CHAPTER 14

The Psychophysiology of Sport

A Mechanistic Understanding of the Psychology of Superior Performance

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J. Williams and Krane (1998) described the ideal performance state that athletes typically report in conjunction with the experience of a peak performance as follows:

- Absence of fear—no fear of failure.
- No thinking about or cognitive analysis of performance.
- A narrow focus of attention concentrated on the activity itself.
- A sense of effortlessness—an involuntary experience.
- A sense of personal control.
- A disorientation of time and space, in which the perception of time is slowed.

The ideal performance state represents the ultimate goal that applied sport psychologists attempt to achieve when delivering performance enhancement services to athletes. In phenomenological terms, the ideal performance state is characterized by an absence of negative self-talk (Meichenbaum, 1977), high self-efficacy (Feltz, 1984), an adaptive focus on task-relevant cues during the negotiation of the challenge (Landers, 1980), and a similarity to the concept of flow, as outlined by Csikszentmihalyi (1975). Such psychological constructs represent foundational issues in the scientific study of sport psychology. Attainment of the ideal performance state increases the probability that the high-level athlete will perform effectively and in a state of automaticity as defined by Fitts and Posner (1967), without interference from irrelevant cognitive and affective processes. Walter Payton, one of the premiere running backs in the history of the National Football League, reported an example of this psychological state that richly reinforces the concept of efficiency discussed throughout this chapter:

> 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 am able to 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. (qtd. in Attner, 1984, pp. 2–3).

This state seems to be characterized by efficient allocation of psychological resources such that the athlete's thoughts are limited to task-relevant processes. Conceptually, it is important to note that the mental state described earlier relies largely on activation of appropriate parts of the nervous system and on a consistent basis. It is generally agreed that expertise results from an extended duration of deliberate practice (Ericsson, Krampe, & Tesch-Römer, 1993). Furthermore, expertise appears to result from the long-term changes or adaptations in the manner in which the brain (Elbert, Pantev, Weinbruch, Rockstroh, & Taub, 1995; Issacs, Anderson, Alcantara, Black, & Greenough, 1992) and other relevant systems of the body (Selye, 1976) respond to situations. Additionally, the physical changes that result from training and conditioning, as well as the experiences of success and failure achieved in practice and competition, alter higher-level psychological constructs such as the self-image and confidence of the performer (Breger, 1974; Feltz, 1984). These phenomenological alterations may, in turn, influence the concomitant changes accruing in the central nervous system (CNS). As such, there appear to be reciprocal interrelationships among psychobiological variables at different levels of analysis that result in an optimal mental state during performance.

Such deliberate practice and effort over an extended period of time can fundamentally alter and specifically shape the involved neural processes (Bell & Fox, 1996;

Smith, McEvoy, & Gevins, 1999). Again, the fundamental neurobiological changes may emerge on a phenomenological level of analysis as a significant contributor to the confident and focused psychological state typically reported by the superior performer. Additionally, the reciprocal influences between factors at the different levels of analysis (i.e., neural and psychological) would ultimately manifest themselves in the nature of the involved motor control processes and the quality of the neuromuscular, autonomic, and endocrine action during the skilled performance (see Figure 14.1). Accordingly, an environmental challenge results in changes in cortical activity which, in turn, influences the emergent psychological state (e.g., self-efficacy, focus, mood). The psychological state then alters the resultant motor control processes (which are mediated by the motor loop), autonomic, and endocrine system functions, resulting in changes in the quality of physiological state and the resultant movement outcome.

Importantly, the changes achieved with expertise are guided by a process of adaptation that can generally be described as efficient (Sparrow, 1983). The attainment of such adaptations directly influences the quality of expression of the resultant outcome (i.e., physical performance). Therefore, one purpose of this chapter is to articulate and offer evidence for such a concept. The evidence offered herein is of a psychophysiological nature and is based primarily on electroencephalographic (EEG) studies of skilled athletes as well as participants in research who were asked to master novel psychomotor tasks. Additional studies that report peripheral measures of the psychological state (e.g., eye movement, autonomic, electromyographic) are also presented in an attempt to provide convergent evidence for the efficient psychological state.

