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The Cognitive and Affective Neuroscience of Superior Athletic Performance

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Introduction

Sport is a pervasive phenomenon throughout the world and is characterized by three major elements: (1) psychomotor skills, (2) institutionalized rules for competition, and (3) public evaluation of the competitive process and outcome. The athlete typically executes coordinated and goal-directed movements in a highly competent and consistent manner in an environment marked by social comparison. Of course, he or she must embody the required physical attributes of muscular strength, power, endurance, speed, and flexibility, but the fundamental principle that the present chapter describes to explain superior sport performance is that of neural efficiency, which was originally employed to describe the brain processes of individuals with high measured intelligence (i.e., IQ) who solved cognitive problems with reduced brain activation when compared to others of lower IQ (Haier et al., 1988). More recently, Del Percio et al. (2008) described neural efficiency in the context of motor behavior as spatially focused cerebral cortical activity in experts during motor performance. In an earlier report Hatfield and Hillman (2001) identified a special case of general neural efficiency, identified as psychomotor efficiency, which referred to refinement or attenuation of any non-essential neural input to central motor preparatory processes from associative cortex or emotion-related processes, thus promoting efficacy of performance (Bertollo et al., 2016). Beyond neural efficiency, the performer's resilience to mental stress is considered in an inclusive model, labeled the cognitive-affective-motor neuroscience model of human performance, to explain the capacity of the superior athlete to regulate central neuromotor processes and exhibit the desired movements during the pressure of competition.

We develop the model discussion in the following order: (1) neural, psychomotor, and net efficiency, (2) the measurement of brain dynamics, (3) cognitive inference from brain activity, (4) brain dynamics of expert-novice comparisons, (5) practice-induced changes in brain dynamics and translation to performance, (6) the impact of mental stress on brain activity and performance, (7) brain processes underlying resilience to mental stress, (8) the influence of trust and team dynamics on brain performance, and (9) a summary and identification of future directions in this area of study.

The cognitive neuroscience approach to understand sport performance is adopted throughout and is based on knowledge of functional neuroanatomy and the description of brain processes that underlie constructs like attention, executive function, memory, emotion, motivation, mental stress, and other psychological phenomena, such as the mental processes that underlie team cohesion and trust (Hatfield & Kerick, 2007). This level of explanation does not extend to the molecular biology of the brain, but rather subscribes to higher-level assessment of regional brain activation, connectivity between brain regions, and measurement of neural responses to sensory and psychological stimuli using neuroimaging and electrophysiology (Bear, Connors, & Paradiso, 2001). Cognitive neuroscience offers a mechanistic explanation for human behavior rooted in brain biology and empirical evidence from relevant psychophysiological studies. A major development, still in its infant stages, is that of affective neuroscience applied to human performance (Paulus et al., 2010). In essence, this approach involves the assessment of brain activity during emotional states and is based largely on a "marriage" of concepts from LeDoux (1996), on the central role of the amygdalae in fear-related processes, and the work of Davidson and

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colleagues (1988, 2002, 2004), as well as that of Ochsner and Gross (2005), on the role of frontally mediated processes in the regulation of emotion. The pivotal role of prefrontal activity in the management of emotion (i.e., fear and anxiety) is described in the context of the cognitive-affective-motor neuroscience model such that the physiological consequences or sequelae of fear and degradation of performance may be attenuated or effectively managed by the cognitive appraisal of the situation. In this manner, the chapter attempts to explain superior performance by discussion of (1) the brain processes associated with expert performance, (2) how the brain and performance are affected by mental stress, and (3) how resilience mediates the relationship between mental stress and cognitive-motor behavior to preserve superior performance.

Neural, Psychomotor, and Net Efficiency

Efficiency has been recognized for some time in the physiological domain. Herbert deVries (1968) explained the concept of efficiency of electrical activity of muscle (EEA), a measure derived from electromyographic (EMG) recordings during force production. Accordingly, a muscle with a high capacity to produce force will exhibit lower levels of integrated EMG (IEMG), an index of motor unit recruitment, during the same percentage of submaximal work when compared to the IEMG produced by a muscle with lower capacity (i.e., a “weaker” or untrained muscle) (deVries & Housh, 1994). According to the general adaptation syndrome (GAS), repeated stress or alarm states in any biological system results in chronic change or adaptation—a state that allows a system to respond to the stressor with less strain or effort (Selye, 1976). In essence, genes are “turned on” by the internal milieu of changes induced by training stress to initiate tissue reconfiguration through protein synthesis. Each fiber in a trained motor unit gains additional contractile elements such that fewer units are needed to produce a given amount of force. Based on an evolutionary perspective, Sparrow (2000) argued that the dynamics of coordinated muscle activity are organized to minimize energy expenditure in a process of adaptation to constraints imposed by both task and environment. Lay et al. (2002) provided empirical evidence for this notion by assessing EMG of the vastus lateralis and biceps brachii muscles in a group of subjects who underwent training on a rowing ergometer. They reported (1) reduced motor unit activation during rowing stroke production, (2) greater coordination between muscle groups, and (3) greater consistency in the force production and movement pattern on each stroke. Figure 23.1 shows the reduction in motor unit recruitment while generating the same force output.

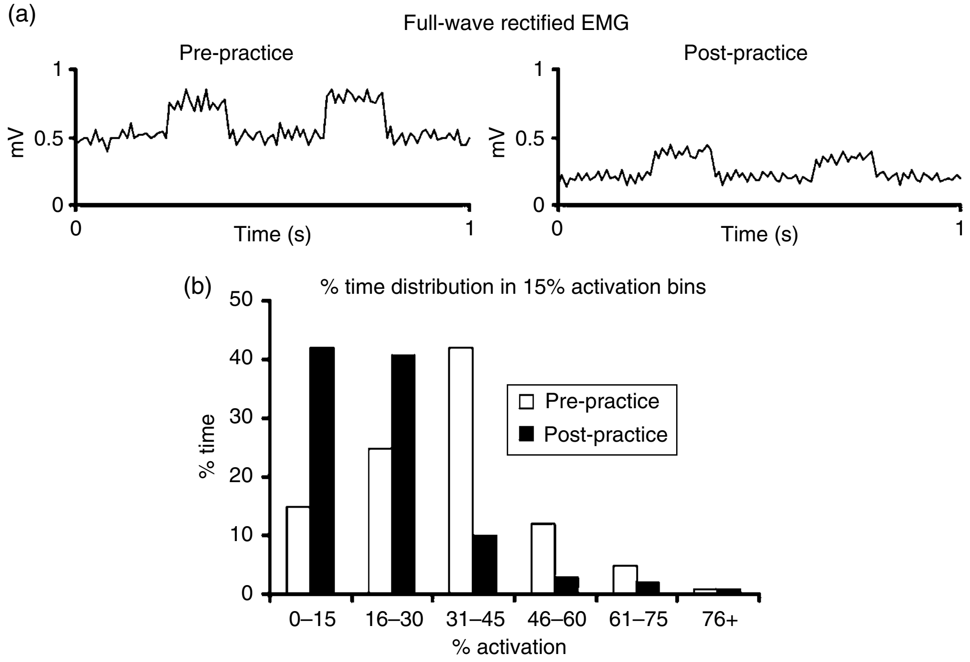

Figure 23.1 Changes in muscle recruitment before and after training. Note the reduction in the overall pattern of activation (a), and % time activated (b). Adapted from Lay, Sparrow, Hughes, & O’Dwyer, (2002). Reproduced with permission of Elsevier.

A related metabolic concept, running economy, was described by Daniels (1985) to explain endurance performance. That is, superior performers in a group of runners characterized by homogeneity of aerobic capacity exhibit lower oxygen consumption (expressed as ml O_2/kg/min) than that shown by slower members of the group when compared at the same level of submaximal absolute work. In this manner, the superior runner consumes less O_2 than the less-accomplished runner (per kilogram of body weight) when both run at the same speed and grade on the treadmill, possibly due to minimization of unproductive and unnecessary muscular activity (e.g., excess circumduction of the pelvis or abduction of the upper extremities) to propel the center of mass through space. There is no wasted or non-essential movement!

A remarkable example of the economy of movement in superior performance is provided in the biography of Red Grange, the great running back who played football at the University of Illinois from 1922 to 1925. Carroll (1999) quoted his coach, Bob Zuppke, as follows: "Grange was a genius of motion. *He ran with no wasted motion* [emphasis added], like Eddie Tolan, Michigan's Olympic sprint champion of '32." Not satisfied with his description, Zuppke related, "I once made a trip to the Kaibab Forest on the edge of the north rim of the Grand Canyon, and a deer ran out onto the grass plains, I said: 'There goes Red Grange!' The freedom of movement was so similar to Red's" (p. 58).

Phenomenological reports of high-performance athletes suggest that economy also characterizes the neural processes of the skilled performer. Williams and Krane (1998) described several psychological qualities associated with the ideal performance state in elite athletes, including a sense of effortlessness, an absence of thinking during performance, and an involuntary experience. Such subjective experience is consistent with the notion of automaticity in skilled motor behavior advanced by Fitts and Posner (1967), who described three progressive stages that the learner experiences evolving from the beginning stage of cognitive analysis, to the intermediate stage of association during which conscious regulation of motor processes is required but reduced, and, finally, to the advanced stage of automaticity in which the performer negotiates task demands without conscious effort. In this way, the association areas of the cerebral cortex become relatively quiescent with practice so as to minimize interference with the central neuromotor processes responsible for the execution of skilled neuromuscular activity, which can be captured by the concept of *psychomotor efficiency*.

As opposed to a general state of efficiency, van Mier et al (2004) described the neural processes of the expert such that some brain structures *increase* in activation as a result of motor learning while others exhibit *reduced* activation. From their work, it is reasonable to deduce that essential task-related neural processes are highly engaged with practice and experience while all non-essential processes are inhibited or become quiescent, resulting in a *net efficiency*. In this manner, the cortical association areas that deal with cognitive processes are intricately interconnected to the "motor loop," which is comprised of the striatum, globus pallidus, ventro-lateral nucleus of the thalamus with projection to the motor cortex to enable depolarization of motor neurons for ultimate activation of skeletal muscle motor units (Kandel & Schwartz, 1985). Refinement of associative processes owing to practice results in specific networking to active and essential motor processes and reduction of interference (i.e., noise) thereby reducing complexity in the orchestration of musculoskeletal actions involved in the intended movement. In this manner, great performers appear to simplify the process of motor control compared to novices. Less complexity in the processes associated with motor control or a reduction in the degrees of freedom of relevant neural network actions may lead to greater consistency of the resultant motor performance because of less variability in the preparation of the movement. Such a process underlies how the skilled athlete executes precisely what he or she intended.

