Brain Biomarkers of Neural Efficiency during Cognitive-Motor Performance: Performing under Pressure

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Abstract. The concept of neural efficiency provides a powerful framework to assess the underlying mechanisms of brain dynamics during cognitive-motor performance. Electroencephalography (EEG) studies have revealed that as cognitive-motor performance improves non-essential brain processes are progressively disengaged resulting in brain dynamics leading to a state of neural efficiency. Multiple factors such as practice, genetics, mental stress, physical fitness and social interaction (team dynamics) can influence such cortical refinements positively or negatively and translate into an enhanced or deteriorated quality of performance. This paper provides a report of brain activity, assessed via fMRI, in a group of athletes who perform well under conditions of mental stress. Better understanding of brain states associated with such groups can enhance the ability to detect and classify adaptive mental states and increase the possibility of employing field-friendly brain monitoring tools such as EEG in ecologically valid situations for assessment of cognitive-motor performance in challenging real-world settings.

Keywords: Neural efficiency, expertise, fMRI, emotion regulation.

1 Introduction

Converging neuroimaging data suggest that experts require less neuronal resources compared to novices to accomplish the same task in their domain of expertise, and that this cortical refinement can be characterized as psychomotor efficiency, which is a special case of neural efficiency that refers to the magnitude of communication or input of non-motor brain activity to motor planning processes during movement preparation and execution [1]. Thus, one of the hallmarks of highly skilled individuals is the ability to perform using minimal effort and refined cortical processing specific to the action demands [2]. Many investigators have employed precision aiming tasks

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(shooting tasks) to explore this notion of efficiency since these kinds of tasks involve minimal movement artifact, and the advantage of ecological validity (e.g.[3]). This research has consistently revealed that the cerebral cortex reduces its activity during task execution, particularly in the left temporal region (associated with verbal analysis), and is characterized by automaticity of motor control [3]. Collectively, these findings imply a refined recruitment of the essential neural networks required for skilled performance. The opportunity to achieve such an adaptive state of cerebral cortical dynamics can be influenced by numerous factors. Personality characteristics, perceptual or attentional styles, trait anxiety, genetic influence on brain processes (e.g., 5-HTT polymorphic influence on emotional states in response to fear-eliciting stimuli), practice, expertise, and social influence as mediated by team dynamics can all affect cortical dynamics to facilitate refinement of networks or introduce nonessential activity that interferes with refinement and efficiency. The relevance of neural efficiency for military operational environments is that state-sensitive biomarkers, such as EEG, heart rate variability, etc., (individually or collectively) could be used to classify if a human operator is in such an adaptive state.

Importantly for this study, such neural efficiency of brain dynamics can become disrupted by mental stress leading to performance decline under pressure [4, 5]. Traditionally, the relationship between stress and performance can be characterized by the organizing principle of the inverted-U, termed the Yerkes- Dodson law [6]. According to this model, performance varies as a function of the stress activation continuum: with an under-aroused-state resulting in sub-optimal performance (in part due to decrements in attention & lack of engagement); a central zone where stress levels are consistent with behavioral adaptability, optimal performance and psychomotor efficiency and extreme excitation, which can become manifested as anxiety, also resulting in performance decline.

As such, the management of high levels of arousal is critical to the performance of tasks under conditions of mental stress. Anxiety-induced disruption of the central zone of optimal arousal may act to perturb the refined process associated with psychomotor efficiency [6]. Such negative appraisal accompanied by elevated arousal, is typically coupled with increased amygdala activity, which, in turn, influences the thalamus, hypothalamus, striatum, and brainstem areas in addition to numerous sensory and association cortical areas [7], creating neuromotor noise. Thus the regulation of emotion (which can be manifested as anxiety), is critical in determining the quality of cognitive-motor performance.