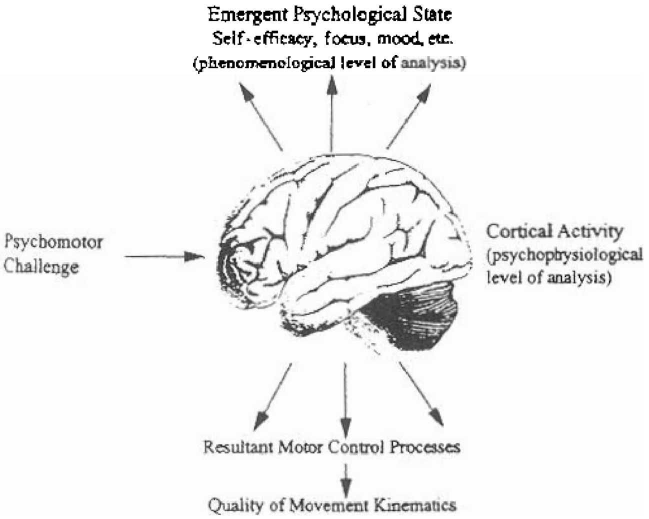

Figure 14.1 Illustration of the relationship among the neurobiological response to challenge, the emergent psychological state, and the resultant psychological processes.

SPECIFICITY OF ADAPTATION

To illustrate the principle by which changes in the brain of the expert performer may occur, analogies are offered that are based on the changes or adaptations known in other biophysical systems. The process of adaptation revolves around the principle of specificity, which suggests physiological conformity to the particular overload imposed by the constraints of a given training process (McArdle, Katch, & Katch, 1986). The goal of conformity is to achieve an efficient physiological system capable of meeting the demands of the particular task with economy of effort and reduced stress on the system. Researchers have shown that athletes conditioned for a specific aerobic activity (e.g., running) are not equally fit (as indicated by VO_2 max) for other endurance activities (e.g., cycling) when challenged with sport-specific tests of their aerobic capacity that mimic those different activities (Hoffman et al., 1993; Withers, Sherman, Miller, & Costill, 1981).

Specific metabolic adaptations also occur in the muscles recruited for the sport or exercise pursued. These adaptations are not only sport-specific (e.g., differentially involve the primary muscles involved in cycling versus running) but are metabolically specific as well (i.e., aerobic and anaerobic). McArdle et al. (1986) listed a number of physiological changes that occur in the process of aerobic training. Among these changes are an increase in capillarization, mitochondrial densify and size, and oxygen extraction capability with a concomitant increase in the capacity to generate adenosine triphosphate (ATP). Furthermore, there are increases in the ability to mobilize and oxidize fat and carbohydrates as energy substrate, as well as increases in heart size (i.e., both weight and volume), stroke volume, and cardiac output. Different adaptations occur with anaerobic training. All of the aerobic and anaerobic adaptations occur with overload training so as to create a more efficient system that is uniquely capable of responding to a specific demand with the most adaptive resources possible, while reducing strain on the system. Such a process also occurs in the brain.

Accordingly, in terms of central neural structures, Isaacs and colleagues (1992) noted a differential angiogenic effect in rats' cerebellum based on the type of physical activity involvement to which they were customarily subjected. Specifically, they noted that aerobically trained rats (i.e., engaged in treadmill and wheel running) exhibited shorter diffusion distances from blood vessels in the molecular layer of the paramedian lobule relative to sedentary controls and acrobatically trained rats (i.e., engaged in obstacle maneuvering and motor skill learning). The latter group experienced an increase in the volume of the molecular layer per Purkinje neuron that was complemented by a vascularization effect that maintained the diffusion distance. Elbert et al. (1995) also noted a fundamental neural difference in the contralateral motor cortex between the brains of highly skilled violinists and controls such that the neural resources available for fine motor control were increased in the musicians for the hand that specifically controlled the strings of the instrument.

The process of specificity of adaptation may also extend to the psychological level of analysis. The precise matching or pairing of neural resources with task demand may help to optimize the athlete's behavioral transaction with the environment. For example, the psychological state experienced during competition may differ significantly from that associated with the practice environment. This difference may be due to novel stimuli introduced during the contest relative to the more familiar routines associated with practice. Some athletes may perform better under practice conditions because they have adapted to the familiar routines. During competition, when the stress of performance evaluation is exaggerated, the cognitive-affective state may be different from the typical style of attentional resources allocation such that the athlete is indecisive (Baumeister, 1984; Landers, 1980).

