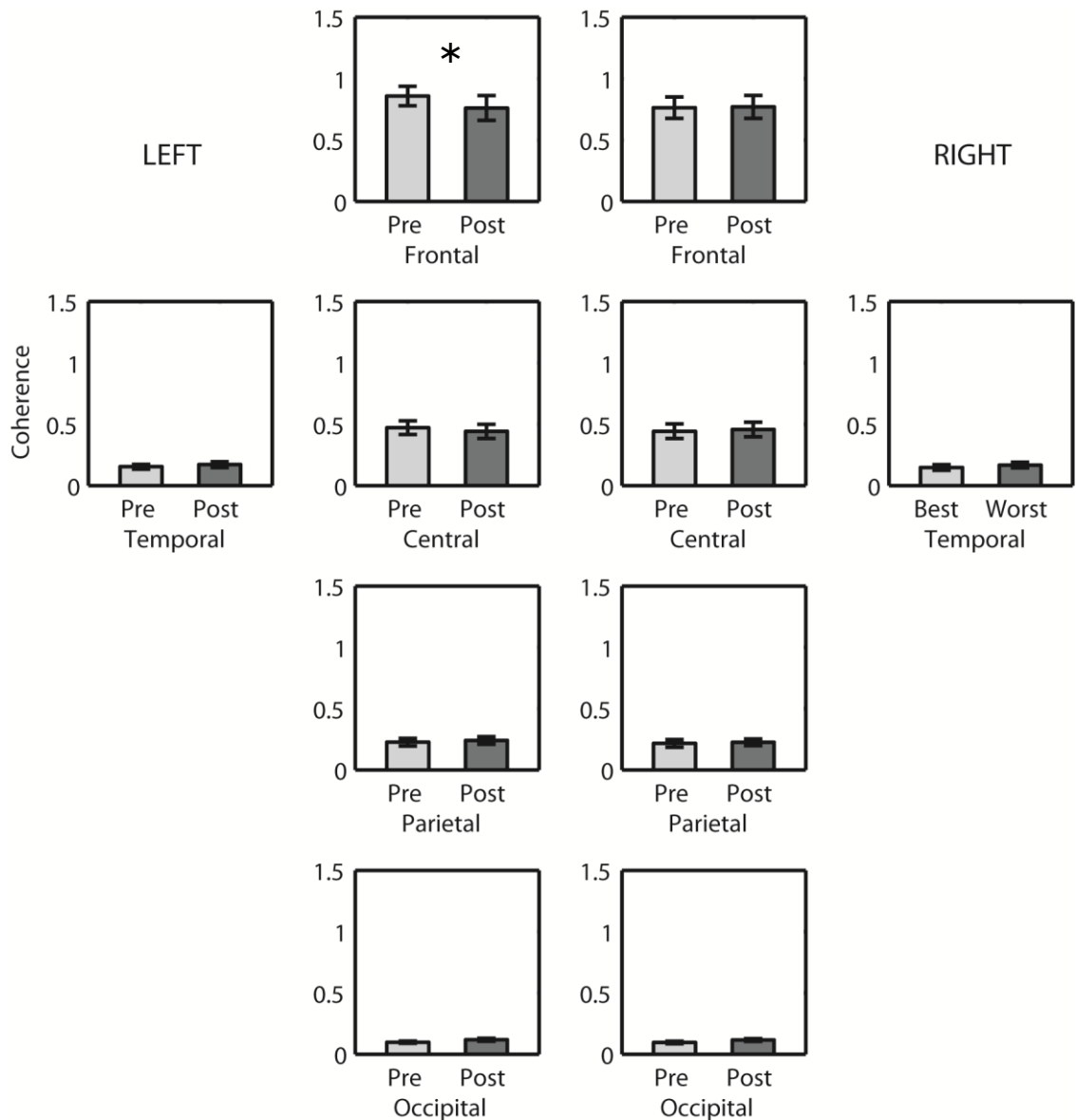


Figure 2.5. EEG theta band coherence across hemisphere and regions during 'Pre' and 'Post' skill training competition. Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

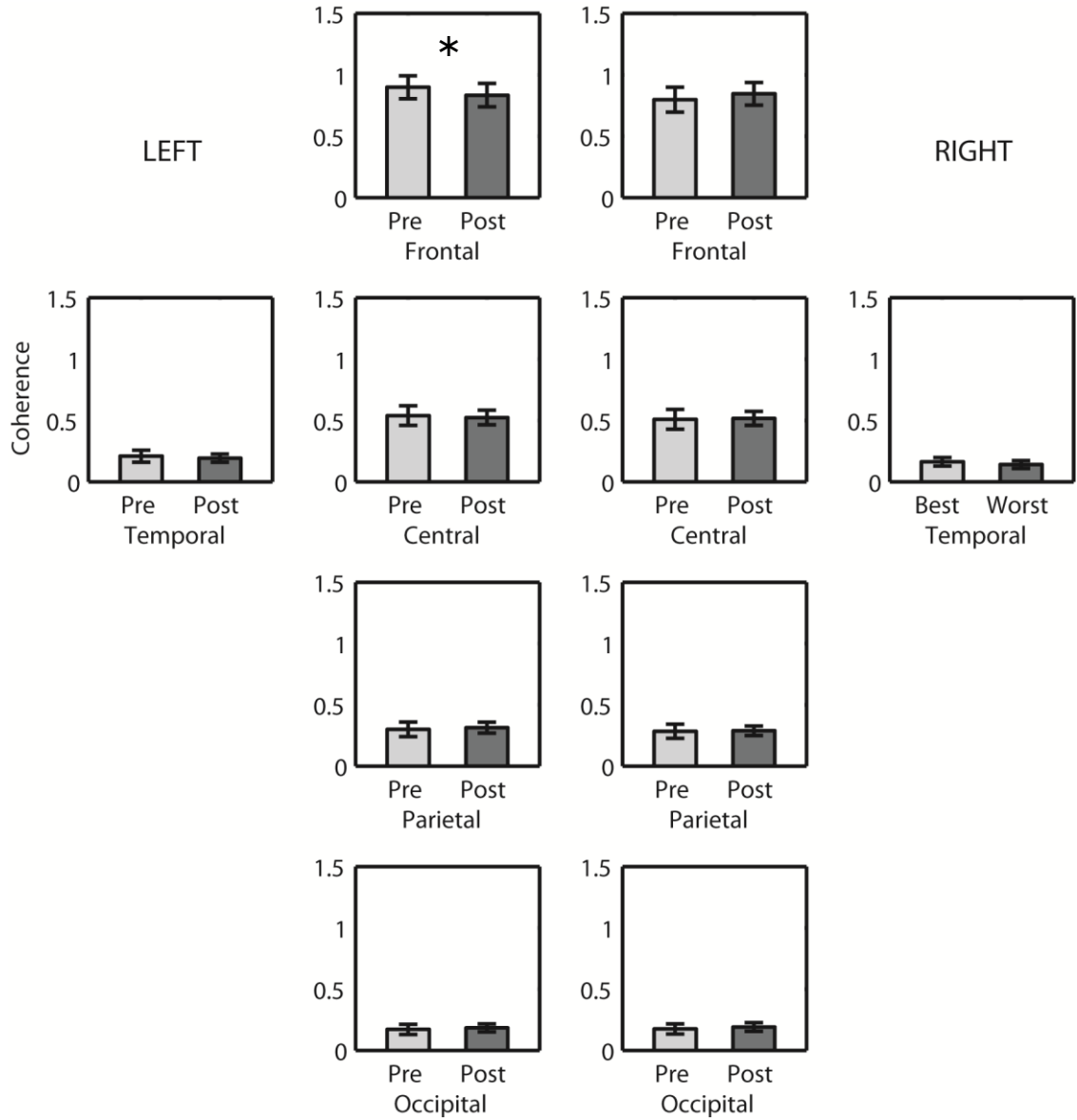


Figure 2.6. EEG alpha band coherence across hemisphere and regions during 'Pre' and 'Post' skill training competition. Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

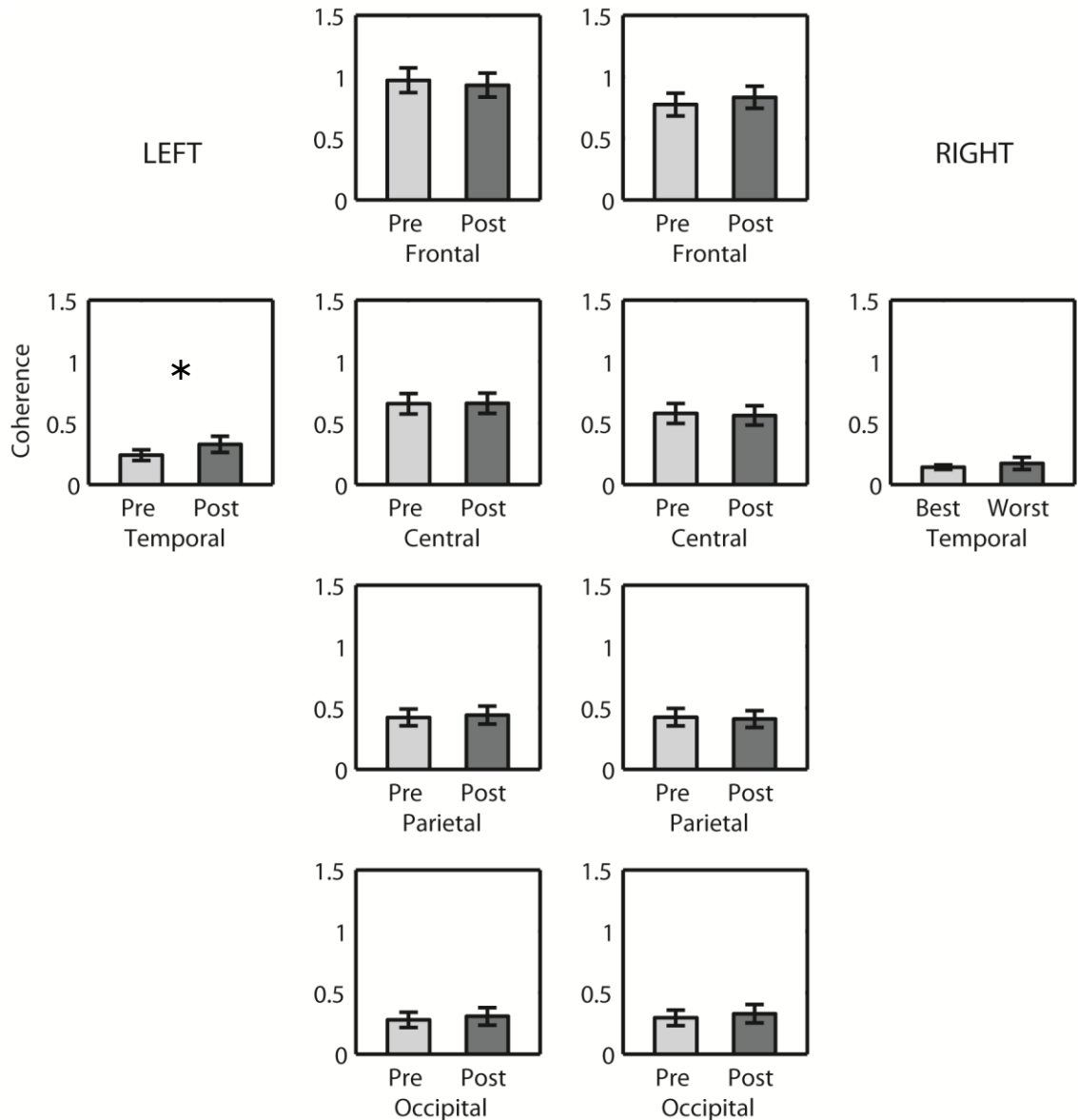


Figure 2.7. EEG low-beta band coherence across hemisphere and regions during 'Pre' and 'Post' skill training competition. Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