Simply stated, efficiency is defined as Work Output (or Motor Behavior)/Neuromotor Effort. The denominator of the efficiency formula is the cognitive workload, which is defined as the resources currently being used to perform a given task (Gopher & Donchin, 1986). Cognitive workload must consider the interaction between the task and the person performing the task (Gopher & Donchin, 1986). *Attention*, defined as the allocation of limited cognitive resources to execute a task, is typically divided among several tasks in proportion to each of the various demands. The used and unused portions of the full attention capacity of an individual are termed *cognitive workload* and *attention reserve*, respectively (see Figure 23.2). For example,

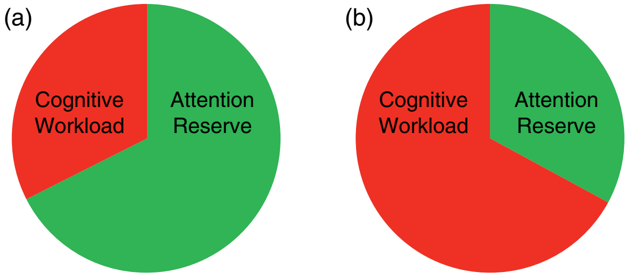

Figure 23.2 Panels (a) and (b) show the proportions of cognitive workload and attention reserve during relatively easy and challenging tasks, respectively.

under identical game conditions, a novice soccer goalkeeper, monitoring player position and ball possession and all future probabilities, would experience relatively high levels of cognitive workload and low levels of attentional reserve compared to an expert goalkeeper who would have greater ability to predict action outcomes. Although they can be assessed subjectively, there are also objective psychophysiological methods with which to measure cognitive load and attention reserve, which are described in the next section on measurement of brain activity. The findings provide confidence that neural efficiency during expert motor performance can be empirically assessed with objective measures.

Measurement of Brain Dynamics

The brain processes that mediate cognition, affect, and motor behavior can be detected with a high degree of temporal and spatial resolution by employing several neuroimaging techniques. Most of these techniques are non-invasive, meaning that no injections or "breaking of the skin" occurs; however, some involve the injection of harmless radioactive isotopes of water or glucose that are then metabolized by the brain so that a signal is emitted for detection of activation. Several imaging techniques are currently available including EEG, magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), positron emission tomography (PET), and single photon-emitted tomography (SPECT). One of the challenges to contemporary neuroscientists is to select the appropriate measure, or a combination of measures, in a programmatic line of research to understand the role of the brain in sport performance. This challenge, in large part, is due to the restrictions on movement or the sensitivity to motion artifact while measuring brain activity that affects all the measures to some degree.

Electroencephalography and Event-Related Potentials

The EEG is composed of a time series of electrical voltages (i.e., measured in microvolts or millionths of a volt) that are collected from sensors positioned at specific locations on the scalp based on the International 10–20 system (Jasper, 1958). The name of the system derives from the placement of the sensors at 10% and 20% of the distance between major landmarks on the head such as the tip of the nose and the protrusion on the occipital bone, the inion. The voltages are generated by the dynamic oscillatory summation of inhibitory and excitatory post-synaptic potentials that are compared to a neutral reference site such as the skin overlying the mastoid bone (i.e., a unipolar recording) or to another active site such as that placed on the vertex area at the top of the scalp (i.e., a bipolar recording). The former is commonly used to assess regional activity at the recording site while the latter is useful in the assessment of relative activation such as the difference between the left and right hemispheres of the brain. Figure 23.3 illustrates a marksman being monitored for EEG while focusing and aiming at the target. The utility of the marksmanship task is that of active attentional engagement while remaining motionless during the aiming period. The

Table 23.1 Broad overview of the conventional bands of activation from the EEG signal. Adapted from Schomer & da Silva (2010).

Bands (Hz)	Main behavioral trait	Typical studies
Delta (1–4)	• Deep non-REM sleep (known as slow-wave sleep)	• Sleep • Sleep disorders
Theta (4–8)	• Brain processes underlying working memory • Consciousness slips toward drowsiness • Serve as long-distance carrier frequency across brain regions	• Visuospatial navigation • Mental workload
Alpha (8–13)	• Relaxed awareness without attention • Increased with closed eyes	• Attention • Meditation • Biofeedback training
Beta (13–30)	• Active concentration or anxious thinking • Motor planning and execution	• Stimulus-induced alertness • Motor control
Gamma (30–100)	• Carrier frequency for binding sensory impressions of an object to a coherent form • Neural processes such as eye movements and microsaccades	• Microsaccade

Figure 23.3 Experimental setup with EEG cap placed on the head of the participant. Adapted of Oh et al. (2013). Reproduced with permission of Springer Nature.

stable shooting position allows for high-fidelity EEG recordings. In addition, study participants may be experts who have completed years of practice that enables high-quality studies of expertise.

The EEG frequency range or spectrum extends from direct current to approximately 100 cycles per second (Hz). In essence, the raw signal is composed of a mixture of the frequencies in the spectrum, and it can be decomposed into its sinusoidal components by the Fast-Fourier Transform (FFT). Such a process provides a spectral analysis to determine activation in the area of the recording sites (Schomer & da Silva, 2010). Theta power is highly informative of neural processes as it is positively related to effortful engagement of working memory when recorded in the frontal region (Jensen, & Tesche, 2002), while alpha power is indicative of regional "idling" or inhibition of regions that are unrelated to task demands (Pfurtscheller, Stancak, & Neuper, 1996). Alpha power has also been divided into "low-alpha" (8–10 Hz), which is inversely related to general arousal, and "high-alpha" (10–13 Hz), which is inversely related to task-relevant attentional processes (Budzynski, Budzynski, Evans, & Abarbanel, 2009). The advantage of EEG is that it not only captures fast-changing events, which implies excellent temporal resolution, but it can also be used to detect the connectivity in the form of cortico-cortical communication between different regions of interest (ROIs) by means of coherence analysis. Similarity in the spectral content of EEG recorded at different sites is assumed to indicate cortico-cortical communication between the regions. As such, EEG coherence is critical to the study of psychomotor efficiency as it allows for determination of the "input" from various cortical regions to the frontal and central motor planning (premotor and supplementary motor areas—FZ site) and the motor cortex (C3, Cz, and C4 sites). For example, Zhu et al. (2011) have examined connectivity between the left temporal region (T3) and Fz in golf study participants and, as expected, observed that performance was inversely related to interconnectivity between T3 and Fz. They reasoned that superior performance was enabled by the reduced connectivity suggestive of an autonomous state, as described by Fitts and Posner (1967), that would reduce any noisy input into the frontal motor planning processes.

A major limitation of EEG, however, is the problem of volume conduction or the spreading of electrical charge throughout the liquid medium of the brain so that the signal is also detected (albeit with reduced influence) by sensors other than those overlying the tissue of the region of interest (ROI). For this reason, EEG is said to be poor in spatial resolution. A related technique is MEG, which measures the magnetic fields produced by the electric currents that originate in the brain, which offers the same temporal resolution as EEG but without the limitation of volume conduction. However, the participant in a MEG study must be confined to a supine or sitting position with their head inside of the MEG device and no movement is allowed. The advantage of EEG to the study of motor behavior is that it can be recorded while the sub-

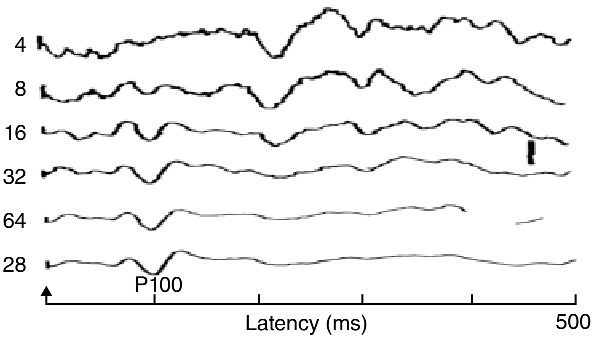

Figure 23.4 Illustration of the signal averaging process for the assessment of event-related potentials. Positive is down. Adapted from Chiappa (1990). Reproduced with permission of Wolters Kluwer.

ject can move and engage with limited mobility in their surroundings. This advantage of EEG can be extended significantly with the use of virtual reality (VR) to simulate real-world movement and sport scenarios.

Beyond the information about cerebral cortical activity provided by EEG, the ERP derived from it provides an index, which is generated from averaging several EEG epochs or short time periods (e.g., 1-s in duration) that are time-locked to repetitive stimuli (i.e., basic auditory, visual, or tactile stimuli). See Figure 23.4. In this manner the amplitude and latency of critical components like the P300, a positive-going waveform typically seen between 300 and 500 ms, can provide a simple yet powerful index of basic cognitive function that can be assessed in relation to sensory, perceptual, and attention-related processes (Chiappa, 1990).

The application of these measures to assess both cognitive workload and attention reserve, which are critical to research on neural efficiency, was recently described by Jaquess et al. (2017). Specifically, they employed spectral measures of cortical activation to assess cognitive workload while amplitudes of the P3a component of event-related potentials (ERPs), generated in response to the presentation of unattended "novel" sounds, were used to assess the complementary attention reserve in novice pilots during a simulated airplane flight task. The assessment of attention reserve was based on the procedure reported by Miller et al. (2011). As expected, the EEG revealed a progressive increase in cerebral cortical activity with the increased difficulty of the flight tasks while the P3a component showed a progressive reduction in amplitude. In addition, canonical correlation of the two "families" of measures related to workload and reserve revealed a strong negative relationship supporting the complementarity of cognitive workload and attention reserve. Such a finding provides confidence in using EEG and ERPs to study neural efficiency and is extended by the employment of EEG coherence to assess psychomotor efficiency.

Functional Magnetic Resonance Imaging (fMRI)

Beyond the electrocortical and MEG measures, the Blood Oxygen Level Dependent (BOLD) signal, derived from fMRI, provides superior spatial resolution, but at the cost of relatively lowered temporal resolution. In addition, the study participant is highly constrained as he or she must be completely immobile during the scanning period. Relative to EEG, which is limited to the capture of cortical dynamics, the BOLD hemodynamic response provides for the imaging of both cortical and subcortical activity as well as connectivity between ROIs. The study results reported by Milton et al. (2007), as shown in Figure 23.5, illustrate the neural efficiency of expert golfers during an imagined pre-shot routine owing to the spatial resolution of subcortical activity compared to the elevated brain activity in novices for which the BOLD signal is significantly higher. In addition, the structural MRI provides for anatomical imaging of the brain (e.g., tissue density and the volume of ROIs).

Importantly, the simultaneous employment of EEG and fMRI offers the opportunity to assess the net efficiency of brain processes during cognitive-motor performance. As described by van Mier et al. (2004), some brain regions increase while others decrease in activity as a result of practice and skill acquisition. The essential

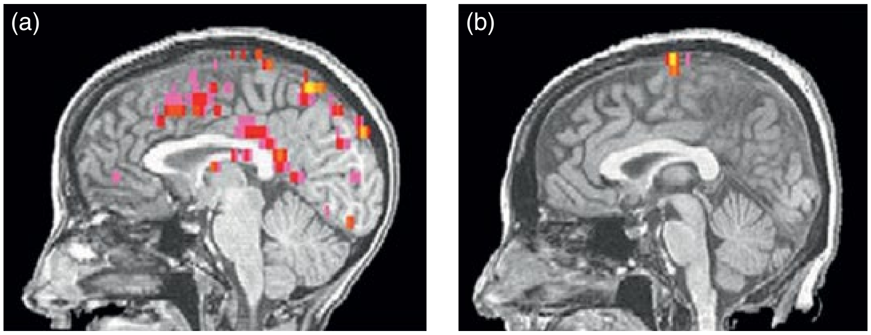

Figure 23.5 BOLD signal during the mental imaging of the pre-shot routine for novice (a) and expert golfers (b) which illustrates the elevated level of neural engagement for the novices. Adapted from Milton et al. (2007). Reproduced with permission of Elsevier.

motor processes orchestrated by subcortical and cortical structures would likely show increased BOLD and attenuated alpha power, respectively, as a result of practice while all non-essential brain processes (i.e., those that decrease in activity) would be in an "idling state" and reveal as lower BOLD signal and elevated EEG alpha power. Such a psychophysiological profile may well explain the focused state of concentration experienced by athletes who achieve the ideal performance state as described by Williams and Krane (1998).