The concept of specific adaptation in the psychological realm can be extended to other areas, such as the nature of the task with which the athlete is confronted. For example, the challenges faced by a starting pitcher may differ greatly from those associated with a relief pitcher. The former role is typically characterized by a higher degree of perceived control and the latter by a lower degree of perceived control and increased uncertainty of outcome. These differences in perception may further relate to specific adaptations in cognitive management and resource allocation by the two athletes. That is, when challenged with a very uncertain and potentially critical situation in regard to the outcome of the game, the relief pitcher may be experienced in the suppression or inhibition of distracting cues. He or she may effect a matching of relevant neural resources (e.g., visual-spatial processes) with the demands of his or her position as compared to athletes who typically negotiate situations characterized by a higher degree of certainty in outcome. The precise pairing of resources with demand would serve to optimize the behavioral transaction with the environment, and the relief pitcher would be described as focused.

On the other hand, the starter may likely engage in increased verbal-analytic processing because of the novelty of the situation (i.e., one to which he or she has not specifically adapted). Self-talk, accruing from self-doubt or the overanalysis of skill execution, would likely be inconsistent with the task demands (Williams & Krane, 1998). Such a response could be described as a nonspecific allocation of neural resources to the task at hand. Furthermore, the misappropriation of resources could result in interference with the normal patterns of neural activity that precede the execution of the motor commands to the muscles involved in the execution of the pitch. This interference could alter the timing and sequencing of motor unit recruitment in the agonistic, antagonistic, and synergistic muscles so as to alter the quality of the performer's movement. To deal more effectively with the anxiety-provoking situations, it would follow from the previous discussion that the athlete would need to repeatedly confront such situations while attempting to inhibit the attendant distractions (i.e., adaptive suppression). Therefore, repeated challenge may result in reduced novelty and increased familiarity with task demands to promote a more efficient transaction with the environment.

THE PRINCIPLE OF PSYCHOMOTOR EFFICIENCY

Efficiency, which is the conservation of effort to accomplish a given interaction with the environment, would appear to be a fundamental organizing principle of the human condition. In the field of physics, efficiency is defined as:

$$\text{Efficiency} = \frac{\text{Work}}{\text{Effort}}$$

This formula has significant psychological implications when considering the nature of efficiency as the minimization of resources to successfully negotiate a challenge. It is this conservative manner that enables the organism to respond to any new or additional demands placed on it. In extreme instances, this conservation of resources acts to preserve coping resources for "surprise" demands and could result in the survival of the organism. Accordingly, any principle of behavior that is adaptive for survival would appear foundational to our nature and, therefore, exert its influence across a broad expanse of situations. Additionally, efficient allocation of resources serves to reduce strain or wear and tear on the organism. For example, in the physiological domain, efficiency is an adaptive process that is promoted by the effortful training of various physiological systems. Kraemer (1994, p. 137) discussed this notion using muscle endurance training as an example:

> Adaptations in the nervous system play a role in the early stages of endurance training. At the outset, efficiency is increased and fatigue of the contractile mechanisms delayed. The level of motor unit activation in the prime movers needed to maintain a given submaximal force decreases as skill is acquired. Additionally, improved endurance performance may also result in rotation of neural activity among synergists and among motor units within a muscle. Thus, the athlete produces more efficient locomotion during the activity with lower energy expenditure.

DeVries and Housh (1994) also subscribed to the efficiency principle when explaining the action of motor unit recruitment as a result of resistance training. That is, training was shown to result in a decrement in motor unit recruitment (as measured by integrated electromyographic activity [EMG]) when negotiating a given absolute workload relative to the magnitude of recruitment in the untrained state (DeVries, 1968). As stated earlier, this basic organizing principle can be extended to other biophysical systems as well (Sparrow, 1983). For example, Kelso, Tuller, and Harris (1983) postulated that in the nervous system, even the simplest of human movements involved many neuromuscular events overlapping in time. They suggested a need for some type of organizing principle that allowed for the appropriate sets of muscles to be activated in proper sequence, and for correct amounts of facilitation and inhibition to be applied to specific muscles for coordinated action. The coordinative structure or synergy was not viewed as merely a set of similar muscle actions at a joint, or as a reflex mechanism. Rather, it was defined as the functional grouping of muscles that spanned several joints and constrained to act as a single unit. Thus, a complex action characterized by many degrees of freedom was simplified or organized in a more efficient manner.