A significant Time x Hemisphere x Region ($F(2.53, 37.89)=4.19, p=.016$) interactions was revealed in the high-beta frequency band. Tukey's HSD post-hoc revealed only a significant difference between pre and post training high-beta coherence in the left temporal region ($p=.00037$) with lower coherence observed

during pre-training competition ($M=.23$, $se=.041$) compared to post-training competition ($M=.34$, $se=.072$) (see Figure 2.8)

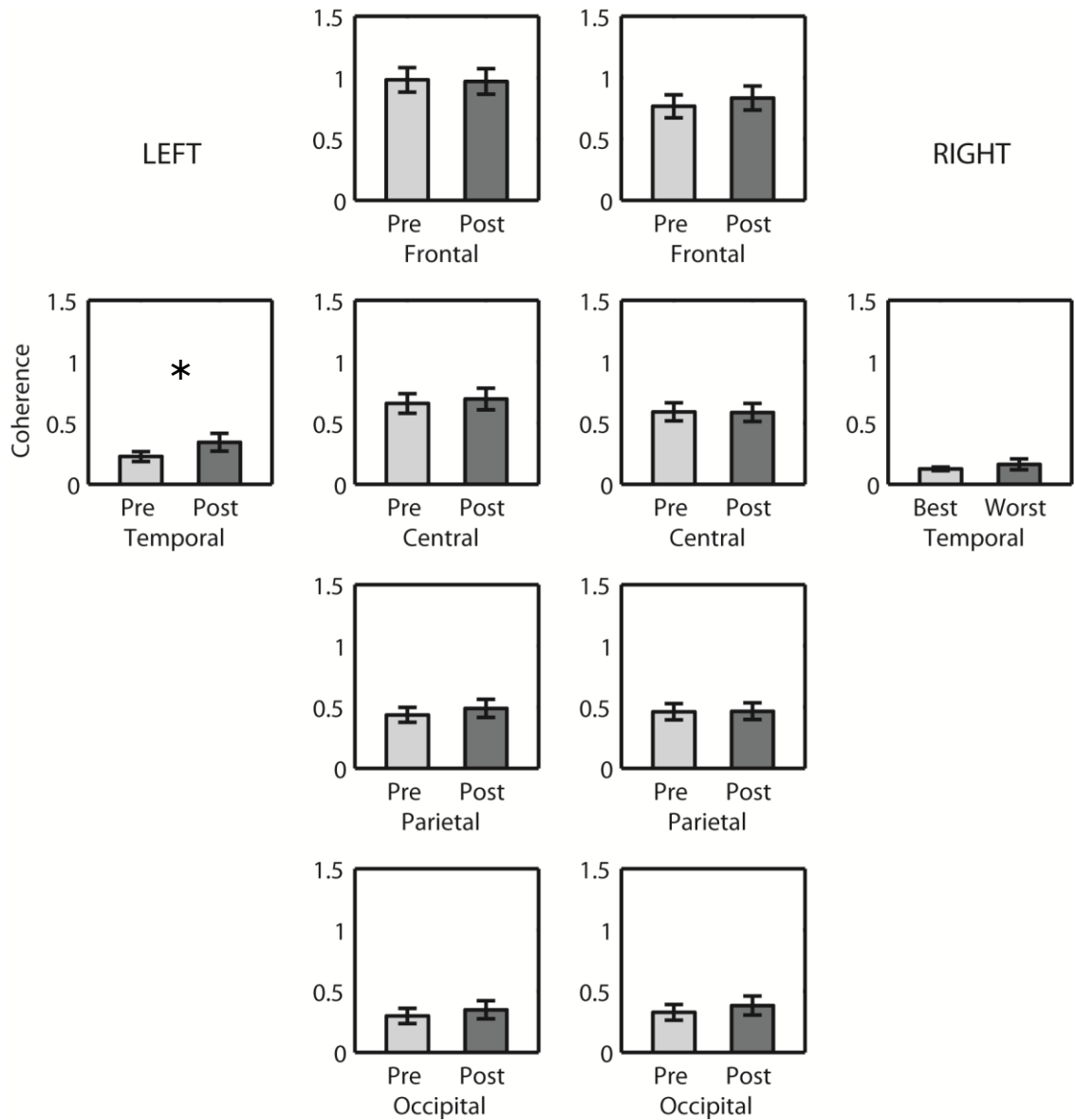


Figure 2.8. EEG high-beta band coherence across hemisphere and regions during 'Pre' and 'Post' skill training competition. Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

Discussion

Previous work by Hatfield and colleagues (2013) manipulated aspects of the environment by having subjects perform a pistol shooting task in both a direct (head-to-head) competition and a 'practice-like' (alone) conditions. Relative to the non-competition alone condition, motor performance during the social evaluative condition of direct competition was accompanied by an increase in both local regional and network cortical activity. This shift in cortical dynamics, brought about by an increase in psychological stress, represents a loss of psychomotor efficiency related to increased extraneous cortical activity or 'neuromotor noise'. Additionally, although the outcome of the motor behavior was similar (scores between conditions were not significantly different), the quality of movement during competition was characterized by decreased fluency. This dysfluency of movement was thought to have been influenced by an increase in 'neuromotor noise' seen as increased cerebral cortical activity in the EEG signals. The current study made use of the same complex stressful environment, 'head-to-head' competition, to examine the impact of skill training or practice on motor behavior and EEG cortical dynamics. Specifically, the goal of this study was to investigate if skill training or practice could return efficiency to the motor behavior and the underlying cortical dynamics, which has been shown to diminish during performance in a stressful environment.

To my knowledge no previous study has attempted to examine the impact of skill training or practice on motor behavior, particularly on the underlying EEG cortical dynamics while performing in a stressful environment. One recent study by Cooke, Kavussanu, Gallicchio, Willoughby, McIntyre, & Ring (2014) did

examine cortical differences between expert and novice performers during golf putting in both high and low pressure environments. They found no differences in cortical activity between the two environmental conditions. Furthermore, Cooke and Colleagues restricted their statistical approach by only examining the local cortical activity of EEG electrodes that overlie areas related to movement control (Fz, F3, F4, Cz, C3, and C4). The approach here includes EEG recorded from all areas of the scalp (frontal, central, temporal, parietal, and occipital regions in both hemispheres) in order to characterize the local regional and networked cortical activity in and between all major regions of the cortex.

Cerin and Barnett (2009) previously found that competition can increase anxiety. In this study, heart rate during competition was significantly elevated suggesting that performer experienced stress under competitive conditions. No differences were found in the current study between the pre-training and the post-training competition's cardiac, psychoendocrine, and psychological self-report measures indicating that participant's perception of the competitive environment were not diminished on the second exposure (post-training competition). This suggests that the environmental conditions posed by 'head-to-head' competition similarly engaged participants before and after training. Hatfield and colleagues (2013) demonstrated that an increase in anxiety produced by a competitive environment reduces the quality of motor performance. They suggested that this loss of movement quality maybe related to 'neuromotor noise', describe by van Galen and van Huygevoort (2000) as extraneous neural activity that promotes movement error. This study finds that motor behavior in a competitive environment improves with skill training.

Participant's displayed significantly improved skill, consistency of performance, and refined quality of movement during competitive performance.

Previous studies examining motor performance in 'practice-like' environments have generally found a refinement of cerebral cortical activity with a reduction of task extraneous processes as evidenced by an increase in EEG alpha power following skill training (Landers, Han, Salazar, Petruzzello, Kubitz, & Gannon, 1994; Kerick, Douglass, & Hatfield, 2004) and in highly skilled performers relative to novice (Haufler, Spalding, Santa Maria, & Hatfield, 2000; 2002; Hatfield, Landers, & Ray, 1984; Hatfield, Landers, Ray, & Daniels, 1982), particularly in the left temporal regions (Hatfield et al., 2004; Kerick et al., 2004; Zhu et al., 2011). In this investigation, EEG alpha power increases after skill training across the scalp demonstrating that experience through deliberate practice promotes refinement of cortical processes related to task performance even while performing in a stressful competitive environment. Decomposing broad band alpha power (8-13 Hz) in to a low-alpha band (8-10 Hz) and high-alpha band (10-13 Hz) has been previously studied (Pfurtscheller and Lopes da Silva, 1999) finding that low-alpha band power reflects a reduction in general cortical arousal while high-alpha band power indicates a reduction in task-specific processes related to attention. No change in the high-alpha power band is shown here which suggests that the attentional demands related to shooting during competition are unchanged by skill training. However low-alpha power is seen to increase during competitive performance after skill training. This reduction in general arousal supports the notion that deliberate skill practice may

diminish the impact that performing in a stressful environment has on cerebral cortical processing (Hatfield et al., 2013).

EEG Coherence has also been shown in previous studies to decrease in highly skilled performers (Deeny et al., 2009) and after skill training (Busk & Galbraith, 1975) reflecting increased cerebral cortical efficiency. Consistent with these studies, the current study reveals a decrease in theta and alpha band coherence between the left frontal region and motor planning area during competitive performance after skill training. This may represent frontal activation related to a decrease of inhibitory processes necessary to suppress the previous representation of the movement (Basso et al, 2006) and updating processes used to build a new movement pattern (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; Shimamura, 2000). As motor learning proceeds through practice and subcomponents are assembled into larger and smoother performing components less cortical resources would be required to suppress previous and update a new motor program. This decrease in network activity between the frontal region and the motor planning areas may also be related to a decrease in executive functions engaging in reappraisal of the stress produced by the competitive environment (Ochsner & Gross, 2008). The experience gained from deliberate practice may reduce the need of performers to reinterpret or diminish the importance of the competition.