Functional Near-Infrared Spectroscopy (fNIRS)

Although fMRI is ideal for detection of whole-brain activity, its use is limited to imagined and virtual movement settings. This is a significant limitation since movement quality is the essential quality of athletic performance. A related hemodynamic measurement technique that does allow for reasonable freedom of movement is that of fNIRS (Chance et al., 1988). Optic sensors are placed on the scalp, typically in the frontal or forehead region, that can detect cortical activity with a high degree of spatial resolution, but limited to a few millimeters of depth. A remarkable benefit of fNIRS is its resilience to movement artifact relative to EEG and, of course, fMRI. In this manner, fNIRS is inferior to EEG and the BOLD signal in terms of temporal and spatial resolution, respectively, but is a promising measurement tool to capture cortical dynamics for motor performance settings in which the EEG is impractical because of its relatively heightened sensitivity to motion artifact. Another strategy, akin to the simultaneous employment of fMRI and EEG, is that of the joint employment of fNIRS and EEG. This partnered measurement strategy would allow for maintenance of brain activity assessment with fNIRS during episodes of EEG signal loss due to movement-induced artifact. Such a back-up recording process would be critical for situations calling for continuous brain monitoring in which the loss of signal would be problematic. For example, this would be a concern for ongoing assessment of cognitive load in airplane pilots and in unmanned aerial vehicle (UAV) operators for whom lapses in attention and maladaptive neural processes could result in catastrophic outcomes.

Figure 23.6 illustrates the general differences in spatial and temporal resolution of the various imaging strategies. Variation of these qualities can be achieved based upon the technology employed. For example, spatial resolution of the EEG can be enhanced with greater density of the electrode arrays. The purpose of the research study (e.g., the need to assess cortical or subcortical processes or both), the speed with which brain activity must be captured, and whether there is need to examine the brain during movement are considerations that will dictate the appropriate measurement tool.

Complementary Psychophysiological Measures of Mental Processes

Eye-Tracking

While such direct measures of brain activity can be cumbersome and expensive, a complementary objective tool, eye-tracking, can serve as an indirect, yet more readily accessible, "window into the brain." Various parameters related to eye movements such as pupil diameter, blinks, fixations, saccades, and scan-path have been commonly used to assess not only behavioral performance but also dynamic brain activity in human cognition (Ahlstrom & Friedman-Berg, 2006; Ellis 2014; Tsai et al., 2007). Pupillometry is informative of autonomic balance and emotional state whereby constriction is indicative of parasympathetic dominance and dilation is indicative of

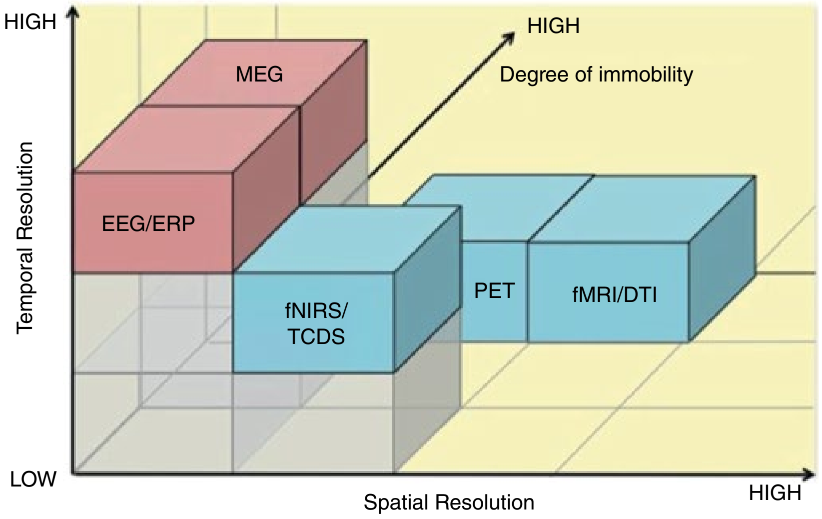

Figure 23.6 A comparison of electromagnetic and hemodynamic neuroimaging techniques for use in neuroergonomics based on temporal resolution (*x*-axis), spatial resolution (*y*-axis), and degree of immobility (*z*-axis). DTI: Diffusion Tensor Imaging; TCDS: Transcranial Doppler Sonography. Adapted from Mehta & Parasuraman (2013).

sympathetic dominance. Numerous studies have shown that pupil dilation is positively associated with cognitive workload (Ahlstrom & Friedman-Berg, 2006; Beatty, 1982; Beatty & Lucero-Wagoner, 2000; Granholm & Steinhauer, 2004), which would allow for convergent assessment of neural efficiency in tandem with any one of EEG, fNIRS, MEG, and fMRI techniques. In addition, scan-path measures trace eye movements as a sequence of fixations and saccades (Noton & Stark, 1971). Scan-path analysis has also been employed in the study of efficiency and cognitive workload (Di Nocera et al., 2006; Ellis 2014; Reinerman-Jones et al., 2010).

Electrocardiogram (ECG)

An additional psychophysiological measure that can detect autonomic balance, emotional state, and cognitive workload is the heart period variability or heart rate variability (HRV). The oscillatory shortening and lengthening of the successive inter-beat intervals over time is indicative of sympathetic and parasympathetic influence, respectively. HRV is indicative of the vagal influence in the autonomic nervous system and can index an individual's emotional state. Complementary assessment of the HRV with neuroimaging tools will provide further insight into the mental state of the performer relative to brain measures alone. For example, in a combined ECG and EEG study, Gentili et al. (2014) observed that HRV was less sensitive to changes in task demand than EEG, but it was inversely related to perceived workload. In particular, elevated HRV was indicative of vagal influence to the heart and was greater in participants who perceived less effort at a given task demand.

Cognitive Inference from Brain Activity

The psychological processes that influence the quality of motor behavior can be inferred from the psychophysiological measures described above. Specifically, the comparison of the "unknown" preparatory state during motor tasks of interest, like target shooting, can be compared to clearly defined tasks such as those along the verbal-analytic to visual-spatial dimension. Such an approach subscribes to a cognitive inference strategy described by Cacioppo and Tassinary (1990). In essence, the EEG captured during the performance of interest, in this case the preparatory aiming period, is compared to that recorded during the known referent conditions to determine similarity. If the EEG during the task of interest is similar to that during a referent condition, then similarity is assumed in the underlying cognitive states. A convenient metric for deducing cognitive processes from the EEG is the alpha band power asymmetry score derived from homologous sites such as the temporal regions—T3 and T4 for the left and right temporal regions, respectively. Such a score is anchored in the established psychological processes known to be associated with the two cerebral hemispheres.

Of course, such metrics as asymmetry scores must be carefully considered along with the spectral power at the individual sites as ratio score can change in magnitude for a variety of reasons. For example, a rise in T4:T3 alpha asymmetry magnitude over successive epochs could be due to relative stability in T3 with a progressive rise in T4 or could be due to relative stability in T4 alpha power accompanied by a progressive decline in T3 alpha power. In addition, both amplitudes may rise (or fall) but may be more pronounced on one side. Careful examination of both power and asymmetry, in conjunction with comparison to such measures during the "known" mental states, allows for a powerful tool for cognitive inference. In this manner, the study by Hatfield et al. (1984) provided a paradigmatic and conceptual base for much of the succeeding literature in this field and is a strategy for gauging the athlete's "thinking" or absence thereof in the case of automaticity.

Several additional investigators have similarly observed EEG alpha band synchrony or "idling" in the left temporal region of the cortex during the preparatory period prior to the execution of movement during archery and rifle/pistol marksmanship (Bird, 1987; Hatfield, Landers, & Ray, 1987; Hillman et al., 2000; Janelle et al., 2000; Kerick et al., 2000; Kerick et al., 2004; Landers et al., 1991; Landers et al., 1994; Loze et al., 2001; Salazar et al., 1990). Although some investigators have failed to observe EEG alpha synchrony during karate and golf putting performances in this specific region (Collins, Powell, & Davies, 1990; Crews & Landers, 1993) they have observed alpha synchrony in other cortical areas. It may be that the specific demands of the sport tasks imposed on the subjects in these investigations (i.e., karate and golf putting) resulted in the allocation of different and specific neural resources and that the relative quiescence of left temporal activation noted during target shooting may have been inappropriate or irrelevant. In this manner, the principle of neural efficiency would hold while the specific brain regions affected would vary from task to task (i.e., the Specific Adaptation to Imposed Demand [SAID] principle established in exercise physiology).

Figure 23.7 shows that the alpha asymmetry scores observed during the aiming period progressed from similarity to a left hemispheric task to that more akin to a right hemispheric task as the time to trigger pull approached. Alpha asymmetry scores in the shooting condition were significantly lower in Epochs 2 and 3 as compared to Epoch 1. Asymmetry scores did not change across epochs in the non-shooting tasks. That is, a state

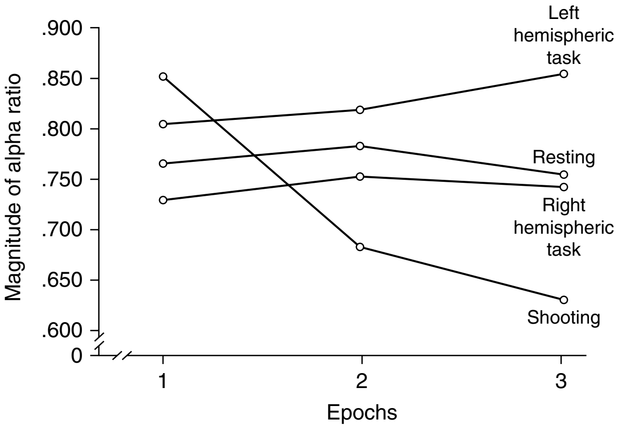

Figure 23.7 Mean EEG alpha (8 – 12 Hz) asymmetry scores (T4:T3) across three consecutive epochs immediately preceding the trigger pull in a rifle shooting task and three comparison conditions. Left hemispheric task: Math and reading task; Right hemispheric task: Mental geometric object rotation. Adapted from Hatfield et al. (1984). Reproduced with permission of the American Psychological Association.

of explicit monitoring and verbal-analytic processing transitioned to a state dominated by visual-spatial processing, which is reasonable given the need to aim the gun in spatial coordinates to achieve accuracy of performance. The interpretation of the results offered by Hatfield et al. (1984) is consistent with the phenomenological reports of athletes such as the one offered by the Hall of Fame football player Walter Payton of the Chicago Bears who was quoted by Attner (1984, pp. 2–3) as follows:

"I'm Dr. Jekyll and Mr. Hyde when it comes to football. When I'm on the field sometimes I don't know what I am doing out there. People ask me about this move or that move, but I don't know why I did something, I just did it. I can focus out the negative things around me and just zero in on what I am doing out there. Off the field I become myself again."