Nonetheless, some individuals are able to maintain a high level of performance during stressful events and, therefore, demonstrate qualities of stress resilience. Stress resiliency encompasses the ability to adaptively cope with adversity and can be examined at behavioral, psychological, and neural levels [8]. For the purpose of the study we define our stress resilient population as individuals who have a history of successful performance (1) senior varsity athletes in the sport of American football 2) letter award winners 3) who typically play a starting role on the team 4) supported by a partial or full athletic scholarship) under conditions of emotional challenge (high-level competition). Examination of elite performers (intercollegiate athletes) holds promise for understanding the neural basis for such abilities to adaptively cope with stressful events, and more specifically, elite athletes may be uniquely resilient to stress perturbation through the ability to regulate their emotions. Such a population offers a relevant vehicle with which to examine the impact of stress on human performance and can serve as an analogue to military populations who are also challenged with stress while attempting to maintain adaptive performance (i.e., brain) states. The ability to manage or regulate emotion under conditions of mental stress is critical to the quality of performance under such pressure.

There are numerous strategies through which to engage emotion regulatory brain networks, but one strategy, cognitive reappraisal, is a particularly adaptive means of emotion. Cognitive Reappraisal is a "cognitive-linguistic strategy that alters the trajectory of emotional responses by reformulating the meaning of a situation" p 1, [9], and this results in a decrease in the reported negative emotion [10]. In other words, the result of cognitive reappraisal is that it attenuates negative emotional experience resulting in an enhancement in cognitive control of emotion. This implies it is important to consider not only the stressful event, but the individual's perception of the stressor, to understand how skilled performers maintain consistency under various challenges and during mental stress.

In support of this notion, the dynamics between stress (i.e. anxiety) and performance can be further characterized by the transactional model described by Staal (2004) [11]. Specifically, stress is conceived as the aggregate result of the interpretation of the environmental challenge, as well as the objective challenge. In particular, this model integrates human performance and information processing capacity with the notion of appraisal of threat, controllability, and predictability for understanding how stress affects performance. As such, a key element is the individual's appraisal of the situation. This implies that a great deal of individual variation in the response to the stressor may be a consequence of the perception of the event rather than the actual environmental stressor. Therefore, the perception of the stimulus is essential rather than the objective stimulus and, furthermore, the perception may be highly related the individual's experience (i.e. domain specific).

Consequently, elite athletes may have developed a domain-specific reaction to stressful challenge, which through experience and training, allows them to endogenously regulate their affective response to known stressors and efficiently respond to affective challenge. In summary, the present work examined the neuropsychological processes that may well contribute to a state of psychomotor efficiency under stress. Using elite athletes as a model for a stress-resilient population this study attempted to provide insight into the mental approach these individuals employ to maintain mental stability as they engage in sport-specific challenges. A model of stress resiliency is proposed which is characterized by an economy of affective neural processing and an experience-dependent automaticity of neural processes associated with cognitive reappraisal.

2 Materials and Methods

2.1 Participants

Twenty-five male participants between the ages of 18 and 22 were recruited and of these 13 were football athletes (M=21.46 years; SD=0.776) and 12 were non-athletes (M= 21.08 years; SD=2.19).

The football athletes were 1) senior varsity athletes 2) letter award winners 3) typically play a starting role on the team 4) on a partial or full athletic scholarship. The non-athletes were healthy subjects who never played football at a college level, but reported familiarity with the goal and rules of the sport; this is critical to ensure that all subjects understand the meaning of the negative sport-relevant images. Additional selection criteria included that the subjects must have been (a) native English speakers (b) free of current or past diagnosis of neurological or psychiatric disorders, and (c) MRI compatible (e.g., no metal in body, no tattoos on face, no medicine delivery patch). All subjects gave their written informed consent and all experimental procedures were approved by the University of Maryland Institutional Review Board with proper notification IRB of record for Hyman Subject Research Projects performed at the Georgetown University Center for Functional and Molecular Imaging.

2.2 Stimuli

Negative and neutral images were selected from the International Affective Picture System (IAPS). In addition we developed Sport-Specific (SS) images by searching internet databases (e.g., Google Images) to find images representing unpleasant events experienced during football competition: for example: 1) injuries; 2) embarrassment due to loss (i.e., dejected players); 3) critical coaches. SS images were rated with a valence rating mean of 4.131 and arousal mean rating of 4.824. In turn, IAPS images were selected with matching valence means scores of 4.116 and arousal mean scores of 4.896 to create equivalence between the two image sets.