While examination of alpha power and its lower subcomponent increase power with skill supporting the notion that experience as a consequence of deliberate practice promotes refinement of cerebral cortical processing, theta band power (4-8 Hz) also increased with deliberate practice. In the current study

EEG theta power is shown to increase during competitive performance after skill training. Power in this frequency band has been associated with working memory (Klimesch, 1999). The increase in cerebral cortical resources related to working memory in the current study is most likely related to the explicit coaching received prior to the first competition. Masters (1992) found that explicit learning promotes susceptibility to the stress that accompanies performance under pressure. After deliberately practicing these step-by-step instructions for approximately nine hours, participants only internalize the competitive shooting technique to a modest degree. When called upon to perform in a stressful competitive environment, the performance required an increase in cognitive resources or 'reinvestment' in the cognitive process of shooting (Masters, 1992).

Increased low-beta and high-beta band coherence was observed between the left temporal region (T3) and motor planning area (Fz) after skill training. Deeny, Hillman, Janelle and Hatfield (2003) found that poor competition performers had increased Fz-T3 coherence compared to superior competition performers. This was taken to represent an increase in processing between verbal-analytical areas and the motor planning region in experienced participants with a history of poor performances in the complex social evaluative environment of competition. In regards to the current study, an increase in working memory processing and communication between the verbal-analytic cortical areas and the motor planning region suggests that, after only nine practice sessions, participants did not reach the autonomous (final) stage of motor learning (Fitts and Posner, 1967), but rather the intermediate associative stage of motor learning.

The current study provides evidence that skill training or deliberate practice does mitigate the reduction of psychomotor efficiency seen while performing in the complex social evaluative environment of competition. Significant improvement in shooting performance and consistency of performance was seen during competition after practicing. Examination of the cerebral cortical activity that underlie motor performance suggest a refinement of cortical dynamics with a reduction of task-extraneous processing in the left frontal region and an enhancement of task-related processing in the left temporal consistent with the skill level reached by participants. The extent that performers benefited from skill training may be related to the type of instruction and the amount of actual practice. Participants in received explicit instructions by video from a qualified coach only twice before engaging in the first competition. Explicit learning is known to be less resilient to the impact of performance stress (Masters, 1992). Between competitions, participants only had approximately nine hours and 360 shots of deliberate practice (9 sessions, 40 shots per sessions). This is far from the 10,000 hours of deliberate practice thought necessary to attain expertise in motor skills (Ericsson, Krampe, & Tesch-Romer, 1993). More likely, the participants here are in the early autonomous stage of Fitts and Posner's model of motor learning and are beginning to assemble smaller subcomponents of the skill into larger, smoother movement components.

Study 3 - The Impact of Motor Skill Training on Motor Behavior and Cortical Dynamics of 'Best' and 'Worst' Performances in a Stressful Social Environment

Introduction

Psychomotor efficiency refers to the refinement of the cerebral cortical activity that accompanies skilled motor performance, which reflects a fine-tuning of the motor control strategy, and is expressed as an increase in the quality and consistency of movement (Hatfield & Hillman, 2001). The early research that provided support for the psychomotor efficiency hypothesis employed electroencephalography (EEG) to measure cerebral cortical activity and was driven by a desire to understand the cognitive-motor basis of elite athletic performers (Hatfield, Landers, Ray, & Daniels, 1982; Hatfield, Landers, & Ray, 1984; Lawton, Hung, Saarela, & Hatfield, 1998). Although it was developed from research that focused on understanding the pattern and degree of cerebral cortical activity related to highly skilled performers, the psychomotor efficiency hypothesis has been successfully applied to the exploration of superior performance (vs. poor performance). Deeny, Hillman, Janelle and Hatfield (2003) examined network cortical activity in highly skilled marksmen with different competitive history's (superior competitive performance vs. poorer competitive performance). EEG coherence between the left temporal region (T3) and the motor planning region (Fz) was significantly lower in superior performers in both the alpha and beta frequency bands, reflecting a decrease in network cortical activity related to verbal-analytic processing. The reduction in coherence that accompanies improved motor skill performance suggests that the reduction of

cortical networks between associative cortical regions and the motor planning region (Fz) may be related to the production of successful motor performance. This notion was supported by Deeny and colleagues (2009) who observed that EEG coherence was positively correlated with variability of movement during skilled performance. That is a decrease in network activity between regional recording sites and the motor planning region was associated with lower variability in the aiming trajectory or better quality of movement. In a small study, Konttinen and Lyytinen (1992) recorded EEG during the aiming period of experts and novice marksmen. Shooting performance was divided into best and worst shots based on score. Slow potentials were increasing negative over the central regions (C3 and C4), consistent with the idea of preparing for motor action. The experts also had less negativity during their best performances compared with their worst, consistent with the notion of refinement of preparatory processing. These studies suggest, consistent with the psychomotor efficiency hypothesis, that better performance (i.e...superior competitive performance, decreased aiming variability, best shots) is marked by a refinement of cerebral cortical activity (i.e...lower EEG coherence, decreased negative slow potentials). It's worth noting that these studies discuss better performance as it relates to experts, even when novice performers were included.

Two recent studies have sought to identify performance differences in non-experts. Dyke, Godwin, Goel, Rehm, Rietschel, Hunt, & Miller (2014) compared the most accurate motor performances with the least accurate in non-experts' during a golf putting task. Non-experts were considered to be participants that might engage in an activity on occasion but not participate in

deliberate practice of the activity. Non-experts' most accurate putts, relative to least accurate, were marked by higher power in the theta frequency band for all cortical regions, higher power in the low-beta frequency band in the left temporal region. Associating theta power with working memory and low-beta power in the left temporal region with verbal analytic processing the authors' suggest that accurate non-expert motor performance is associated with working memory activity related to increased verbal analytic processing. Hunt, Rietschel, Hatfield, & Iso-Ahola (2013) examined the cortical activity associated with successful efforts during 'head-to-head' pistol shooting competition. They compared winning competition performances with losing competition performances. Winning efforts were characterized by decreased high-alpha power across all cortical regions relative to losing efforts which the authors' interpreted as an increase in task-relevant engagement. Winners also reported higher confidence levels compared to losers which suggest that successful competitive performance may be related to psychological state as well as psychophysiological processes. These studies imply that, in non-experts, better performance (i.e...accurate golf putts, winning competitive performance) is accompanied by increased cortical activity associated with verbal-analytic and task relevant processes.

Recent works have examined the impact of performing in social-evaluative (Hatfield, Costanzo, Goodman, Lo, Oh, Rietschel, Saffer, Bradberry, Contreras-Vidal, and Haufler, 2013; Rietschel, Goodman, King, Lo, Contreras-Vidal, & Hatfield, 2011) and social cooperative environments (Miller, Groman, Rietschel, McDonald, Iso-Ahola, & Hatfield, 2013). Hatfield and colleagues (2013)

compared the cortical dynamics of inexperienced performers during a stressful 'head-to-head' competition to performance in a 'practice-like' environment. Relative to the practice condition, the competition condition was accompanied by changes in both physiological and psychological state consistent with an increase in stress. The movement quality was diminished, which was thought to be related to an increase in 'neuromotor noise' induced by competition environment. This increase in 'neuromotor noise' was reflected in the electro-cortical activity as a significant decrease in alpha power across the scalp and a significant increase in coherence between the motor planning region and multiple associative areas during competition. This suggests that the stress produced by competition diminished psychomotor efficiency which was reflected in the quality of motor performance. Rietschel and colleagues (2011) investigated the influence of stress on cerebral cortico-cortical communication and motor behavior during a visual-spatial aiming task performed alone and under social evaluation. Unlike the previous study, participants had the opportunity to substantially practice the task prior to testing. The experience gained through practice was associated with improved quality of movement and a decrease in EEG coherence between the motor planning (Fz) and temporal regions (T3 & T4) during social evaluation. This increase in psychomotor efficiency during the social evaluative condition was interpreted with respect to the inverted-U dose/response curve between arousal and performance suggesting that moderate arousal induces a refinement in nonessential cortical networking, which is accompanied by an increase in the quality of motor performance.

The current study examines the impact of motor skill training on 'best' and 'worst' performances in a stressful, complex social environment. Participants performed a pistol shooting task during 'head-to-head' competition both before and after a skill practice intervention. Performance quality was partitioned into 'best' shots and 'worst' based on score. The purpose of this study is to examine how cerebral cortical activity associated with 'best' and 'worst' performances in a complex stressful social environment change as a consequence of deliberate practice. Cerebral cortical activity during the aiming period was expected to demonstrate refined cortical dynamics associated with both 'best' and 'worst' performances after the practice intervention, with a magnitude of refinement after practicing higher during 'best' performance, relative to 'worst'. Specifically, the left temporal region, consistent with previous work (Deeny et al., 2003; Dyke et al., 2013), will demonstrate refined local and network cortical activity with the motor areas after deliberate practice and particularly during 'best' performance.

Methods

Participants

Participants were recruited from the University of Maryland's Reserve Officers' Training Corps (ROTC) program. Fourteen right-hand dominant (Oldfield, 1971) and right-eye dominant male cadets ages 19 to 28 years ($M = 22.64$, $SD = 3.25$) voluntarily enrolled in the study. All participants completed a health history questionnaire to ensure that they were free of neurological and psychiatric disorders. No participants had previous history of competitive shooting but all met a minimum performance level during a preliminary practice session for inclusion in the study. Prior to testing, all participants were

provided written informed consent approved by the Institutional Review Board and were informed that they were free to withdraw from the study at any time.

Task

Participants completed a dry-fire pistol shooting task using their right (dominant) hand at a target 5m away. The target was scaled to maintain a proportionate diameter consistent with that of an official competitive target (i.e., at a distance of 50 ft, or 15.24 m). Participants received instruction regarding a standard shooting posture; feet positioned approximately shoulder-width apart and nearly perpendicular to the shooting lane to minimize sway, extended the shooting arm while aiming and sighted the target with their right eye (the left eye was occluded). Participants received visual feedback after each trial (shot) consisting of the score and the position of the shot on the target. Scoring was consistent with the rules of competitive shooting with the center ring or Bull's eye worth a score of 10 and the outermost ring a score of 1. The pistol was equipped with the Noptel ST-2000 optical tracking system to monitor the aiming motion of the pistol barrel and shooting performance (shot placement on the target).