Insights into the brain processes underlying the quote by Payton are provided by the psychophysiological studies of human performance described below and are largely based on the relative activation of the two cerebral hemispheres that differ in neurocognitive function (Springer & Deutsch, 1998). One of the earliest studies of cerebral hemispheric activity during psychomotor performance was conducted by Hatfield et al. (1982), who assessed EEG activity at four recording sites (T3, T4, O1, and O2, commonly referenced to Cz) during the aiming period in 15 elite world-class competitive marksmen just prior to trigger pull. The study was based on an earlier report by Pullum (1977), who reported robust increases in EEG alpha power during superior marksmanship performance, in combination with the classic notions of hemispheric asymmetry of cognitive function (Galin & Ornstein, 1972; Springer & Deutsch, 1998). This foundation guided Hatfield and colleagues to address one of the prevalent themes in sport psychology at that time from a cognitive neuroscience perspective; that is, the notion of attenuated self-talk during superior performance (Gallwey, 1974; Meichenbaum, 1977). Because EEG alpha power is indicative of decreased activation—the concept of "cortical idling" later advanced by Pfurtscheller (1992)—the investigators predicted that left temporal alpha power would be relatively higher than that observed in the right temporal region in such highly skilled performers. Such a finding would offer objective evidence for attenuation of covert self-instructional activity or verbal-analytic processing in highly skilled athletes and be consistent with attainment of the stage of automaticity. Twelve of the 15 study participants exhibited a marked elevation in left temporal (T3) alpha power averaged across three successive 2.5-second epochs during the aiming period just prior to trigger pull, relative to the level observed during rest, accompanied by desynchrony (i.e., less power) of EEG alpha in the right temporal region (T4). These changes resulted in a remarkable degree of EEG alpha asymmetry (i.e., temporal region) during aiming with the relative desynchrony of alpha power observed in the right temporal region (T4) during shooting indicating reliance on visuospatial processing during the aiming period, an event entirely consistent with the specific demands of target shooting.

The findings can also be interpreted from the viewpoint of an intention to act, as outlined by Shaw (1996), as opposed to a simple reduction in attention or cognitive processing, as the athlete is likely to have a well-established mental routine or approach to achieve their goal that internally guides the behavior with less emphasis on external feature detection. The well-developed routine or intention to act might well activate very specific brain regions and subcortical processes while limiting several irrelevant cortical processes, resulting in a net increase in cortical relaxation or idling (i.e., net efficiency). Moreover, recent work has indicated that cortical relaxation may be achieved via inhibition of non-essential processes (Klimesch, Doppelmayr, Schwaiger, Auinger, & Winkler, 1999). In either case, the significance of such neural adaptations implies a reduction in cognitive association processes and detailed analysis of environmental stimuli. Such detailed or effortful processes in the absence of refinement or reduction in cortico-cortical communication between phonological and motor regions could influence motor control processes in a negative manner such that they would remain variable and inconsistent. As stated above, the lessening of any such communication or neuromotor noise would likely result in greater stability and consistency of the motor processes and muscle action that mediate the quality of performance (Lay et al., 2002; Milton et al, 2004). This early work by Hatfield et al. (1982, 1984) was followed by more contemporary studies that have provided remarkable support for the presence of neural efficiency as a robust marker of superior motor and sport performance. These studies will be discussed in the next section.

Brain Dynamics in Expert-Novice Comparisons

Evidence for neural efficiency and the special case of psychomotor efficiency is provided by several studies of that report a contrast of brain activity during skilled motor performance in experts and novices, which are guided in theory by the reduction in cognitive workload expected with the progressive stages of learning described in the human performance theory by Fitts and Posner (1967).

Strong evidence of task-specific neural efficiency in experts was provided by Haufler et al. (2000) in a study titled "Neuro-cognitive activity during a self-paced visuospatial task: Comparative EEG profiles in marksmen and novice shooters." Specifically, EEG spectral estimates for theta, alpha, and gamma power were obtained from skilled marksmen and novice shooters at bilateral frontal, central, temporal, parietal, and occipital sites during the aiming period (6 s) of a target shooting task for each of 40 trials up to the execution of the trigger pull in order to determine regional differences in cortical activation. In addition, the EEG power obtained during the aiming period was compared to that observed period during the processing of novel verbal and spatial cognitive challenges that were presented via projection on a screen and viewed by the participants in the standing shooting position while holding the rifle in the standard pose. The postural stance was constant across conditions to facilitate comparison of the brain activity (i.e., nothing differed except for the cognitive state), which provided a strategy for cognitive inference. The findings revealed that the expert marksmen exhibited lower activation than the novices over the cortex during the aiming period with a pronounced difference in the left hemisphere central-temporal-parietal area. In support of the SAID principle, few differences between the groups were observed during the verbal and spatial tasks. The marksmen generally exhibited lower cortical activation during the aiming period when contrasted to that during the novel comparative tasks, while novices exhibited similar levels of activity and were effortfully engaged across all tasks. Figure 23.8 (left panel) shows the striking difference between the groups in gamma power such that experts exhibit lower cortical activity during the shooting task and relative similarity during the novel tasks. The right panel illustrates the comparative spectral power profiles in the two groups during aiming period with a higher level of alpha power and lower gamma power in the experts. Such a pattern clearly supports neural efficiency in the experts.

A more recent report by Baumeister et al. (2008) reveals similar findings using a different task. EEG was assessed in expert and novice golfers during a putting task while EEG power was assessed for the theta (4.75–6.75 Hz), low-

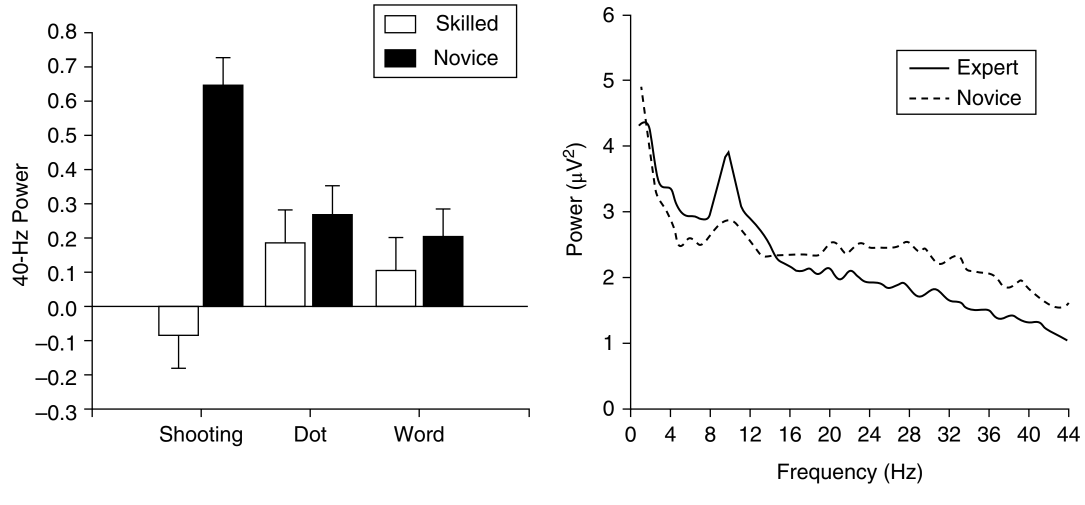

Figure 23.8 EEG spectral power from expert shooters and novices during performance in a shooting task, a dot probe task, and a semantic word task. Left panel: Spectral power at 40 Hz for both experts and novices during performance of the three tasks. Right panel: Power spectra of the experts and novices during the shooting task. Adapted from Haufler et al. (2000). Reproduced with permission of Elsevier.

(7–9.5 Hz), high-alpha (9.75–12.5 Hz), and beta bands (12.75–18.5 Hz). The experts exhibited superior performance accompanied by heightened fronto-midline theta power as well as higher high-alpha power in the parietal lobes compared to the novices. The skill-related differences suggest that the experts were engaged in a state of highly focused attention, as indicated by the elevated theta power, and a refinement (i.e., reduction) in the associative and sensory processes of the posterior parietal regions, as indicated by the bilateral alpha synchrony. In essence, they "lock in" essential neural networks while minimizing any distractions. Such a state could influence the physical performance by reduction of any interference with the central neuromotor processes.

Del Percio et al. (2009) conducted a comparative EEG profile of elite and novice pistol shooters with the dual purpose of assessing (1) comparative cortical activation between the groups and (2) the relationship between the magnitude of cortical activation and performance in the elite athletes. Eighteen experts and 10 novices were monitored for 56 channels of EEG, and volume conduction was managed by a surface Laplacian estimation, which enhances spatial resolution by consideration and subtraction of the surrounding EEG time series from each of the recording sites of interest. Compared to a resting baseline period, the experts did show less cortical activation during aiming compared to novices, as indicated by attenuated event-related desynchrony (ERD) proceeding from baseline to shooting, which provides additional support for overall neural efficiency with expertise. In addition, the performance accuracy of the expert marksmen was positively related to cortical "idling" or regional relaxation, as indexed by event-related synchrony (ERS) of alpha power during aiming relative to baseline, in both the right parietal and left central areas. Such a finding implies refinement or filtering of extraneous visuospatial processing (i.e., focused attention) and efficient activation in the contralateral motor cortex that controls the trigger finger in this right-handed group. Such relationships with performance were not observed in the novices who were likely inconsistent and noisy in the orchestration of cortical activity from shot to shot. The authors concluded that the findings indicate selective attentional processing and neural efficiency in experts during the execution of visuomotor performance.

In addition to the assessment of regional cortical activation, Del Percio et al. (2011) conducted a study with elite pistol shooters and novices to determine the stability of brain processes, specifically cortico-cortical activation or coupling between brain regions, assessed via EEG coherence in multiple frequency bands, in the posterior parietal region that is critical to the visuomotor processes in precision aiming tasks. The results revealed relative stability of both intra- and inter-hemispheric coupling in the elite athletes. Stability of brain processes likely underlies the behavioral consistency of cognitive-motor performance and the popular notion that superior performers are characterized by mental consistency, which leads to consistency of action. That is, the high-level performer executes what they intend to execute, and they do it repeatedly.

The studies that have appeared in the literature provide remarkable support for neural efficiency of brain processes in experts, but only a few expert-novice contrasts have directly assessed the psychomotor efficiency hypothesis that posits that the association areas of the cerebral cortex become *progressively quiescent* with practice and enhanced skill level, which minimizes interference with the central motor control processes responsible for the intended neuromuscular activity (i.e., reduces neuromotor noise). This is a special case of neural efficiency and is focused on connectivity from all regions of the cortex to the frontal motor, with particular focus on the left temporal and motor communication (i.e., EEG sites T3 and Fz). Such a study was reported by Deeny et al. (2009) entitled, "Electroencephalographic coherence during visuomotor performance: A comparison of cortico-cortical communication in experts and novices." The authors calculated coherence and phase angles among the prefrontal (F3, F4) and ipsilateral cortical regions (central, temporal, parietal, occipital) during the aiming period and observed that the experts generally exhibited lower coherence compared to the novices, with the effect most prominent in the right hemisphere. This finding is relevant to that of reduced activation in the right parietal region as reported by others and supports a refinement of visual-spatial input into the motor planning processes in such fine motor skill execution. Furthermore, the coherence estimates were positively related to aiming movement or variability in the trajectory of experts such that reduced "traffic" to the frontal region was associated with a stable trajectory.