2.3 Task

Each trial was composed of four events: First, instructions (watch or decrease) appeared centrally for 2 seconds. On "decrease" trials, participants were instructed to engage in cognitive reappraisal and on "watch" trials participants will be instructed simply to look at the image and respond naturally. Second, an aversive or neutral image appeared centrally for 8 seconds. While the image remained on the screen, participants performed the evaluation operations specified by the prior instructional cue. Third, a rating scale appeared immediately after presentation of the image for 4 seconds to determine "How negative do you feel" with a rating from 1 to 5 (1 not at all, 3 moderately, 5 extremely). Fourth, the transition task of a fixation cross appeared for 4 seconds in the center of the screen cuing participants to relax until the next trial.

Each subject was cued to passively view or reappraise 48 domain non-specific negative images (24 each) and 48 domain- specific negative images (24 each) in addition to the passive viewing of 24 neutral images during randomly intermixed trials over 4 MRI scanning runs. Each image was shown only once for a given participant.

2.4 Imaging Parameters and Data Analysis

Functional and structural magnetic imaging data were acquired on a 3TSiemens Magnetom Trio system equipped with gradients suitable for echo-planar imaging sequences. Thirty-eight axial slices (3.2 mm thick in plane) were acquired using an echo planar imaging (EPI) pulse interleaved sequence (TR 2000 ms; FOV 205; TE 30ms). The DICOM images imported Statistical Parametric Mapping, SPM5. Slice timing and head motion correction, was followed normalization into MNI format (template EPI.mni). Default SPM5 settings were used to warp volumetric MRIs to fit the standardized template (16 nonlinear iterations), and normalization parameters were applied to subject's functional images. Normalized images were resampled into 2 × 2 × 2 mm voxels and smoothed. Preprocessed images were entered into a General Linear Model in SPM5 that modeled the canonical hemodynamic response function convolved with an 8-second boxcar representing the picture-viewing period. Motion parameters, the instructional cue period, and the rating period were entered into the model as additional regressors. Contrasts were created for each condition relative to the neutral baseline. These individual contrasts were then entered into a Full Factorial design of a 2 x 4 ANOVA Group by Conditions to perform a random-effects group analysis. The Group factor consisted of Athlete and Control and the Condition factor consisting of Cognitive Reappraisal SS, Passive Negative SS, Cognitive Reappraisal IAPS, and Passive Negative IAPS. Whole brain analysis was examined for each group relative to the neutral condition. Region of interest analysis was executed for the Cognitive Reappraisal SS vs Passive Negative SS, Cognitive Reappraisal IAPS vs Passive Negative IAPS in the prefrontal cortex (BA 8, 9, 10, 11, 45, 46, 47, taken from the Wake Forest Pick Atlas indication of Brodmann Areas). All results were FDR corrected for multiple comparisons ($p<0.05$) unless otherwise noted.

3 Results

3.1 Whole Brain Analysis

Whole brain analysis revealed that during the natural response of the athlete group to generalized negative images (IAPS) (relative to the neutral baseline) significant activation occurred in the left dorsolateral prefrontal cortex (DLPFC), left inferior frontal gyrus (IFG), left dorsomedial prefrontal cortex (DMPFC), left ventrolateral prefrontal cortex (VLPFC), bilateral orbitofrontal cortex (OFC), bilateral superior parietal lobule (SPL), right lingual gyrus, bilateral parahippocampal gyrus, bilateral premotor cortex (PMC), right cerebellum, superior temporal gyrus (STG) and right middle temporal gyrus (MTG). In the control group significant activation was observed in the bilateral DLPFC, left DMPFC, left IFG, left VLPFC, the bilateral OFC, the right STG, left inferior temporal gyrus (ITG) and right middle occipital gyrus (MOG), right anterior cingulated cortex (ACC), bilateral PMC, left SPL, right lentiform nucleaus and right postcentral gyrus.