Measures

Motor behavior. The Noptel optical shooting simulator system was used to record the aiming trajectory of the pistol in two dimensions and its position on the target at the time the trigger was pulled (shooting score). The aiming point trajectory on the target in mm was sampled at 66 Hz.

Cerebral cortical activity – EEG. Scalp electroencephalographic (EEG) data were collected using tin electrodes housed within a stretchable lycra cap, (Electro-Cap International, Inc.). EEG signals were referenced to linked earlobes

and a common ground (FPz), and impedances were maintained below 10 kΩ. All channels were amplified 500 times using Neuroscan Synamps 1, and recorded using Neuroscan software (version 4.3.3). Online bandpass filters were set at 0.01–100 Hz with a sampling rate of 1000 Hz. Electrodes were placed above and below the left eye over the orbicularis oculi muscle to assess VEOG and at the outer canthi of both eyes (HEOG) to record eye blinks and lateral movements. An electronic pulse was generated by the shooting simulator to mark the trigger pull in the continuous EEG recording. Data were acquired from 30 sites (FP1, FP2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, CZ, FZ, PZ, FCZ, CPZ, CP3, CP4, FC3, FC4, TP7, TP8, FT8, OZ, FT7). From these sites, 10 homologous sites of interest (F3, F4, C3, C4, P3, P4, T3, T4, O1, O2) were subsequently chosen to capture the major regions within each of the cerebral hemispheres for the purpose of spectral and coherence analyses. The Fz electrode served as the common site of interest in all electrode pairings for the coherence analysis (e.g., Fz-F3, Fz-F4, Fz-C3, etc.) to enable examination of cortico-cortical communication between all regions with the motor planning region (Fz).

Procedure

This study required participants to complete two competition testing sessions ('Pre' and 'Post' training) and nine skill training session (practice) falling between competitions over three weeks. Prior to the initial test session all participants were brought in to the testing environment to become familiar with the study procedures and to demonstrate that they could perform to the criterion skill level (i.e., ability to hit the target 80% of the time while executing 40 shots).

All participants were informed of the requirements of the experiment and provided an opportunity to ask questions before they provided consent. In order to reduce any novelty effect that might be observed on the actual testing day, the EEG and heart rate (HR) monitors were placed on the participants for familiarization during the orientation session. They also completed the psychological assessments (VAS, State Anxiety Questionnaire), and were instructed on the acquisition procedures for salivary cortisol (i.e., oral swab). Participants also viewed a videotape generated by a National Collegiate Athletic Association (NCAA) Division I pistol shooting coach through which instructions about shooting mechanics and safety were provided. Participants were then asked to begin the practice session consisting of three blocks of 20 trials (shots) each. The first block was considered a “warm up” and did not contribute to the study selection criteria. Selection criteria for participation in the study required that 80% of shots during blocks 2 and 3 of the orientation practice sessions be located inside the outermost ring of the target. This performance criterion was established to assure that study participants were relatively similar in their ability and could complete the shooting task successfully.

Participants were asked to be well rested and refrain from consuming any alcoholic or caffeinated beverages on the day of testing. Upon arrival, the participants were provided with a brief review of the instructional video that they had viewed during the orientation session and were familiarized with the tasks associated with the test session (see Figure 3.1). Prior to commencement of the competition participants were allowed 10 practice shots and a 1-min EEG

baseline was recorded in the shooting position (standing with arm extended toward the target without the pistol).

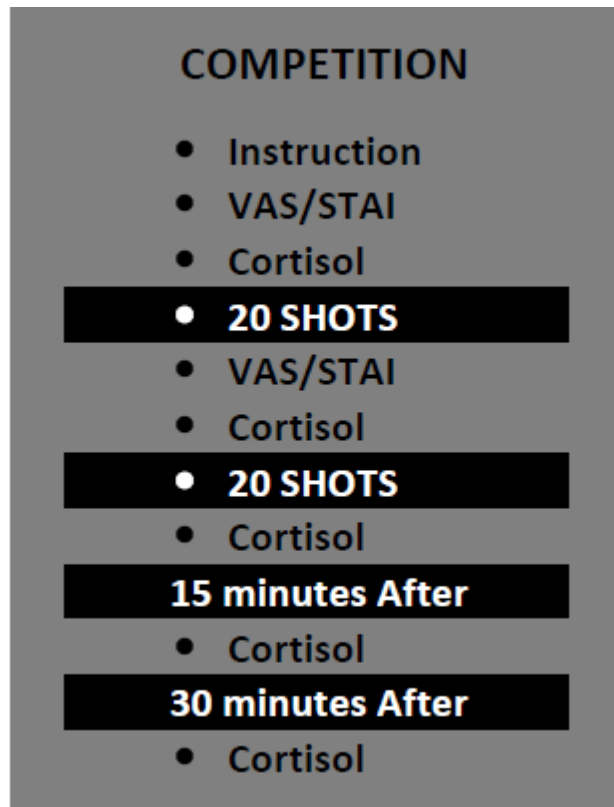


Figure 3.1. Competition protocol indicating the timing of arousal measures relative to task performance.

Competition. Competition involved a direct comparison of shooting performance to another study participant. Participants took turns shooting at the targeted such that one shot while the other observed the opponent's performance. The shooting order was alternated such that in one trial, participant A shot first followed by participant B, but during the next trial participant B shot first, followed by participant A. Participants were instructed to set the pistol down between each shot and to remain standing throughout the competition. Scores

were presented to the competitors after each trial and a winner of that trial was declared. The competitive setting included: 1) social evaluation by a superior officer who conspicuously took notes and evaluated the participants' shooting technique and accuracy; 2) financial loss or gain of 50 cents per round, from a starting sum of \$20 (in the case of a tie, the sum at stake (\$1) carried over to the next round), a dollar bonus for a bull's-eye and a dollar loss for missing the target completely; 3) a 30-s time constraint for each shot, beginning when the participant first grasped the pistol to initiate the shot; 4) video camera recording; and 5) social responsibility as participants were placed on teams and their score contributed to the team's overall score, both of which were displayed outside the ROTC field house. Participants were explicitly informed of all of these pressures during the instructional period prior to task execution and were encouraged to win the competition.

Skill Training/Practice. Practice was executed without evaluation of performance. Participants were instructed to remain focused and relaxed during this period. Detailed shooting technique guidelines were posted in the practice area for review. Participants completed 40 self-paced shots during each of nine practice sessions between the competitions (Pre-training and Post-training competitions).

Signal Processing and Data Analysis

Motor behavior. Mean score and variability of score were computed based on the distance from target center (Bull's eye). The aiming point trajectory on the target in mm was sampled at 66 Hz. Shooting scores were used to identify the five 'best' and five 'worst' performances during both the 'pre' training and

'post' training competitions. This approach to partitioning data on the basis of quality of performance is consistent with previous studies (Landers et al., 1994; Loze et al., 2001; Dyke et al., 2014). Best and worst performances were co-registered and trials were only included for analysis if simultaneous motor behavior, and EEG data were available. Of the 280 trials generated by the participants across the two competitions, approximately 6% of the trials failed to achieve this criterion and were discarded from consideration.

Cerebral cortical activity – EEG. EEG data were analyzed using Neuroscan 4.3 edit software. In order to reduce the influence of eye blinks an ocular artifact-correction regression procedure to remove vertical eye movements and blinks was applied to the EEG recordings (Semlitsch et al., 1986). After visual inspection, the EEG time-series were band-pass filtered from 1 to 50 Hz with a 24 dB/octave rolloff. A 4-s period of continuous EEG data prior to the completion of each shot (i.e., trigger pull) was baseline corrected by subtracting the average voltage value and linear detrended. A final visual inspection of all sweeps was performed to remove any 4-s segment that still contained significant artifact. These averages were then natural log transformed prior to statistical analysis. Spectral power was calculated using the procedure described by Cooley and Tukey (1965), which is employed in the Neuroscan edit software. More specifically, EEG spectral power was calculated for each 4-s segment corresponding to the 'best' and 'worst' performances from each competition. Spectral averages were derived by averaging the power over 1-Hz for the bands of interest, theta (3–8 Hz), low alpha (8–10 Hz), high-alpha (10–13 Hz), and broad band alpha (8-13 Hz)

EEG coherence was defined as $|C_{xy}(f)|^2$. Coherence was computed across 1-Hz bins, and averaged for the frequency bands of interest between electrode Fz, which overlies the motor planning region and the following electrodes: F3, F4, C3, C4, T3, T4, P3, P4, O1, and O2. All coherence values were subjected to a Fisher z-transformation prior to statistical analysis to approximate a normal distribution. Coherence was computed for the theta (3–8 Hz), alpha (8–13 Hz), low-beta (13–20 Hz), and high-beta (20–30 Hz) frequency bands in order to examine intermediate and long range cortico-cortical communication (Von Stein and Sarnthein; 2000).

Statistical Analysis

A 2 × 2 (Competition × Performance) within-subjects ANOVAs was employed to evaluate the effect of stress on shooting performance.

Separate 2 × 2 × 2 × 5 (Competition × Performance × Cerebral Hemisphere × Cortical Region) within-subjects ANOVAs were performed on both spectral power and coherence to the respective frequency bands of interest. The competitions were 'pre' and 'post' training, the performance were 'best' and 'worst', the hemispheres were left and right, and the cortical regions were comprised of the frontal, central, temporal, parietal, and occipital regions.

The Greenhouse-Geisser epsilon (ϵ) was reported when there was the potential to violate sphericity (i.e., more than two levels of a within-subjects variable). Tukey's HSD method was employed for post hoc comparison of means when interactions were observed from spectral and coherence ANOVAs. Paired one-tailed t-tests were used to examine interactions related to score. All criterion alpha levels were set to $p < .05$.