One of the limitations of the literature reported so far is the self-paced nature of the tasks employed in most of the investigations (e.g., golf and marksmanship). In a study of expert-novice brain processes during a reactive-type sport, Hung et al. (2004) conducted a study titled "Assessment of reactive motor performance with event-related brain potentials: Attention processes in elite table tennis players." Motor readiness, visual attention, and reaction time (RT) were assessed in elite table tennis players relative to novices during Posner's cued attention task. In this task, participants must react to one of two visual stimuli that are presented simultaneously and preceded by a directional cue that predicts the imperative stimulus with 80% accuracy. Both hands are employed and used to react to the imperative stimulus on the corresponding side. As such, the participant must anticipate reacting as quickly as possible with the appropriate hand without getting "faked" by the directional arrow. One would guess that elite table tennis players would excel at this task. Motor readiness of the hands was measured by the lateralized readiness potentials (LRP) that were derived from contingent negative variation (CNV) at the homologous sites C3 and C4 located on the primary motor cortex. The CNV were elicited between presentation of directional cueing (S1) and the appearance of the imperative stimulus (S2), and preparation for a right-hand movement would reveal as heightened amplitude on the left or contralateral cortex. Visual attention was assessed from P1 and N1 component amplitudes derived from occipital event-related potentials (ERPs) in response to S2. In this manner, one could discern hand preparation and the attentional spotlight for the participant's vision. As expected, the results revealed that both groups were faster in response to validly cued stimuli, but the athletes were faster than the controls for both validly and invalidly cued stimuli. The EEG measures revealed that the athletes generated larger LRPs to prepare the hand for quick response to the side of the cued location while at the same time directing greater visual attention for movement to the side of the uncued location, the latter which defines an inverse cueing effect for N1 amplitude (i.e., amplitude of N1 to the uncued stimulus > amplitude of N1 to the cued stimulus). The control subjects visually attended to both locations equally. The authors concluded that expert table tennis players "preserve superior reactivity to stimuli of uncertain location by employing a compensatory strategy to prepare their motor response to an event associated with high probability, while simultaneously devoting more visual attention to an upcoming event of lower probability" (p. 317). Such a diversified attentional investment strategy by the experts is highly adaptive to avoid being taken by surprise or influenced by attempted efforts to fake movements by an opponent. Although spectral analysis was not reported, it would be interesting to assess whether such a smart strategic effort was also associated with neural and psychomotor efficiency. If so, one can see how the brain processes could provide a remarkable advantage to orchestrate fast and high-quality movements to overtake an opponent!

Practice-Induced Changes in Brain Dynamics

Although important insights of the brain processes underlying skilled motor behavior can be drawn from the expert-novice contrast, longitudinal design involves practice in understanding the development and refinement of these processes.

To investigate changes in brain dynamics during skill acquisition, Kerick, Douglass, and Hatfield (2004) monitored alpha band activity from the EEG signal of 11 individuals at the beginning and end of a 12-week training period, during which they learned the skill of pistol shooting. Seeking to extend previous expert-novice comparisons by Hatfield and colleagues (Haufler, Spalding, Santa Maria, & Hatfield, 2000; Janelle, Hillman, Apparies, Murray, Meili, Fallon, & Hatfield, 2000), it was predicted that as the skill of shooting was acquired through the training period, high-alpha power in the seconds preceding trigger pull would increase in the left temporal region, indicating a reduction of task-related verbal-analytical processes. These predictions were validated via observations of increased high-alpha power from pre- to post-training in the seconds prior to trigger pull in both the shooting condition, during which participants attempted shots on a target, and the postural condition, during which participants maintained the shooting posture aiming the pistol down sight toward the target. This is in contrast to no change in left temporal high-alpha power in a standing control condition from pre- to post-training, during which the participant simply gazed at the target. Additionally, increases in high-alpha power during shooting due to practice were not only limited to left temporal regions but were more widespread throughout the cortex, indicating a more global reduction in task-related cortical activation under conditions of task performance. The authors argued that the refinement in cortical dynamics was likely due to improved sensorimotor integration and a reduction of mental workload due to increased automaticity. Indeed, it has been shown that various features of the spectral-domain of the EEG signal, including alpha band activity, are indicative of mental workload (Jaquess et al., 2017). This finding is supportive of the literature that mental workload during task performance is reduced as a result of increased task learning, resulting in neural efficiency. See Figure 23.9. Note that the brain maps become progressively lighter in shade over the 6 s prior to the trigger pull (i.e., 0 s) after 3 months of practice (Time 3), relative to the progressive change observed at the beginning of training (Time 1), indicating higher levels of EEG alpha power and cortical relaxation as the trigger pull is approached.

Although reduced brain activation would seem to be a desirable characteristic of superior motor performance it also depends on the stage of the learner. Although neural and psychomotor efficiency emerge with extended practice, those at the early stages of learning need to effortfully engage with the task demands to improve. This was clearly demonstrated in a recent study by Gallicchio

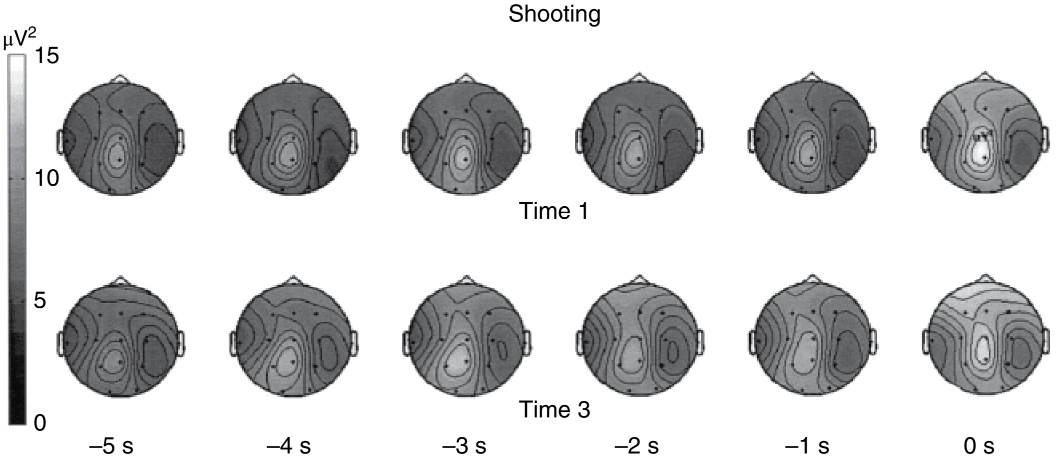

Figure 23.9 Topographical maps of event-related alpha power (ERAP) for successive 1 s periods during baseline and target shooting before (Time 1) and after (Time 3) marksmanship training. The magnitude of alpha power is indicated by the scaling bars illustrated on the left side of the figure. From Kerick, Douglass, and Hatfield (2004). Reproduced with permission of Elsevier.

et al. (2017), who examined the influence of practice of a putting task on brain processes (i.e., EEG alpha power and connectivity between T3 and Fz) and performance through employment of a longitudinal design with a group of recreational golfers (age: M 21 years; handicap: M 23) before and after three practice sessions. As expected, performance did improve, but contrary to expectation, the results revealed increased cortical activation and elevated connectivity. However, a mediation analysis revealed a "gating" on the increased brain activity such that those who constrained the increase of cortical activation, as well as the connectivity between T3 and Fz, exhibited the best performance. The finding makes sense in that the global increase in brain activity was likely due to greater engagement with the task demands during the practice trials. This seems particularly so regarding the connectivity between the left temporal and motor planning regions, as the former would likely be engaged in explicit monitoring of the movement because of conscious effort to improve performance. Importantly, the authors concluded support for psychomotor efficiency since the "increased efficiency was manifested at the neurophysiological level as selective inhibition and functional isolation of task-irrelevant cortical regions (temporal regions) and concomitant functional activation of task-relevant regions (central regions). These findings provide preliminary evidence for the development of greater psychomotor efficiency with practice in a precision aiming task" (p. 89).

The importance of the network connectivity between the left temporal region, which underlies verbal-analytic declarative processes as well as explicit monitoring of movement, and the prefrontal motor planning region was underscored by Zhu and colleagues (2011). Their findings support a reduction in cortico-cortical communication or refinement of neural activity with practice of the golf putt. Supporting evidence was provided in an earlier study by Deeny et al. (2003), who reported reduced connectivity, as measured by EEG coherence, between the left temporal cortex and prefrontal region in expert competitive marksmen during the aiming period as compared to those who performed less well in competition.

Further support of psychomotor efficiency was offered by Gentili et al. (2015), who examined cortical dynamics during a cognitive-motor adaptation task that required inhibition of a familiar motor plan—that is, learning a new visuomotor mapping to visual distortion when reaching to target stimuli. EEG coherence between the motor planning (Fz) and left hemispheric region was progressively reduced over trials (low-beta, high-beta, gamma bands) along with faster, straighter reaching movements during both planning and execution. The major reduction in coherence (delta, low/high-theta, low/high-alpha bands) between Fz and the left prefrontal region during both movement planning and execution suggests gradual disengagement of the frontal executive following its initial role in the suppression of established visuomotor maps. The reduction of cortico-cortical communication, particularly in the frontal region, and the strategic feedback/feedforward mode shift translated as higher quality motor performance. This study extends our understanding of the role of the frontal executive beyond purely cognitive tasks to cognitive-motor tasks. The efficiency of connectivity was robustly reflected in improved kinematics of the pointing movement such that by late adaptation, movement trajectories were faster, straighter, and with a level of error like early exposure. Compared to the early adaptation stage, movement time, movement length, and the root mean square of the error were significantly smaller during late adaptation.

Based on these findings, it would be informative to extend such a longitudinal design to multiple practice sessions over many weeks or months in a group of novice golfers, as reported by Kerick et al. (2004) with novice marksmen, to determine the dynamic trajectory of cortical change. In accord with the stages outlined in the human performance theory (i.e., cognition through automaticity), it may be that an inverted-U pattern between brain activity and the volume of practice is revealed.