Whole brain analysis results indicate that during passive viewing of sports-specific (SS) images, the athlete group exhibited significant activation in the left DMPFC, left insula, right lingual gyrus, left DLPFC, bilateral VMPFC, left IFG, right OFC, bilateral PMC, bilateral SPL/precuneous, left postcentral gyrus, bilateral ITG, the right STG, bilateral parahippocampal gyrus, left putamen and left thalamus. During the passive viewing of SS images, the control group exhibited significant activation in the bilateral DLPFC, bilateral VMPFC, right IFG, left OFC, left insula, bilateral STG, left ITG, right lingual gyrus, bilateral parahippocampal gyrus, bilateral PMC, bilateral SPL, left precentral gyrus, and left and right lentiform nucleus.

Cued cognitive reappraisal of generalized negative images (IAPS) resulted in significant activation of the left DLPFC, bilateral VMPFC right VLPFC, bilateral OFC, right lingual gyrus, bilateral premotor cortex, bilateral parahippocampal gyrus, left post central gyrus, right SPL, bilateral ITG, left MTG, bilateral cerebellum, left uncus and left lentiform nucleus in the athlete group. Significant activation in the left DLPFC, left DMPFC, bilateral OFC, bilateral IFG, bilateral PMC, right SPL, left supramarginal gyrus, left amygdala, right MOG, left posterior cingulated, right STG, right ITG, left MTG, and the right cerebellum was observed in the control group during cued reappraisal of IAPS images.

The cued cognitive reappraisal of SS images revealed significant activations in the left DLPFC, left VLPFC right OFC, bilateral PMC, right lingual gyrus, bilateral parahippocampal gyrus, left supramarginal gyrus right postcentral gyrus, bilateral SPL,

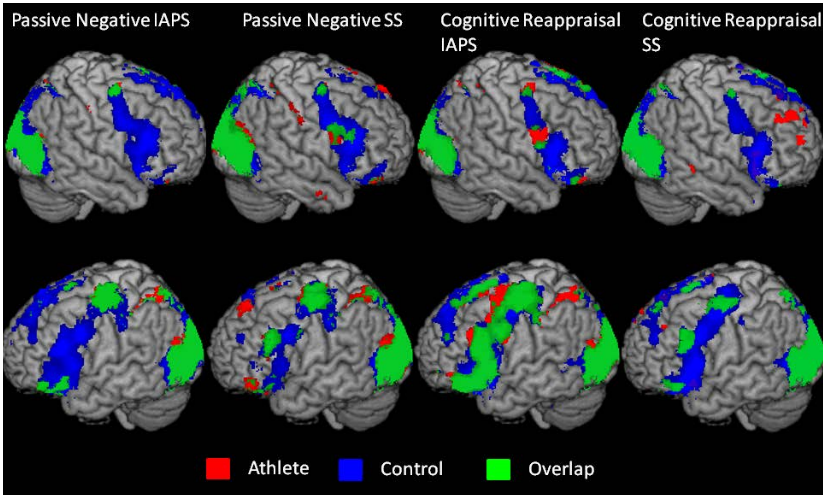

Fig. 1. Results of whole brain analysis. Passive Negative IAPS, Passive Negative SS, Cognitive Reappraisal IAPS, and Cognitive Reappraisal SS contrasts are relative to the neutral baseline. The red indicates the unique activation for the athlete group, the blue indicates the unique activation of the control group, and the green indicates regions where both groups showed activation (overlap), $p<0.05$, FDR corrected.

left STG, left MTG, left lentiform nucleus and left cerebellum in the athlete group. Activation was observed in the control group in the bilateral DLPFC, left IFG bilateral VLPFC right VMPFC bilateral medial OFC right cuneus, left parahippocampal gyrus, bilateral PMC, left MTG bilateral SPL, bilateral lentiform nucleus, bilateral STG, right motor cortex left posterior cingulate and bilateral insula.