Results

Motor Behavior

Score was significantly higher during 'Post' training competition ($M=7.19$, $se=.23$) when compared to 'Pre' training competition ($M=5.77$, $se=.28$) ($F(1,13)=47.73$, $p<.001$). Score was significantly higher during 'Best' performances ($M=9.41$, $se=.12$) when compared to 'Worst' performances ($M=3.56$, $se=.38$) ($F(1,13)=345.19$, $p<.001$). A significant Time x Performance interaction was revealed for score ($F(1,13)=38$, $p<.001$). Paired samples t-test revealed a significant differences between 'Pre-Best' and 'Post-Best' performances ($t(13)=-3.63$, $p<.001$), between 'Pre-Worst' and 'Post-Worst' performances ($t(13)=-6.66$, $p<.001$), between 'Pre-Best' and 'Pre-Worst' performances ($t(13)=17.95$, $p<.001$), and between 'Post-Best' and 'Post-Worst' performances ($t(13)=13.73$, $p<.001$) (see Figure 3.2)

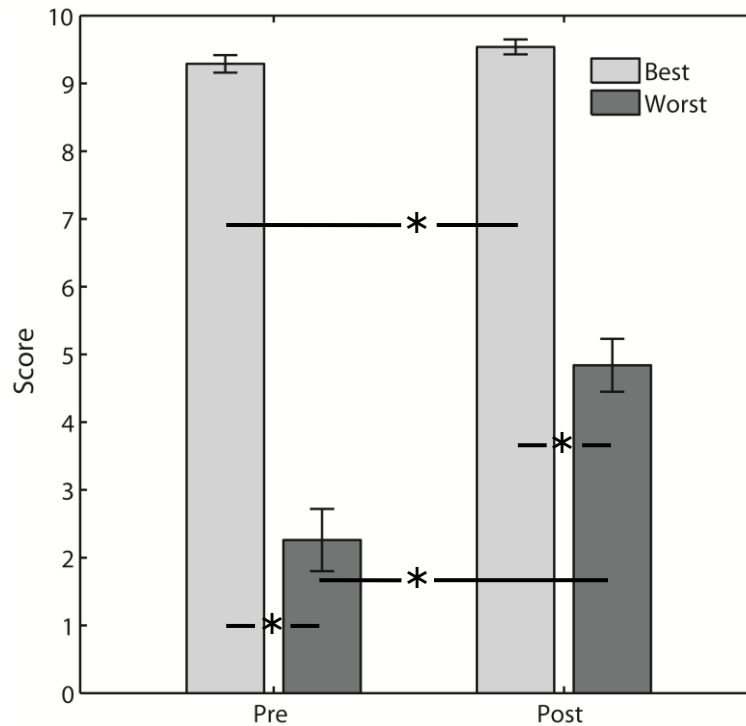


Figure 3.2. Score for 'Best' and 'Worst' performances during 'Pre' and 'Post' skill training competition. Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

Cerebral Cortical Activity – EEG

Spectral power. Main effects were significant in the theta band (4-7 Hz) for both Time ($F(1,13)=5.94, p=.030$) and Performance ($F(1,13)=5.16, p=.041$). Theta power was higher during the post-training competition ($M=1.023, se=.10$) when compared to the pre-training competition ($M=.85, se=.11$) and higher for Worst shots ($Ms=1.00, se=.11$) when compared for Best shots ($Ms=.88, se=.11$). There was a significant Performance x Region interaction ($F(2.04,26.54)=3.77, p=.035$). Tukey's HSD post hoc mean comparisons found significant differences in the central ($p=.043$), parietal (.00028), and occipital ($p=.00015$) regions with higher theta power observed during 'worst' shots relative to 'best' shots for each region. The Performance x Hemisphere x Region interaction approached

significance ($F(2.43,31.56)=2.99$, $p=.056$). Tukey's HSD post hoc mean comparisons found significant differences in the right central ($p=.001$), and parietal ($.00017$) with higher theta power observed during worst shots relative to best shots for each region (see Figure 3.3).

Main effects were significant in the high-alpha frequency band (4-7 Hz) for both Time ($F(1,13)=17.32$, $p=.001$) and Performance ($F(1,13)=9.93$, $p=.008$). High-alpha power was higher during the post-training competition ($M=.84$, $se=.10$) when compared to the pre-training competition ($M=.31$, $se=.15$) and higher for 'worst' shots ($Ms=.71$, $se=.11$) when compared for 'best' shots ($Ms=.43$, $se=.13$). A significant Performance x Region interaction was revealed ($F(2.34,30.36)=6.81$, $p=.002$). Tukey's HSD post hoc mean comparisons found significant differences in all regions (frontal ($p=.00015$, central ($p=.00015$), parietal ($.00015$), occipital ($p=.016$), and temporal ($p=.017$)) with higher high-alpha frequency band power observed during 'worst' shots relative to 'best' shots for each region. A significant Performance x Region x Hemisphere interaction was revealed ($F(2.93,38.09)=2.89$, $p=.049$). Tukey's HSD post hoc mean comparisons found significant differences in all regions except the left temporal and occipital regions with higher high-alpha frequency band power observed

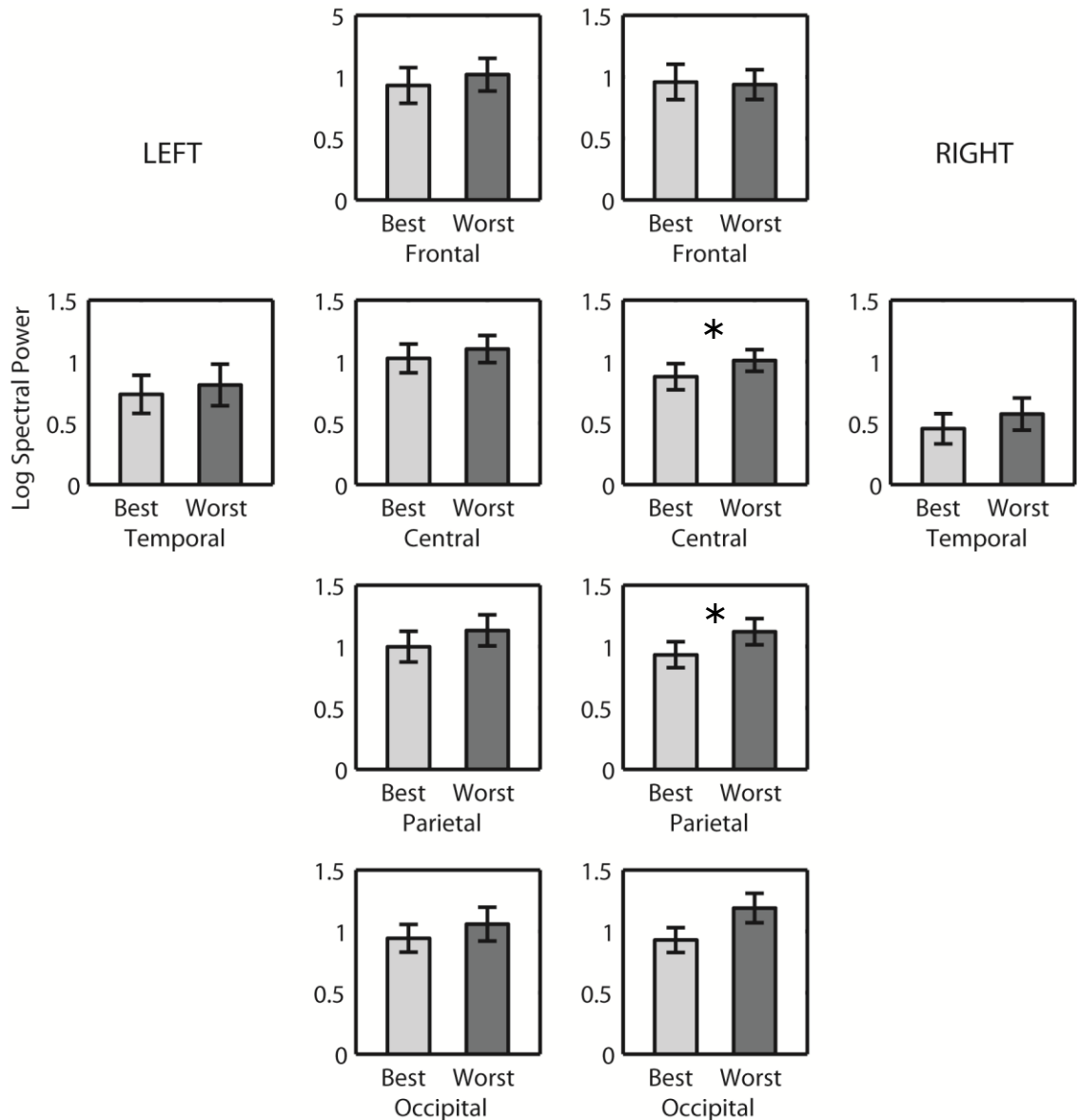


Figure 3.3. EEG Theta band spectral power across hemisphere and regions during 'Best' and 'Worst' performances in competition. Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

during best shots relative to worst shots for all regions except the right occipital (see Figure 3.4). A significant Time x Performance interaction was revealed ($F(1,13)=9.68, p=.008$). Tukey's HSD post hoc mean comparisons found significant differences in post-training competition worst shots when compared to

pre-training competition worst shots ($p=.00021$) and post-competition best shots ($p=.0015$), with higher high-alpha frequency band power observed during worst shots relative to best shots for each region. A significant Time x Performance x Region interaction was revealed ($F(2.54,32.96)=7.37$, $p=.001$). Tukey's HSD post hoc mean comparisons found significant differences during the post training competition in all regions (frontal ($p=.00017$), central ($p=.00017$), parietal ($p=.00017$), occipital ($p=.00017$), and temporal ($p=.00017$)) with higher high-alpha frequency band power observed during worst shots relative to best shots for each region (see Figure 3.5).

Coherence. A significant Performance x Hemisphere interaction was revealed ($F(1,13)=4.98$, $p=.044$). Tukey's HSD post hoc mean comparisons found significant differences in between best shots and worse shots in the left hemisphere ($p=.032$), with theta frequency band coherence during worst shots relative to best shots (see Figure 3.6).

A Performance x Region interaction approached significance for coherence in the beta frequency band ($F(4,52)=2.47$, $p=.056$). Tukey's HSD post hoc mean comparisons found significant differences between the frontal ($p=.044$) and occipital regions ($p=.00017$), and the motor planning region with higher beta frequency band coherence observed during best shots relative to worst shots for each region.