A novel approach to the study of neural efficiency was taken recently by Rietschel et al. (2014) based on the assessment of attention reserve described earlier by Miller et al. (2011) using ERPs to novel sounds during practice of a task. Rietschel et al. sought to extend the work of Kerick et al. (2004) by investigating changes in attentional reserve during motor learning, specifically motor adaptation. Participants performed a task in which they were instructed to perform a reaching task using their non-dominant hand under conditions of distorted visual feedback to which they had to adapt. The goal of the task was to reach for the target as quickly and accurately as possible from a predefined starting position. During adaptation, participants passively listened to auditory probes of "novel" sounds (Fabiani, Kazmerski, Cycowicz, & Friedman, 1996) to elicit ERPs. The P3a, or "novelty P3," component of the ERP waveform is thought to reflect the involuntary orienting of attention and has been related to attentional reserve (Jaquess et al., 2017). Initially, participants performed poorly at the task as a result of the distorted visual feedback, and P3a amplitudes were low, indicating a lack of attentional reserve. However, as participants adapted to the distortion, not only did performance improve, but the amplitude of the P3a component increased, indicating an elevation in attentional reserve over the course of the experiment as shown in Figure 23.10. This change is highlighted by the fact that the control group, who experienced no visual distortion during the task, displayed no change in performance or P3a amplitude.

Based on the studies reported above and those that are reported in Table 23.2, which includes the results of studies on expert-novice contrasts and practice-induced changes in brain dynamics, it seems that there is solid support for economy and minimization of non-essential processes as one becomes more skilled. Such adaptations likely facilitate the fast and instinctive muscle actions or movements of the high-level performer during performance (e.g., Walter Payton) as well as the graceful and fluid movement that characterize the beauty of their movements (e.g., Red Grange).

In addition to traditional forms of cognitive-motor practice, attaining the expert brain state may be accelerated through employment of mental training and technology to facilitate learning. One notable methodology in mental

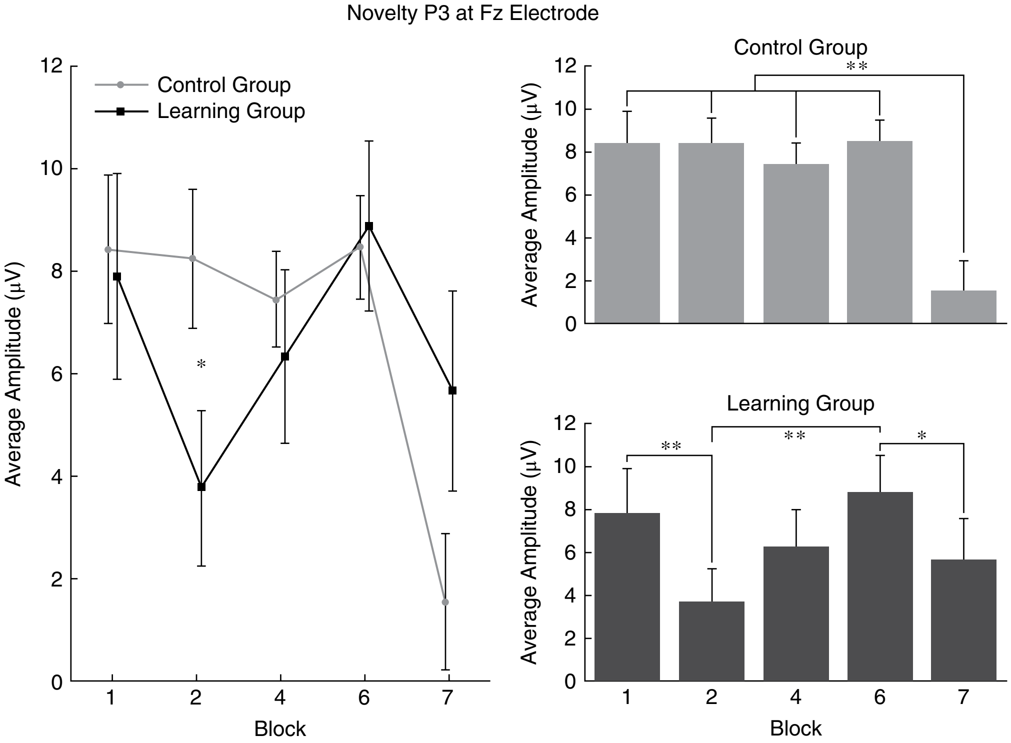

Figure 23.10 Novelty P3 amplitude changes over the course of training relative to a control group who received no training. From Rietschel et al. (2014). Reproduced with permission of Elsevier.

Table 23.2 List of relevant references of expert-novice comparisons and practice studies related to athletic performance. Inclusion criteria are as follows: directly relevant to athletic/sport performance, featured neuroimaging, published during or after 2005.

Expert-novice Contrasts	Task	Imaging modality	Finding
Baumeister, Reinecke, Liesen, & Weiss, 2008	Golf putting	EEG	Neural efficiency, Net efficiency
Del Percio, C., Babiloni, C., Bertollo, M., Marzano, N., Iacoboni, M., et al., 2009	Marksmanship	EEG	Neural efficiency
Del Percio, Iacoboni, Lizio, Marzano, Infarinato, et al., 2011	Marksmanship	EEG	Neural efficiency, Net efficiency
Deeny, Haufler, Saffer, & Hatfield, 2009	Marksmanship	EEG	Psychomotor efficiency, Net efficiency
Milton, Solodkin, Hluštík, & Small, 2007	Golf putting	fMRI/BOLD	Neural efficiency, Psychomotor efficiency, Net efficiency
Wright, Bishop, Jackson, & Abernethy, 2010	Badminton shot anticipation	fMRI/BOLD	Net efficiency
Kim et al., 2008	Archery	fMRI/BOLD	Psychomotor efficiency, Net efficiency
Tomasino, Maieron, Guatto, Fabbro, & Rumiati, 2013	Action judgment (volleyball)	fMRI/BOLD	Psychomotor efficiency
Wei & Luo, 2010	Imagery (diving)	fMRI/BOLD	Net efficiency
Del Percio, Brancucci, Vecchio, Marzano, Pirritano, et al., 2007	Image recognition (karate)	EEG	Neural efficiency
Doppelmayr, Finkenzeller, & Sauseng, 2008	Marksmanship	EEG	Net efficiency
Guo, Li, & Yu, 2017	Target recognition (table tennis)	fMRI/BOLD	Neural efficiency
Babiloni, Marzano, Infarinato, Iacoboni, Rizza, et al., 2010	Action judgment (karate)	EEG	Neural efficiency
Nakamoto & Mori, 2012	Target interception (baseball)	ERP	Net efficiency
Practice	**Task**	**Imaging modality**	**Finding**
Gallicchio, Cooke, & Ring (2017)	Golf putting	EEG	Psychomotor efficiency
Rietschel, McDonald, Goodman, Miller, Jones-Lush, et al., 2014	Reaching	EEG	Neural efficiency, Psychomotor efficiency
Choe, Coffman, Bergstedt, Ziegler, & Phillips, 2016	Flight simulation	EEG & fNIRS	Net efficiency
Gentili, Bradberry, Oh, Costanzo, Kerick, et al., 2015	Reaching	EEG	Psychomotor efficiency
Ikegami & Taga, 2008	Kendama	fNIRS	Psychomotor efficiency

training is that of mental imagery. Yao et al. (2013) recently employed movement-related brain potentials to further understand the mechanisms through which such training impacts physical performance. They observed that with increases in muscular strength of the biceps brachii, there were increases in amplitude of the motor-related cortical potential (MRCP) recorded from the contralateral motor cortex. For more direct modulation of neural activity, transcranial direct current stimulation (tDCS) has been shown to be effective for facilitation of learning in airplane pilots (Choe et al., 2016). In addition, neurofeedback in various forms, typically EEG, have supported a causal link between cortical activation and motor performance, such as target shooting. Landers et al. (1991) conducted one of the earliest studies in which biofeedback was used to alter brain activity in an attempt to facilitate archery performance. A recent review by Mirifar et al. (2017) summarizes the literature on neurofeedback as supplementary training for the optimization of athletic performance and provides implications for future research. Based on the literature to date, it would seem that self-regulation of the activity in the left temporal region (T3), as well as the global topography, accompanied by attenuation of connectivity between T3 and the fronto-central motor planning regions would be promising for performance enhancement. A study by Hung (2009) subscribed to this approach by regulation of T3 EEG alpha power in elite pistol shooters who underwent 16 sessions of neurofeedback training and subsequently showed significant improvement in target shooting accuracy as well as overall neural efficiency. The finding of elevated performance in such high-level athletes by thoughtful application of neurofeedback is compelling both for the science of cognitive-motor performance and for practical translation to training and coaching!

Impact of Mental Stress on Brain Dynamics and Performance

Many times, motor performance occurs in a social context involving competition and mental stress and is particularly problematic for those plagued by competitive trait anxiety. In essence, one could speculate that stress reverses the brain state associated with superior performance from that of automaticity and efficiency to a more novice-like state associated with cognitive analysis and explicit monitoring of performance (i.e., a reversion model). Consistent with this view, Masters and Maxwell (2008) reviewed the relevant literature and described the impact of conscious attention to movement via Reinvestment Theory (Masters, 1992; Masters, Polman, & Hammond, 1993), which "suggests that relatively automated motor processes can be disrupted if they are run using consciously accessed, task-relevant declarative knowledge to control the mechanics of the movements on-line. Reinvestment Theory argues that the propensity for consciousness to control movements on-line is a function of individual personality differences, specific contexts and a broad range of contingent events that can be psychological, physiological, environmental or even mechanical" (p. 160).

Based on this theory, one could argue that the brain will become inefficient as a result of mental stress and which would revert to heightened cortical activity and elevated connectivity, possibly due to "overthinking." Support for this notion was recently provided by Hatfield et al. (2013) in a study of competition and the impact on brain processes and pistol shooting performance titled "The influence of social evaluation on cerebral cortical activity and motor performance: A study of 'Real-Life' competition," in which motor performance in a social-evaluative environment was examined in participants who completed a pistol shooting task under both performance-alone and competitive conditions. EEG, autonomic, and psychoendocrine activity were recorded in addition to kinematic measures of the aiming behavior, and the results revealed that state anxiety, heart rate, and cortisol were modestly elevated during competition accompanied by relative desynchrony of high-alpha power as shown in Figure 23.11, increased cortico-cortical communication between motor and non-motor regions, and degradation