3.2 Region of Interest Analysis

The region of interest analysis of the Cognitive Reappraisal of IAPS images and the Passive Response to IAPS images indicated activation in the left DLPFC, the bilateral DMPFC, bilateral VLPFC, right VMPFC and left IFG ($p<0.05$, uncorrected) in the athlete group (Figure 2). Direct comparisons within the IAPS image set between Cognitive Reappraisal and Passive Negative revealed that during cued cognitive reappraisal the left IFG ($p<0.05$, uncorrected) was active in the control group (Figure 2).

The region of interest analysis revealed that no difference ($p<0.05$, uncorrected) was detected during the Cognitive Reappraisal SS- Passive Negative SS contrast in the prefrontal for the athletes (Figure 2). Direct comparisons of Cognitive Reappraisal SS - Passive Negative SS revealed greater activation in the left DMPFC (BA 8), left IFG (BA 47), and right IFG ($p<0.05$, uncorrected) in the control group (Figure 2).

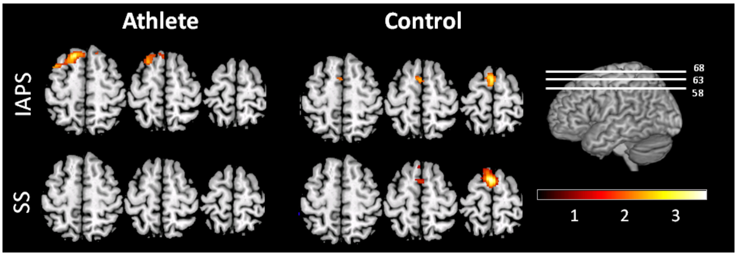

Fig. 2. Axial slices from prefrontal cortex region of interest analysis for the Athlete (left panel) and Control (right panel) groups. Contrast: Cognitive Reappraisal - Passive Viewing. IAPS. Generalized Negative Images. SS. Sports-Specific Negative Images. Slice numbers and t-score color bar is provided ($p<0.05$, uncorrected).

4 Discussion and Conclusion

There is a robust relationship between one's emotional state and the ability to effectively perform cognitive-motor skills. Elite performers must balance competing task demands such as physical requirements (dexterity, force), physiological recovery (metabolic rate, body temperature), psychological focus (memory, decision making), etc. during high levels of performance [12]. Critical to the orchestration of adaptive responses to the challenge of competitive sport, is the management of the emotional component of the task. Mental stress can lead to detrimental outcomes like state anxiety, burnout, exhaustion, strain, and tension, but it can also evoke adaptations such as hardiness, resilience and resistance [13]. Thus, these divergent outcomes must be explained not only in terms of the nature of the stressor but also in terms of the individual's perception of the challenge. Our data revealed a generalized neural processing efficiency during affective challenge (Figure 1) in which elite athletes are less perturbed by mental stress and suggests this may be a critical quality contributing to their stress resilience. When examining the specific patterning of neural processing during the natural response of the elite athletes to stressful challenges, our data show that they demonstrate similar neural processes to those used during cognitive reappraisal, but this is only within their domain of expertise (Figure 2). Thus, the confluence of experience based-factors such as controllability, emotional coping strategies, motivational efforts, trait/state anxiety and individual personality, in addition to the qualities of the objective stressor, cumulatively interact to produce the stress response.

The disruptive effects of stress on human performance can be classified as a loss of neural processing efficiency [1] leading to hyperactivity of non-essential brain regions that interfere with the cognitive-motor task demands. Conceptualized as "neuromotor noise," [14] this process affects cortical arousal and redistributes processing resources away from those dedicated to the goal-directed behavior. The loss of neural processing efficiency caused by stress-induced neuromotor noise may explain the phenomenon of "choking" or performance decline under pressure [4, 5]. However, elite-level athletes are typically resilient to such stress perturbation, enabling them to maintain a high level of performance during stressful conditions. The whole brain analysis result, which revealed more focused brain activity in the athletes during all conditions, suggests that neural efficiency in the motor domain as reported in the literature [1] extends to the emotional domain (Figure 1). This, in turn, would promote an overall refinement of cortical activity necessary for successful performance under mental stress and allow for a greater capacity to handle stressful events (i.e., less neuromotor noise).