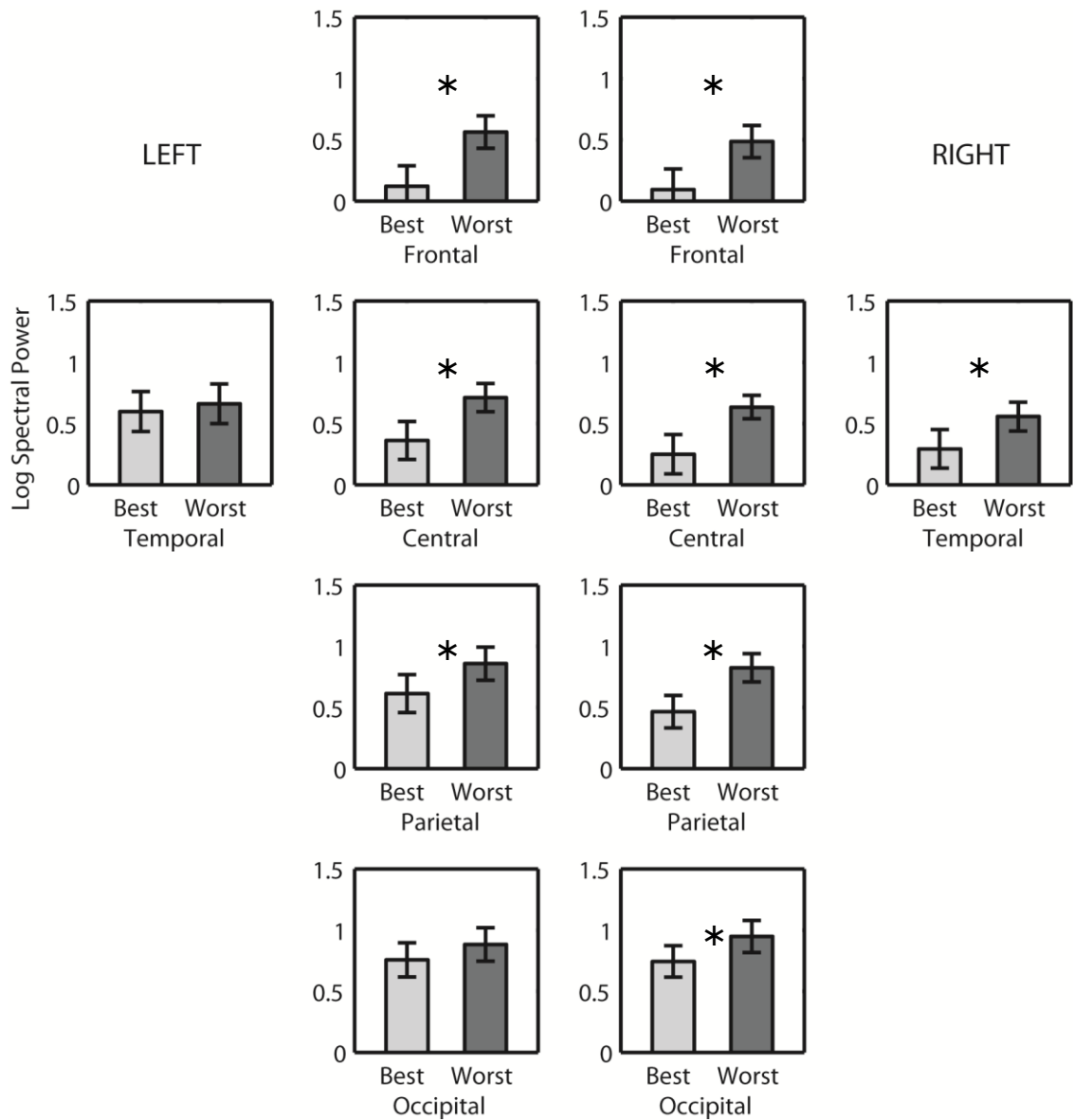


Figure 3.4. EEG High Alpha band spectral power across hemisphere and regions during 'Best' and 'Worst' performances in competition. Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

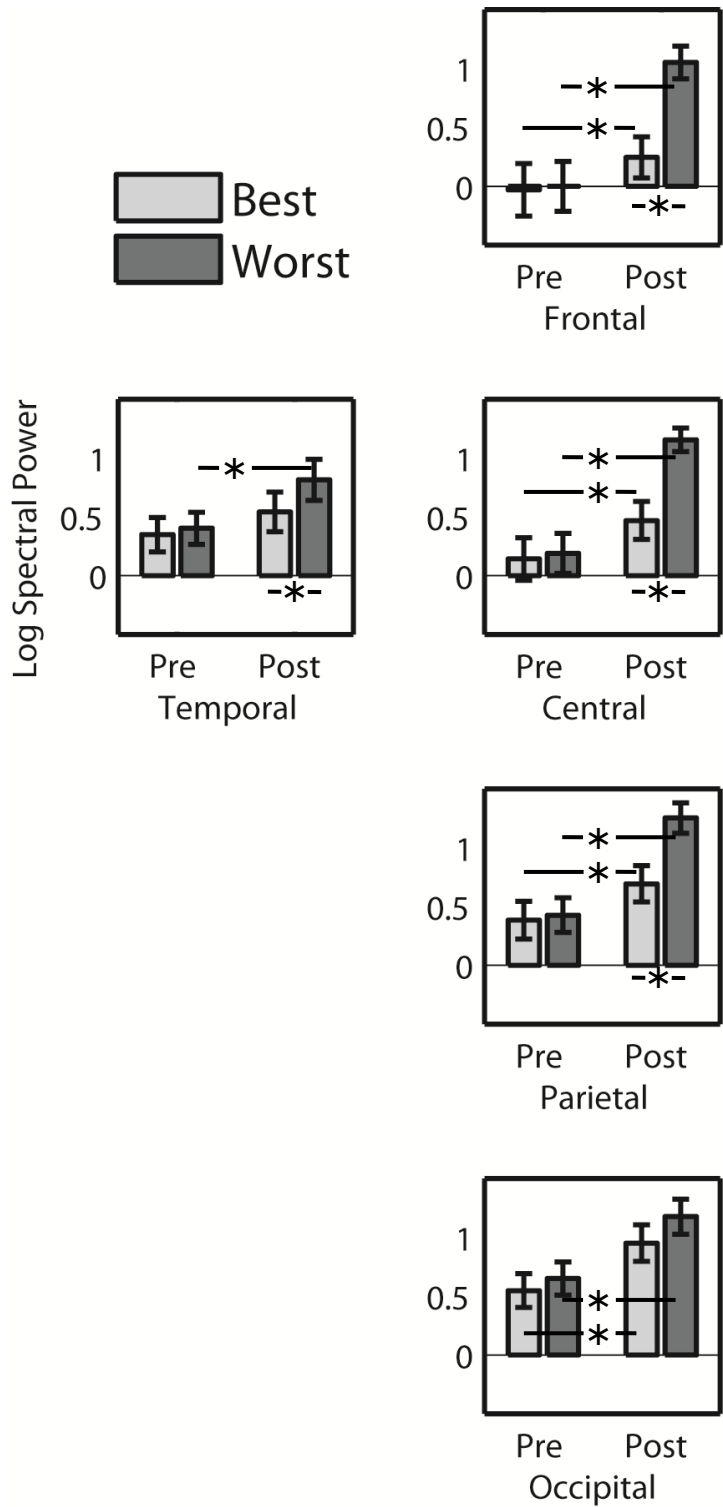


Figure 3.5. EEG High Alpha band spectral power across regions during 'Best' and 'Worst' performances in 'Pre' and 'Post' skill training competition. Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

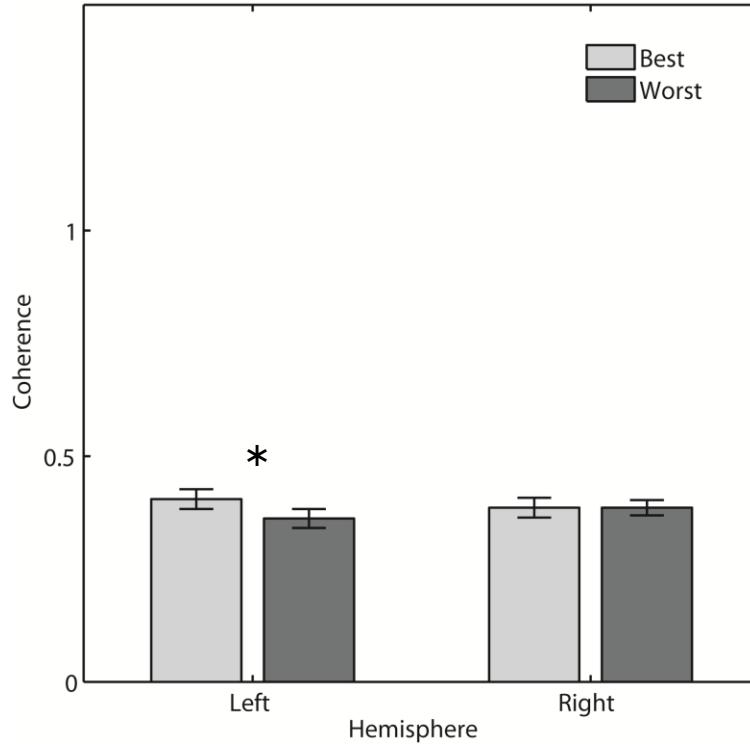


Figure 3.6. EEG Theta band coherence across hemisphere during 'Best' and 'Worst' performances in competition. Asterisk (*) denotes statistical significance at $p < 0.05$. Note: error bars represent SEM.

Discussion

Previous work by Hatfield and colleagues (2013) demonstrated that performance in a stressful competitive environment produces extraneous cerebral cortical activity and diminished the quality of motor performance when compared to a 'practice-like' environment. These changes in performance were attributed to an increase in 'neuromotor noise' that accompanies performance in a complex social evaluative environment and is consistent with the notion that performance fundamentally different than practice. In the previous study (see Chapter 2) motor behavior and EEG cortical activity related to the aiming period during a pistol shooting task was examined in a stressful competitive

environment both before and after undergoing a modest amount of deliberate practice. EEG activity after the practice intervention reflected refinement of cerebral cortical dynamics with a reduction of task-extraneous processing in the left frontal region and an enhancement of task-related processing in the left temporal consistent with the level of skill reached by the participants. This study examines the impact of skill training on the cerebral cortical activity associated with motor planning of the 'best' and 'worst' shooting performances in the same stressful competitive environment employed by Hatfield et al., (2013) and previous study (Chapter 2). Specifically, the goal of this study was to determine if skill training would promote efficient cerebral cortical activity during 'head-to-head' competition, particularly during the most accurate or 'best' performances relative to the least accurate or 'worst' performances.

To my knowledge no previous study has attempted to examine the impact of skill training or practice on motor behavior and the cortical dynamics associated with 'best' and 'worst' performances in a stressful environment. A recent study by Cooke, Kavussanu, Gallicchio, Willoughby, McIntyre, & Ring (2014) did examine cortical differences between holed and missed putts in expert and novice performers during golf putting in both high and low pressure environments, however they restricted their statistical approach by only examining the local cortical activity of EEG electrodes that overlie areas related to movement control (Fz, F3, F4, Cz, C3, and C4). Furthermore, they found no differences in cortical activity between the two environmental conditions. The current study included EEG recorded from all major cortical areas (frontal, central, temporal, parietal, and occipital regions in both hemispheres) in order to

characterize the local regional and networked cortical activity in and between all major regions of the cortex.