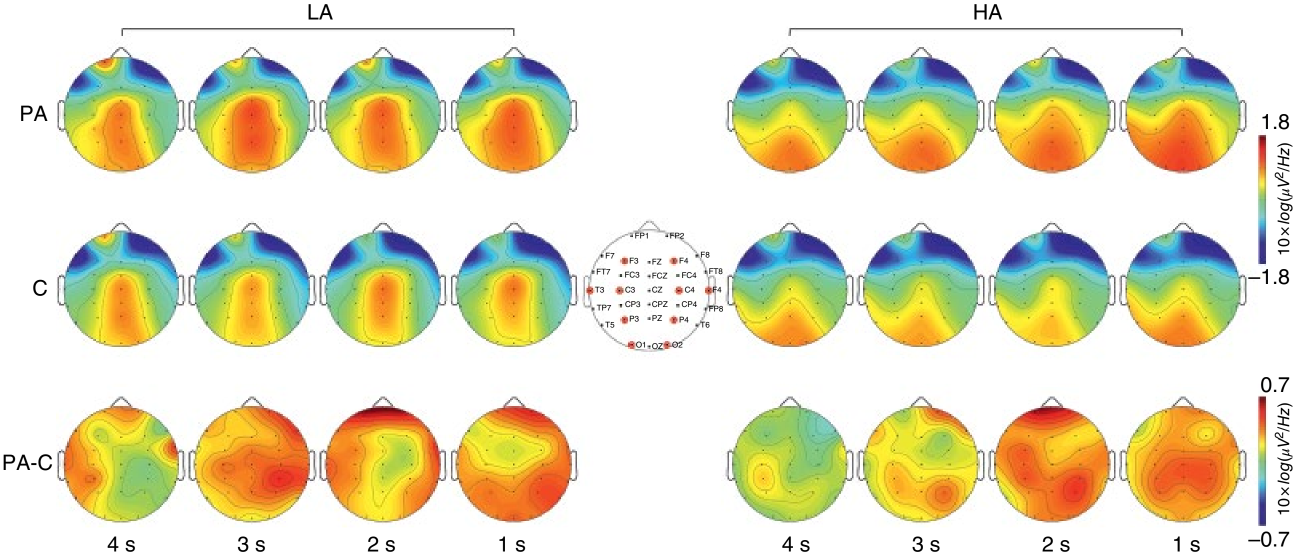

Figure 23.11 Low-alpha (LA, 8—10 Hz) and high-alpha (HA, 10–13 Hz) power during performance alone (PA) and competition (C) averaged across trials and subjects from four seconds before trigger pull (4 s) to the final second before trigger pull (1 s). PA-C represents the difference between condition topographic scalp maps (PA minus C). From Hatfield et al. (2013). Reproduced with permission of Elsevier.

of the fluency of the aiming trajectory, but maintenance of performance outcome (i.e., score). In support of the predictions the findings reveal that cognitive-motor performance in a complex social evaluative environment, characterized by competition, results in elevated cortical activity beyond that essentially required for motor performance that translated as less-efficient motor behavior. The findings of Hatfield et al. (2013) were complemented by those of Oh et al. (2013), who reported an increase in the number of neural sources, based on employment of Low-Resolution Electromagnetic Brain Tomography (LORETA) (Pascual-Marqui, Michel, & Lehmann, 1994), during competition, which would again support a stress-induced noisy and inefficient state.

Basically, it appears that stress manifests as heightened cognitive load, which can alter the quality of motor performance. This is clearly supported by the classic work of Beuter and Duda (1985) and that of Weinberg and Hunt (1976). The former study showed that kinematic qualities of gait were marked by a decrease in efficiency of motion in the lower limbs of young children who were subjected to a stressful intervention resulting in increased psychological arousal. The authors state that the task of stepping, which was controlled automatically in a low-stress condition, became less smooth and efficient as volitional control took over under high stress. In a similar vein, Weinberg and Hunt observed heightened motor unit activation and co-contraction (loss of reciprocal inhibition in the antagonists) of the involved muscles in an overhead throwing motion in college students who were also subjected to mental stress. As such, the link between cognitive-affective states and the quality of motor performance seems causal in nature, but the central mechanisms of effect from such studies are unclear and may be due to heightened "cross-talk" between cortical association and motor regions as described in Section 6 on the impact of mental stress. Less reliance on feature detection of environmental cues and refinement of strategic neural processes with experience seems entirely consistent with the formation of a memory-based internal model that guides skillful movement (Bell & Fox, 1996; Contreras-Vidal & Buch, 2003; Contreras-Vidal et al., 1997; Kinsbourne, 1982).

Rebert, Low, and Larsen (1984) published a classic report on EEG alpha power in the left temporal and parietal regions recorded during the performance of a video game that also demanded intense visual-spatial processing. Remarkably, the participants exhibited increasing right temporal activation during the rallies (in this report, asymmetry metrics were employed by which increasing magnitude implied relative right hemispheric activation), which began to decline or reversed direction just prior to the commission of an error that terminated the rally. Of note, the temporal and parietal asymmetry profiles that were observed during the rallies were absent during the intervening rest intervals when the subjects were not actively engaged with the visual-spatial processes as demanded during the rallies. Again, it may be inferred that the move toward increased left temporal activation (increased verbal-analytic processing), observed in the participants just prior to initiation of error, resulted in an attentive state that was inconsistent with the task demands of the video game. Although speculative, such an incongruent state may have interfered with the essential visuomotor processes and could be described as "overthinking" the task demands, resulting in "choking."

In an early study, Deeny, Hillman, Janelle, and Hatfield (2003) extended the work of Busk and Galbraith (1975) by assessing coherence estimates in skilled marksmen between motor planning (Fz) and association regions of the brain by monitoring EEG at sites F3, F4, T3, T4, P3, Pz, and P4 as well as the motor cortex (C3, Cz, C4) and visual areas (Ol and O2). More specifically, EEG coherence was assessed during the aiming period just prior to trigger pull in two groups of participants who were similar in terms of years of training but differed in competitive performance history. One group was labeled experts and exhibited superior performance during competition; the other group was labeled skilled shooters and was characterized by relatively poor performance during the stress of competition. Both groups were highly experienced (approximately 18 years). Given that specialization of cortical function occurs as domain-specific expertise increases, experts were predicted to exhibit less cortico-cortical communication, especially between the cognitive and motor areas, relative to that observed in the lesser skilled group. The primary analysis involved a comparison between the groups of the coherence estimates between Fz and the lateral sites examined in each hemisphere. Interestingly, in terms of alpha band coherence, there were no differences between the groups at any site except for the Fz-T3 pairing in the left hemisphere, at which the experts revealed significantly lower values. Lowered coherence between Fz-T3 in the experts was also observed for the beta band. The authors concluded that the experts could limit or reduce the communication between verbal-analytic and motor control processing. On a more global level, this finding would imply that those who performed better in competition did not overthink during the critical aiming period. Again, the potential importance of this refined networking in the cerebral cortex in regard to superior motor behavior is the reduction of potential interference from irrelevant associative, affective (e.g., limbic), and executive processes with the motor loop (basal ganglia) connections to the motor cortex that largely controls corticospinal outflow and the resultant quality of the motor unit activation (Grafton, Hari, & Salenius, 2000). Excessive networking may result in undesirable alterations in the kinematic qualities of limb movement. Conversely, refinement or economy of cortical activation would more likely result in smooth, fluid, graceful, and efficient movement. Any reduction of associative networking with motor control processes would also help to reduce the complexity of motor planning and should result in greater consistency of performance.

Finally, there are individual differences in reactivity of the amygdalae in response to stressful events based on genetic factors. Variation in anxiety-related personality traits is 40–60% heritable. The dysregulation of cortical processes with presentation of stress may be particularly problematic for carriers of the short alleles of the serotonin (5-HT) transporter gene (5-HTT), as this gene variant is strongly associated with hyperactivity of the amygdalae during emotional tasks (Hariri et al., 2002). The polymorphism has been identified in the transcriptional control region of the 5-HTT gene such that a long promoter allele (L) is associated with transcriptional efficiency while the short allele (S) is associated with transcriptional deficiency. According to Lesch et al. (1996) "genotyping of approximately 500 individuals revealed allele frequencies for the L and S types of 57% and 43%, respectively with S dominant. The genotypes are distributed according to the Hardy-Weinberg equilibrium as follows: LL—32%, LS—49%, and SS—19%." As such, there is a high degree of prevalence of this anxiogenic S allele. The S-type allele of the 5-HTT promoter region holds significant implications for information processing and motor control and is a critical component of a proposed individual differences model of the stress response. A more efficient response to stress would lead to enhanced information processing, more decisive decision making, and improved coordination of motor skills (a more adaptive response to the stimuli). S carriers may be considered "stress-prone" while L carriers may be considered "stress-regulators." Recently, it has been well documented that the promoter region of the serotonin transporter gene on chromosome is polymorphic such that those with the short allele (about 50% of population) show heightened activation of the amygdalae to emotion-eliciting stimuli while those carrying the long allele show attenuation of fear (Hariri et al., 2002). This would imply that frontally mediated executive control of the "fear circuit" is critical for a large segment of the population who are predisposed to be especially reactive to emotion-eliciting stimuli. In addition to such biologically based differences in anxiety response, genetic variation or polymorphism in neurotrophic factors such as brain-derived neurotrophic factor (BDNF) and nerve growth factor (NGF) would imply that some individuals could experience adaptive alterations in the brain due to neural plasticity from practice and performance more so than others. This would imply that some individuals have an advantage in altering the architecture of the central nervous system to reap any benefits from practice and training such as efficiency of neural networks.

Model of Stress-Induced Cortical Dynamics

Consistent with the cognitive-affective-motor neuroscience model of human performance, Figure 23.12 provides an illustration of the processes and outcomes underlying stress reactivity and integrates affective and cognitive activity with motor performance. A central tenet is that lack of frontal executive control over subcortical processes would result in heightened emotional influence (limbic structures) that, in turn, disrupts higher cortical

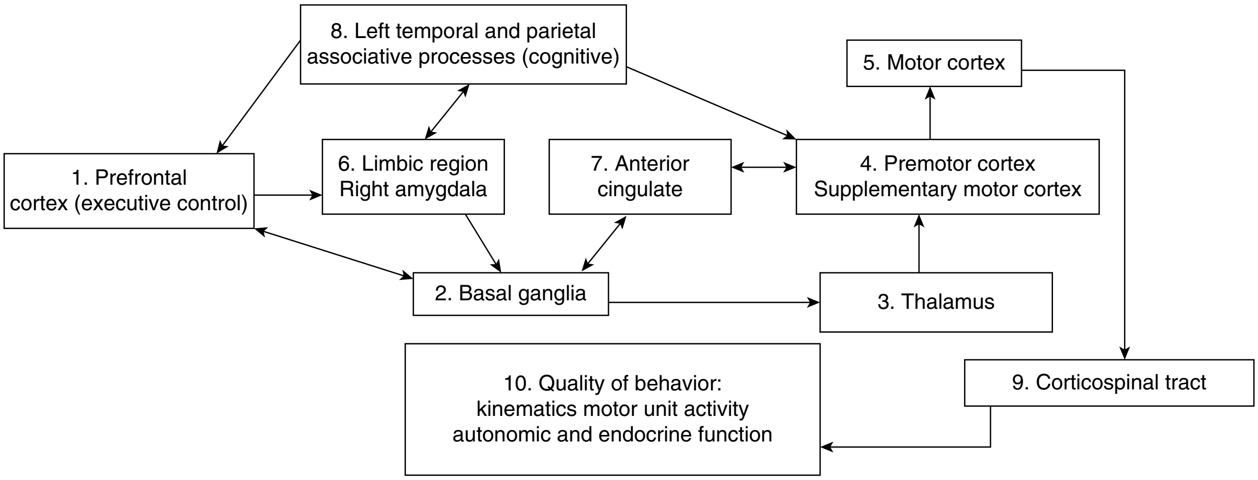

Figure 23.12 Flowchart of stress-related brain processes (taken from Hatfield and Kerick, 2007). Reproduced with permission of John Wiley and Sons.

association processes that result in alterations in the activation of the motor loop—the fronto-basal ganglia structures that initiate and execute movement. Such dysregulation interferes with attention and the motor loop connections (i.e., basal ganglia) to the motor cortex that largely control corticospinal outflow and the resultant quality of the motor unit activation (Grafton et al., 2000). Excessive networking in the cortex may result in undesirable alterations in information processing as well as inconsistency of motor performance. In this manner, the motor cortex becomes “busy” with excessive input from limbic processes via increased neocortical activity in the left hemisphere and then inconsistent motor behavior would likely result (Deeny et al., 2003). Refinement or economy of cortical activation would more likely result in enhanced attention and smooth, fluid, graceful, and efficient movement. Any reduction of associative networking with motor control processes would also help to reduce the complexity of motor planning and should result in greater consistency of performance.