Interestingly, the elite athletes demonstrate efficiency during both specific (sport-specific) and generalized (IAPS) challenge. On speculation, this pattern may be a consequence of repeated exposure to competitive stress, which can lead to active coping strategies that would translate to an ubiquitous planning and problem solving approach to challenge [8]. Our results also support efficiency in brain regions sensitive to social competence and understanding, which may promote adaptive neural processing mediated by oxytocin (reduces fear response) [8]. In addition physical fitness is associated with altered behavioral and neuromodulator responses to stressors (e.g.[15]). Lastly, genetic factors could also contribute to adaptive responses to stress by way of mediating reward circuits and protecting against depression [16] and trait disposition to anxiety [17]. Our present design cannot address the speculations identified here, but we examined one specific element of stress resiliency, cognitive reappraisal.

Cognitive reappraisal is a cognitive-linguistic strategy that changes the trajectory of emotional responses by reformulating the meaning of a situation such that negative affect experience is reduced [9]. Thus cognitive reappraisal serves 1) as a means for understanding the qualities that contribute to the unique features of stress resilient population compared to a representative sample population and 2) a critical reference for understanding what stress resilient individuals do when responding naturally to stressful events. Neuroimaging studies have examined this cognitive approach to mental stress and have revealed that frontally mediated executive processes act to manage the response of the amygdala (central to emotional processing)[9].

We examined if those who have demonstrated stress resilience (superior performance under pressure) exhibit such a specific pattern of neural responses characterized by this adaptive emotion regulatory strategy (cognitive reappraisal) in the prefrontal cortex. In addition, as stated earlier, the transactional model [11] predicts a high degree of specificity of the stress response based on an individual's perception and appraisal of the stressful event. Consequently, an athlete may have developed through experience and training a domain-specific reaction to stressful challenge, which allows them to endogenously regulate their affective response to familiar stressors. The region of interest analysis between the sport specific conditions (cued cognitive reappraisal and passive viewing of negative sport-specific images) indicates that through experience, these individuals automatically engage in mental transformation of an emotional event such that the negative consequences are attenuated, (i.e. they appear to endogenously engage in cognitive reappraisal) (Figure 2). This equivalence of processing (no difference during SS in athletes) between the natural response to mental stress and cued cognitive reappraisal is lost during the generalized negative events (IAPS images). Although this work was based on MR imaging future work can employ EEG/fNIRS, which are more appropriate in operational environments. A longer term goal is to develop applications for brain monitoring of emotion level and regulation in the field. Such an approach could be applied to military personnel for monitoring during combat situations for the purpose of stress management, altering workload based on one's state as well as for solider selection for special units if robust profiles emerge.

The results suggest that skilled performers who excel during competitive stress engage in cognitive regulation in their domain of expertise, decreasing physiological arousal thereby enabling them to sustain elevated performance. This specificity suggests that emotion regulation promotes refinement of brain activity resulting in an optimal state for effective task execution particularly under conditions of known stressful challenge (i.e., sport competition). By investigating a stress resilient population (elite athletes), this study provides an assessment of the postulated dynamic between cognitive (prefrontal) and affective (limbic) brain networks as related to skilled motor performance. What emerges is a generalized neural efficiency that appears to be a quality of resiliency to promote a mental state where neuromotor noise is attenuated. However a specific element of resiliency (i.e., automaticity of cognitive reappraisal) is dependent on experience. In the context of performance, cognitive reappraisal, through prefrontal regulation of the arousal, may maintain an adaptive level of arousal to promote a state of psychomotor efficiency during mental stress. The establishment of this protocol as an effective means through which to probe the emotion regulatory processes in elite groups, holds promise to facilitate more tactical psychological interventions that aid in motor performance.

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