As already established in the previous study (see Chapter 2) heart rate in the competitive environment was significantly elevated suggesting that performer experienced increased stress during competition. No differences were found in the current study between the pre-training and the post-training competitions cardiac, psychoendocrine, and psychological self-report measures indicating that participant's perception of the competitive environment were not diminished during the second exposure (post-training competition). This suggests that the environmental conditions similarly engaged participants. Hatfield and colleagues (2013) demonstrated that an increase in anxiety produced by a competitive environment reduces the quality of motor performance. They suggested that this loss of movement quality maybe related to an increase in 'neuromotor noise', describe by van Galen and van Huygevoort (2000) as extraneous neural activity that promotes movement error. This study finds that both 'best' and 'worst' performances in a competitive environment improve with skill training, however the magnitude of improvement was larger for 'worst' performances compared to 'best'. This is mostly like related to the ceiling effect inherent in the scoring system (the highest possible score = 10).

Cerebral cortical activity in the theta frequency band (4-8 Hz) has previously been associated with working memory (Klimesch, 1999). In this study EEG theta power is shown to increase during 'worst' performances relative to 'best', particularly in the right central and parietal regions. Kao et al. (2013) found that expert golf putters least accurate performances was characterized by high

theta frequency band power which was interpreted as an increase in attentional control processes related to working memory. This increase in cerebral cortical processing could be a source of 'neuromotor noise'. Dyke and colleagues (2015) found increased power in the theta frequency band in all cerebral cortical regions during motor planning in non-expert golf putters most accurate performances. This was thought to reflect appropriate working memory load given the non-expert level of the performers. During the current study participants were provided explicit instructions regarding proper competitive shooting technique prior to the first competition. In addition to the emphasis placed on aiming and trigger engagement with the right extremity, reflected in the increase coherence between the regions of the left hemisphere and the motor planning areas during 'best' performances, participants were also coached on the placement and the necessity to relax the left extremity. Relative to 'best' performances, this increase in working memory processing reflected by increased theta frequency band power during 'worst' performances in the right central and parietal regions likely reflects an increase in cognitive resources or 'reinvestment' (Masters, 1992) in the cognitive processes related to the explicit desire to relax the left extremity.

Low-alpha band (8-10 Hz) and high-alpha band (10-13 Hz) subcomponents of the alpha frequency band (8-13 Hz) have previously been studied (Pfurtscheller and Lopes da Silva, 1999). Power in the low-alpha frequency band reflects a reduction in general cortical arousal. In the current study no differences were shown in the low-alpha power between 'best' and 'worst' performances, both before and after the practice intervention, suggesting that the general arousal produced by the competitive environment remain

constant. High-alpha power during motor preparation has been seen in experience performers (Cooke et al., 2013; Crews & Landers, 1993; Hatfield et al., 1984; Haufner et al., 2000; Loze et al., 2001) and is associated with a reduction in task-related processing related to attention (Cooper et al., 2003; Jensen & Mazaheri, 2010; Klimesch et al., 2007). The previous study (see Chapter 2) found no change in the high-alpha power band during competitive shooting performance before and after deliberate skill practice suggesting the processing demands related to shooting during competition are unchanged by skill training. In the current study no differences are seen in high-alpha band power between 'best' and 'worst' performances prior to deliberate practice, but after skill training high-alpha power increases for both. However, 'worst' performances have significantly more high-alpha power relative to 'best' after the practice intervention. This suggests that while both 'best' and 'worst' performances show a reduction in task-specific processes related to attention after deliberate practice, the significant increase in high-alpha power during 'worst' performances relative to 'best' performances likely represents an inappropriate reduction in task-specific attentional processing (i.e., a loss of focus on the task). Furthermore, the reduction in attentional processing during 'best' performances after deliberate practice reflects an optimized level of task-specific attentional processes given their current experience level. This implies that relationship between high-alpha (i.e., task-specific attentional processing) and performance follows an inverted-u similar to the association between arousal and performance described by Yerkes and Dodson (1908). However performance, 'best' or 'worst', prior to engaging in deliberate practice doesn't map on to this

relationship suggesting that performance in untrained individuals is most likely random or by chance and that skill acquired thru practice is an emergent phenomenon (see Figure 3.7).

The current study provides evidence that 'best' performances during a stressful competition when compared to 'worst' performances are characterized by increase cerebral cortical efficiency such that extraneous cortical activities are reduced while task-relevant processes are enhanced. Furthermore, deliberate practice is show to optimize cerebral cortical activity such that 'best' performances are accompanied by a reduction in task-specific processes related to attention while 'worst' performances are characterized by an inappropriate reduction in task-specific processing resulting in a loss of focus.

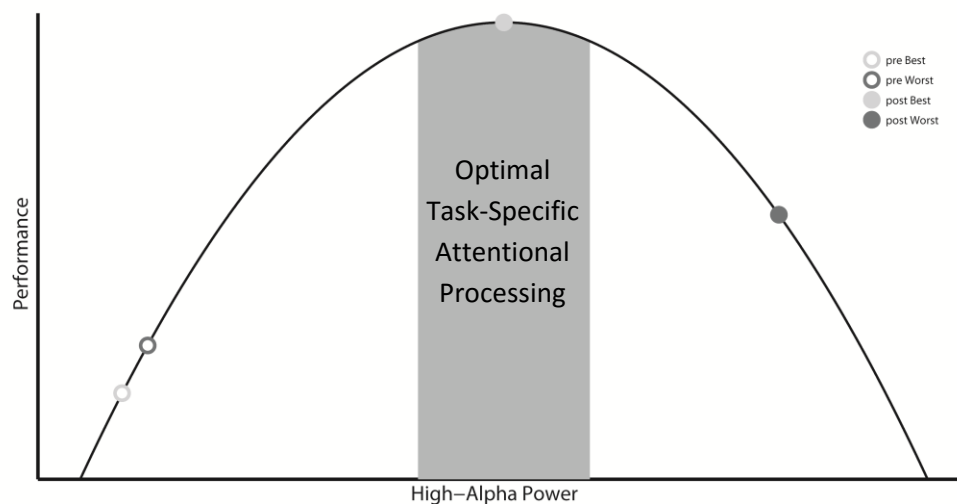


Figure 3.7. Conceptual relationship between high-alpha power and performance.

Limitations, Future Directions, and Conclusions

The current studies examine the impact of skill training on motor behavior and cerebral cortical activity while performing in the complex social evaluative environment provided by 'head-to-head' competition. Physiological and psychological self-report measures indicate that participants experienced stress, though this was likely only moderate in degree. This demonstrates the difficulty of inducing stress associated with motor skill performance in a laboratory environment. The ability to produce higher levels of stress in a controlled environment would provide interesting opportunities for psychophysiological research involving motor control and learning, and should be explored. The current studies would have been strength by the addition of 'practice-like' condition. Although Hatfield et al., (2013) provided evidence that performance during 'head-to-head' competition is stressful compared to a 'practice-like' alone environment, the incorporation of a practice condition would provide a within subjects opportunity to 'baseline' motor behavior and cerebral cortical activity, as well as physiological and psychological self-report measures. This would increase the confidence regarding the degree to which the competitive environment impacts performance and how effective the practice intervention was at mitigating that environmental impact.

Participants in this study received 360 practice shots during approximately 9 hours of deliberate practice. This is less than 1/1000th of the total hours of deliberate practice described by Ericsson et al., (1993) as necessary to reach an expert level performance. Although providing 10,000 hours of skill training in impractical, longer practice interventions, perhaps with multiple testing sessions

along the way, would allow for better assessment of motor behavior and cerebral cortical dynamics related to motor planning and their relative stability.

Participants in the current studies had no prior competitive shooting experience. They were provided explicit instruction via video regarding the particular shooting technique required for competitive performance twice before entering their first competition. Explicit learning had been shown to slow skill learning (Boyd & Winstein, 2006; Wulf & Weigelt, 1997; Green & Flowers, 1991) while implicit learning, which relies less on working memory and verbal-analytic processing, has been shown to provide resilience from the impact of stress (Lam, Maxwell, & Masters, 2009; Masters, Poolton, & Maxwell, 2008; Poolton, Masters, & Maxwell, 2006).

Lastly, the model of constraints put forth by Karl Newell (1986), holds that coordinated patterns of movement emerge from constraints related to the performer, the task to be performed, and the context in which the performance takes place. Beyond physiological adaptations, Motor performance studies employing EEG have shown changes in refinement of cortical activity in predictable directions consistent with the psychomotor efficiency hypothesis when comparing the performer's experience level (Haufler et al., 2000; 2002; Deeny et al., 2009), changing the task difficulty (Rietschel et al., 2012), and altering the perceived importance of the context (Hatfield et al., 2013). Additional studies have shown that experience acquire through practice can enhance cerebral cortical activity of the performers (Gentili et al., 2011; Landers et al., 1994; Kerick et al., 2004) and performance in complex environments (Chapters 2

& 3). Whether practice can enhance cerebral cortical activity associate with performance under complex task constraint remain an open question.

The current studies provide evidence that skill training does mitigate the impact that performing in a complex social environment has on cerebral cortical activity. Although significant improvement in shooting performance was seen during the post-training competition, examination of the cerebral cortical dynamics that underlie motor performance suggest a refinement of cerebral cortical dynamics with a reduction of task-extraneous processing in the left frontal region and an enhancement of task-related processing in the left temporal consistent with the skill level reached by participants. Additionally, deliberate practice appears to optimize cerebral cortical activity such that 'best' performances are accompanied by a reduction in task-specific processes related to attention while 'worst' performances are characterized by an inappropriate reduction in task-specific processing resulting in a loss of focus. Together, these studies demonstrate the power of practice, as a controllable factor, to promote resilience of psychomotor efficiency in complex environments.

Appendix 1

Health Status Questionnaire

Name _____ Telephone _____

Address _____

Date of birth _____ Age _____ Height _____ Weight _____

Hearing impairment Yes _____ No _____ If yes, describe _____

Color blind Yes _____ No _____ Gender M _____ F _____

Years of education (high school = 12, college + 16) _____

Current marital status: Married _____ Single _____ Widowed _____ Divorced _____

Medications Are you presently taking or have taken any of the following medications within the past two months?