According to this model, individuals under high stress will exhibit reductions in prefrontal asymmetry (box 1) compared to a low-stress condition, implying a lack of executive control over the fronto-meso-limbic circuit. Consequently, participants will experience heightened activation of the limbic region (amygdalae) (box 6). The resultant emotional reactivity, in turn, will result in EEG alpha desynchrony, particularly in the left temporal (T3) and parietal (P3) regions (box 8) along with increased cortico-cortical communication between these regions and the motor planning centers (box 4). Such dysregulation of the cerebral cortex will be expressed as inconsistent input to the motor loop (boxes 2 through 5) resulting in degraded corticospinal output and performance (motor unit activity—trigger pull—boxes 9 and 10). It is well established that attention capacity shrinks with arousal and, consistent with this notion, the excessive cortico-cortical networking during heightened stress, as proposed here, would compromise information processing (Easterbrook, 1959). In addition, cardiovascular activity (vagal tone) will be inversely related to the activity in the CNS such that vagal tone will be reduced in the high-stress condition. Cortisol levels will rise. The magnitude of change specified in the model will be related to degradation in performance (i.e., slower and inaccurate).

Brain Processes Underlying Resilience to Mental Stress

Although mental stress can disrupt the involved brain processes and degrade motor performance, some individuals seem impervious to its effects. This may be largely due to perception and the athlete’s cognitive appraisal of the environment. Elite athletes are experts in their chosen sport and thus must be not only adept in the motor domain but must be resilient to performing under the stress of high-level competition. Such stability of performance suggests this population processes emotion and mental stress in an adaptive and efficient manner. Wulf (2013) reported that “over the past 15 years, research on the focus of attention has consistently demonstrated that an external focus (i.e., on the movement effect) enhances motor performance and learning relative to an internal focus (i.e., on body movements)” (p.77). Such a notion was even reflected in the early work of Fenz and Epstein (1967) in their classic work with sport parachutists. They obtained continuous recordings of skin conductance, heart rate, and respiration rate from experienced and novice parachutists during a sequence of events leading up to and following a jump. The novice jumpers showed a sharp elevation in physiological activity up to the final altitude just before jumping from the plane compared to experienced jumpers who produced an inverted V-shaped curve. Importantly, Fenz noted an external focus of attention in the experienced jumpers, while the less-experienced engaged in an internally directed focus with ruminating thoughts of personal harm. More recent support for the role of perception comes from the work of Ochsner and Gross (2008), who articulated the importance of cognitive reappraisal in the management of emotional responsivity to mental stress. Cognitive reappraisal is the interpretation of one’s environment in positive terms. For example, an impending competition may be interpreted as a threat by some but an opportunity to exhibit the proficiency of their skill by others.

An excellent example of the role of reappraisal in the ability to perform under pressure was reported recently by Costanzo et al. (2016). This study sought to determine if NCAA Division I Football Bowl Subdivision athletes with a history of successful performance under circumstances of mental stress (i.e., competition) demonstrate neural efficiency during affective challenge compared to age-matched controls. Using functional magnetic resonance imaging, the BOLD response was recorded during emotional challenge induced by unpleasant (1) sport-specific and (2) general International Affective Picture System (IAPS) (Lang et al., 2008) images. The athletes demonstrated neural efficiency in brain regions critical to emotion regulation (prefrontal cortex) and affect (insula and amygdalae) independently of their sport-specific expertise, suggesting adaptive processing of negative events and less emotional reactivity to unpleasant stimuli. Such efficiency of affective response would result in less overall activation in the brain and prevent disruption of motor processes. In this manner, a “cool” mind would contribute to neural efficiency, psychomotor efficiency, and high-quality motor performance.

Moreover, Costanzo (2011) implemented a protocol developed by Ochsner and Gross (2008) to determine the efficacy of emotion regulation in the football players. Prior to the neuroimaging trials to assess the brain activity related to emotion regulation, the participants were taught how to evoke a positive cognitive reappraisal strategy. Subsequently, they were shown a series of emotion-eliciting scenarios. Half of the trials, in which the scenarios were presented, were preceded by a visual cue to elicit the acquired reappraisal strategy, and the other half were uncued trials to which the participants responded spontaneously or instinctively. The brain responses of the football players to the sport-specific images indicated no difference between their natural response to emotional challenge and that observed during the cued cognitive reappraisal trials. However, the brain responses of the football players to the general images were differentiated between their natural response to emotional challenge and that observed during the cued cognitive reappraisal trials, which supports a domain-specific adaptation (SAID)—i.e., a learned response (see Figure 23.13). That is, they instinctively engaged in a strategy that managed emotional reactivity and reflected in lower BOLD in the amygdalae relative to that observed in controls when presented sport-specific negative emotion-eliciting images.

Another emotion regulation study by Paulus et al. (2010) was conducted with Navy Sea, Air, and Land Forces (SEALs) to determine how they cope with remarkable levels of stress. The participants were challenged with a simple emotion face-processing task (i.e., angry and positive type images) during fMRI while critical brain structures related to emotion were assessed for BOLD response. Navy SEALs exhibited greater BOLD response bilaterally in the insula to the angry stimuli compared to the happy stimuli. These findings support neural efficiency in that the elite warfighters directed greater neural responses toward threat-related stimuli, which implies that in general the elite warfighters engaged a strategy for emotion regulation characterized by more focused neural activation. Accordingly, Paulus et al. (2010) concluded that “greater neural processing resources are directed toward threat stimuli and processing resources are conserved when facing a non-threat stimulus situation” (p. e10096).

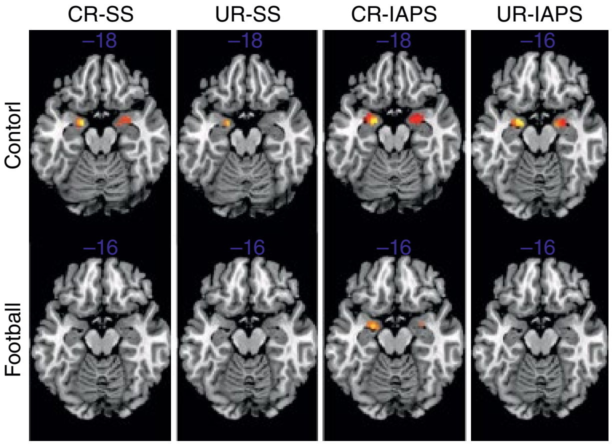

Figure 23.13 MRI slices of BOLD response of the amygdalae ROI; CR-SS, cued response to sports-specific stimuli; UR-SS, uncued response to SS; CR-IAPS, cued response to International Affective Picture System; UR-IAPS, un-cued response to IAPS. Adapted from from Costanzo (2011).

The Influence of Trust and Team Dynamics on Brain Processes and Performance

Beyond the individual factor of resilience, the social environment can also impact brain processes and performance. Many athletes perform sports and display their skill in team environments. As a result, team dynamics can be influential and often play a significant role to determine if an athlete can successfully perform tasks based on how he or she perceives the amount of support and trust from their teammates. While positive team dynamics are beneficial to superior performance simply based on self-reports, studies focused on cerebral cortical processes and attentional reserve provide neurophysiological evidence to elucidate underlying mechanisms. Miller et al. (2014) employed various EEG measures such as EEG spectral power and coherence, as well as ERPs, to investigate the effects of team dynamics on a cognitive-motor task. Participants played Tetris either without or with a teammate. Specifically, when a participant played Tetris with a teammate, the teammate’s assistance could be helpful or detrimental for the participant. As a result, three conditions were manipulated: neutral, adaptive (i.e., a good teammate), and maladaptive (bad teammate). Miller et al. observed best performance in the adaptive condition and stated that “individuals exhibited reduced cerebral cortical activation and increased attentional reserve when performing in adaptive and neutral team environments as compared with a maladaptive team environment” (p. 61). Collectively, these results suggest that adaptive team environments enhance performance without additional neural resource costs, whereas maladaptive team environments undermine performance due to elevated consumption of neural and attentional resources. Such neurophysiological evidence therefore supports the notion that positive team dynamics and trust result in psychomotor efficiency. Additionally, further work has begun to investigate brain dynamics between teammates performing a joint task in order to understand the neural bases of team dynamics (Filho et al., 2016). Such an approach is promising for the future in terms of understanding how the team environment impacts brain processes and sport performance.

Summary and Future Directions

In summary, the chapter has highlighted the study of brain processes during skilled motor performance and the impact of competition-induced stress. There is remarkable support for neural, psychomotor, and net efficiency attributed to practice and expertise, while a reversion to a less efficient noisy state emerges with the introduction of mental stress. The quality of physical movement largely translates from the brain state and can also be described as efficient or noisy as in the case of dysfluency of the aiming trajectory during marksmanship. We have also noted that both cognitive appraisals of one's environment and a supportive team environment can mitigate the disruptive impact of stress on the brain and performance. In addition, there is limited promise of technology-aided training such as neurofeedback to guide and accelerate learning and the achievement of an adaptive brain state.

But what about the future of this area of research? One of the major challenges is moving beyond the laboratory with a restricted emphasis on self-paced skills such as marksmanship and golf putting and extending the study of the brain to dynamic sport scenarios—even during competition. This will necessitate major developments in technology such as portable EEG systems with dry electrodes or sensors that eliminate burdensome preparations. Advancements in signal processing of the EEG, ECG, EMG, eye movement, and other time series will be needed to reduce movement artifact and achieve insights into the mind of the performer by the introduction of machine learning techniques. The field research conducted beyond the laboratory will be aided by the introduction of new technologies that are wearable and provide continuous data streaming for analytics to determine meaningful elements of complex data arrays. There is no question that sport psychologists and cognitive neuroscientists must team with engineers, computer scientists, mathematicians, and statisticians to advance the technology and measure the brain in action. Advances in virtual reality (VR) will help to create immersive sporting and competitive environments accompanied by progress in such imaging technologies as fNIRS, which offers hope for greater resilience to movement artifact than that of EEG. In addition, much more research in the complementary laboratory setting is needed involving imaging of deep brain structures such as the basal ganglia and amygdalae as well as the interconnectivity with critical ROIs such as the frontal lobe in light of its role in executive and emotional processes. Much more is needed in the way of team science, as mentioned earlier, but extended to biomechanicians to assess the quality of movement in tandem with the sport neuroscientist on the quality of the brain. In addition, genetic profiles are helpful as related to critical brain processes.

Finally, such advanced research will demand money/resources, and one possibility is the funding from federal agencies such as the Department of Defense, with the vested interest in human performance as well as the National Institutes of Health to fund research on the impact of stress on brain processes and motor functioning. The future is rich with possibilities, and the understanding of the critical brain processes that underlie motor learning and performance under conditions of practice and the challenges of competition and stress will yield great benefit for the sporting world and society at large.

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