Aspirin Bufferin Anacin Tranquilizers

Blood pressure pills Weight reducing pills

Cortisone Blood thinning pills

Cough medicine Dilantin

Digitalis Allergy shots

Hormones Water pills

Insulin or diabetic pills Antibiotics

Iron or blood medications Barbituates

Laxatives Phenobarbital

Sleeping pills Thyroid medicine

Other medications not listed _____

Have you taken any non-prescription medications or drugs in the past two weeks?

Name what for? Dose/frequency last dose

1

2

3

Do you currently or have you ever had any of the following medical disorders?

Heart attack Yes ____ No ____

Chest pain Yes ____ No ____

Hardening of the arteries Yes ____ No ____

Irregular heart beat Yes ____ No ____

Kidney disease Yes ____ No ____

Diabetes Yes ____ No ____

Cancer Yes ____ No ____

Gout Yes ____ No ____

Asthma Yes ____ No ____

Epilepsy or seizure disorder Yes ____ No ____

Migraine headaches Yes ____ No ____ if yes, frequency/intensity ____

Psychiatric disorder Yes ____ No ____ if yes, what diagnosis _____

List the name of any diseases, illnesses or accidents you have had which required hospitalization. _____

Serious illnesses you have had not requiring hospitalization. _____

Have you ever been told you have high blood pressure?

Yes ____ No ____ if yes, when _____

Do you have any other chronic illnesses or disabilities?

Have you ever lost consciousness in the last 10 years?

Yes ____ No ____ if yes, when and why _____

Do you use tobacco products?

Yes ____ No ____ if yes, number of years _____

Cigarettes ____ Pipe ____ Cigar ____ Chewing tobacco ____

How many alcoholic drinks do you drink on any given day? _____

(1 drink = 12 oz. Beer, 4 oz. Wine, or 1oz. Hard liquor)

How much caffeine do you drink on any given day? _____

(number of cups of coffee, tea, cola; how many ounces)

Time since last intake of:

Caffeine _____

Tobacco _____

Alcohol _____

Appendix 2

EDINBURGH HANDEDNESS INVENTORY

Please indicate your preferences in the use of hands in the following activities *by putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, *put ++*. If in any case you are really indifferent *put + in both columns*.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all of the questions, and only leave a blank if you have no experience at all of the object or task.

		Left	Right
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Toothbrush		
6	Knife (without fork)		
7	Spoon		
8	Broom (upper hand)		
9	Striking match (match)		
10	Opening box (lid)		
i.	Which foot do you prefer to kick with?		
ii.	Which eye do you use when using only one?		

Appendix 3

Self-Evaluation Questionnaire--State

Developed by Charles D. Spielberger
 In collaboration with R. L. Gorsuch, R. Lushene, P. R. Vagg, and G. A. Jacobs

Name _____ Date _____ S _____
 Age _____ Sex: M F T _____

DIRECTIONS: A number of statements which people have used to describe themselves are given below. Read each statement and circle the appropriate number to the right of the statement to indicate how you feel *right now*, that is, *at this moment*. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.

	Not at all	Somewhat	Moderately so	Very Much so
1. I feel calm.....	1.....	2.....	3.....	4.....
2. I feel secure.....	1.....	2.....	3.....	4.....
3. I am tense.....	1.....	2.....	3.....	4.....
4. I feel strained.....	1.....	2.....	3.....	4.....
5. I feel at ease.....	1.....	2.....	3.....	4.....
6. I feel upset.....	1.....	2.....	3.....	4.....
7. I am presently worrying over possible misfortunes.....	1.....	2.....	3.....	4.....
8. I feel satisfied.....	1.....	2.....	3.....	4.....
9. I feel frightened.....	1.....	2.....	3.....	4.....
10. I feel comfortable.....	1.....	2.....	3.....	4.....
11. I feel self-confident.....	1.....	2.....	3.....	4.....
12. I feel nervous.....	1.....	2.....	3.....	4.....
13. I am jittery.....	1.....	2.....	3.....	4.....
14. I feel indecisive.....	1.....	2.....	3.....	4.....
15. I am relaxed.....	1.....	2.....	3.....	4.....
16. I feel content.....	1.....	2.....	3.....	4.....
17. I am worried.....	1.....	2.....	3.....	4.....
18. I feel confused.....	1.....	2.....	3.....	4.....
19. I feel steady.....	1.....	2.....	3.....	4.....
20. I feel pleasant.....	1.....	2.....	3.....	4.....

Appendix 4

Self-Evaluation Questionnaire--Trait

Developed by Charles D. Spielberger
 In collaboration with R. L. Gorsuch, R. Lushene, P. R. Vagg, and G. A. Jacobs

Name _____ Date _____

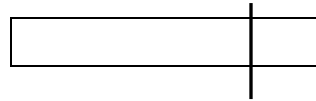
DIRECTIONS: A number of statements which people have used to describe themselves are given below. Read each statement and circle the appropriate number to the right of the statement to indicate how you *generally* feel. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe how you generally feel.

	Not at all	Somewhat	Moderately so	Very Much so
21. I feel pleasant.....	1.....	2.....	3.....	4.....
22. I feel nervous and restless.....	1.....	2.....	3.....	4.....
23. I am satisfied with myself.....	1.....	2.....	3.....	4.....
24. I wish I could be as happy as others seem to be.....	1.....	2.....	3.....	4.....
25. I feel like a failure.....	1.....	2.....	3.....	4.....
26. I feel rested.....	1.....	2.....	3.....	4.....
27. I am "calm, cool, and collected".....	1.....	2.....	3.....	4.....
28. I feel that difficulties are piling up so that I cannot overcome them	1.....	2.....	3.....	4.....
29. I worry too much over something that really doesn't matter.....	1.....	2.....	3.....	4.....
30. I am happy.....	1.....	2.....	3.....	4.....
31. I have disturbing thoughts.....	1.....	2.....	3.....	4.....
32. I lack self-confidence.....	1.....	2.....	3.....	4.....
33. I feel secure.....	1.....	2.....	3.....	4.....
34. I make decisions easily.....	1.....	2.....	3.....	4.....
35. I feel inadequate.....	1.....	2.....	3.....	4.....
36. I am content.....	1.....	2.....	3.....	4.....
37. Some unimportant thought runs through my mind and bothers me	1.....	2.....	3.....	4.....
38. I take disappointments so keenly that I can't put them out of my mind	1.....	2.....	3.....	4.....
39. I am a steady person.....	1.....	2.....	3.....	4.....
40. I get in a state of tension or turmoil as I think over my recent concerns and interests	1.....	2.....	3.....	4.....

Appendix 5

Visual Analog Scale

Please put a vertical line through the rectangle at the point that best represents how you feel right now. The ends of each rectangle represent the opposite extremes of the **same** variable. Ex.



How *competitive* do I feel?

Not competitive

Ultra competitive

How *stressed* am I?

No stress

Completely stressed

How *confident* do I feel?

No confidence

Extremely confident

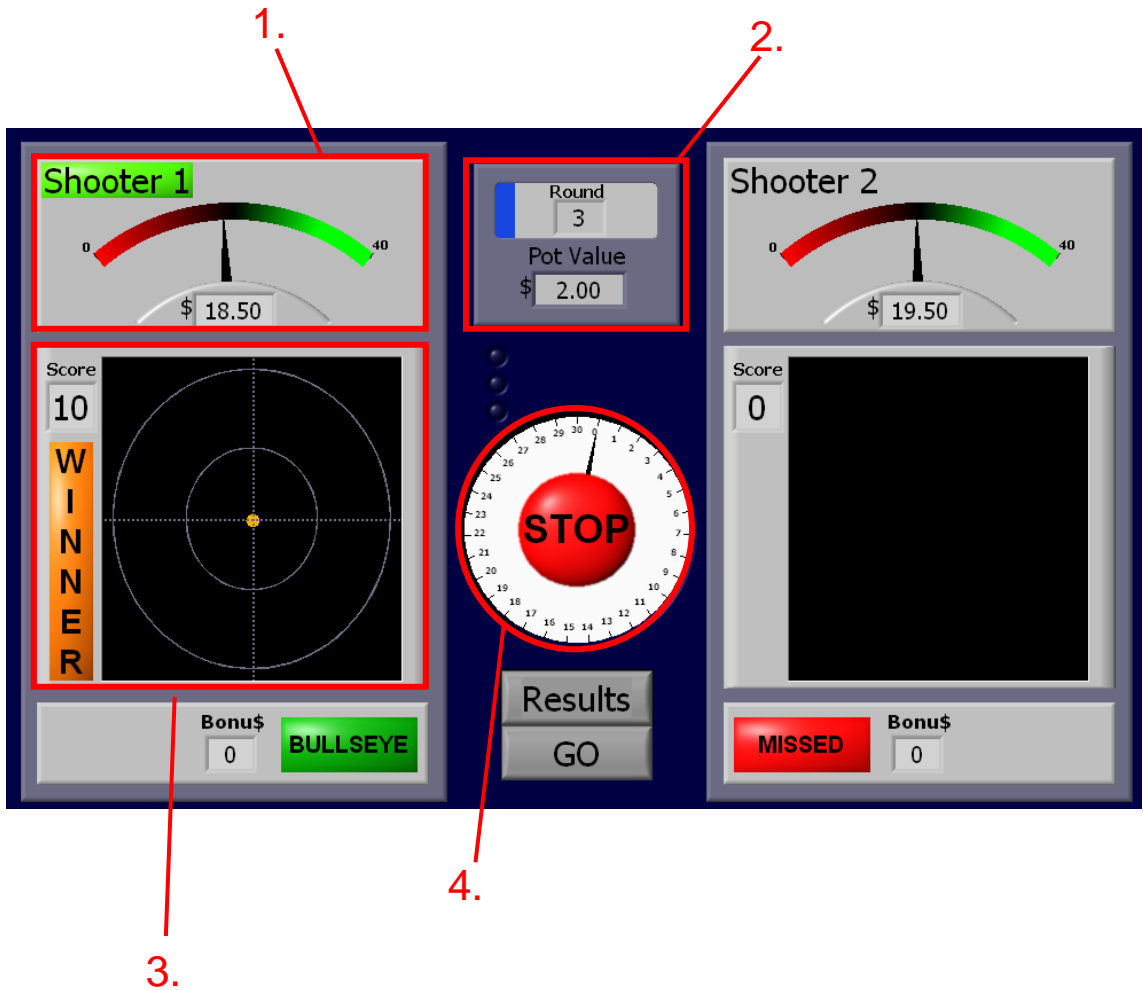
How *relaxed* am I?

Not relaxed

Completely relaxed

Appendix 6

Screen shot of Score board



1. Earnings
2. Round number and value at risk value
3. Performance results
4. Timer

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