It should be noted that the activity that accompanies superior physical performance may not always be expressed in terms of efficiency per se but, rather, as adaptivity. As such, some performance states may be marked by relatively high levels of effort but still precisely matched or titrated to the demands of the challenge. For example, a runner sprinting for the finish at the end of a 10K competition may move in such a manner as to precisely and preferably activate the Type II fast-twitch fibers to accomplish the desired outcome. Although effort is not minimized in an absolute sense, as energy expenditure is higher than that during the earlier phases of the race, it may still be economical relative to an untrained individual who is attempting such a sprint. Furthermore, the effort is "minimized" relative to the work output at that stage of the race. Of course, during most of the competition (i.e., prior to sprinting to the finish line), the most efficient runner with the appropriate physical typology would be able to conserve motor units in such a manner as to economize motor unit recruitment relative to running pace and, therefore, maintain maximal steady-state effort. Daniels (1985) and others (D. Morgan, Daniels, Carlson, Filarski, & Landle, 1991) have discussed the adaptive notion of running economy in endurance performers in which minimization of O_2 consumption relative to absolute work is characteristic of superior endurance performers.

In terms of the application of the adaptivity and efficiency principles to the brain of the superior athlete, one can conceptualize the brain as a system of various resources and neural generators that process information in functional ways with a great diversity of function. That is, the brain has a great repertoire of resources, some for visual-spatial processing, some for logical-sequential processing, some for affective-response orchestration, and some for the spectrum of motor control resources. There are many degrees of freedom regarding the selection of mental resources. However, when the individual precisely matches the appropriate neural resources with environmental demand, an adaptive allocation of neurophysiological resources occurs that may underlie the phenomenological experience of being focused. The process of mental adaptation can be defined as the progressive psychological conformity to a given set of constraints with a concomitant reduction in apprehension, self-doubt, and any habitual cognitive tendencies incongruent with the task. Such a notion is consistent with the concept of the Iceberg Profile advanced by W. Morgan, O'Connor, Ellickson, and Bradley (1988).

The idea of mental adaptation traces its lineage back to the early theoretical position of William James (1977), who posited that learning involves the formation of habits that manifest themselves in new neural pathways of discharge through which all incoming stimuli are processed to a specific end. It is hypothesized that not only is there a formation of new neural pathways in the genesis of mental adaptation, but with this psychological conformity comes a unique reduction or inhibition of the maladaptive processes (i.e., neural noise) that act to hinder one's progress toward an adaptive task focus. Hence, the definition of efficiency in terms of minimization of neural noise during psychomotor performance can be more specifically stated as:

$$\text{Efficiency} = \frac{\text{Psychomotor behavior}}{\text{Neural resource allocation}}$$

The conceptual framework derived by Hans Selye (1976), the general adaptation syndrome (GAS), provides an ideal example of the development of such an attribute. Selye described three universal stages of response to any environmental, physical, or psychological challenge (i.e., stressor). These stages included the alarm, resistance, and exhaustion stages. The alarm stage was defined as a disruption in homeostasis. Resistance was defined by the changes or adaptations that occurred in the organism in response to repetitive challenges. The goal of such adaptive change was to minimize the disruption in homeostasis. Importantly, during the second stage of adaptation, changes occur to help the organism deal with challenges in a more efficient manner. The process of efficient allocation of resources serves to reduce the strain on the organism. Lastly, the exhaustion stage referred to a burned-out phase in which excessive chronic engagement with the stressor exceeded the adaptive capacity of the organism. In the sport sciences, D. Morgan and colleagues (1991) have studied the exhaustion stage in competitive swimmers in terms of overtraining. That is, with excessive challenge, in terms of volume and intensity of training, heightened cortisol secretion occurs, which promotes a catabolic or degradative effect on the muscles and other tissues of the body. This process results in a weakened physical state.

Extension of the GAS principle to a neurophysiological level implies that an organism, when initially confronted with a specific challenge, will respond with global neural activation involving both relevant and irrelevant cortical connections. This results in an overflow of neural communication that is relatively inefficient. With repeated challenge or increased skill level, neural organization becomes more refined. That is, relevant neural pathways are activated while irrelevant pathways are suppressed during this adaptive or learning process (Greenough, Black, & Wallace, 1987). Bell and Fox (1996) have described this phenomenon as a pruning process. Specifically, they suggested that prior to crawling onset in infants, there was an "overproduction of synapses in expectation of behavioral change" (p. 552). However, with experience, pruning of unnecessary synapses occurs, resulting in a more efficient neural adaptation. Busk and Galbraith (1975) also supported this notion with adults involved with learning a novel psychomotor task (i.e., mirror tracing). The participants in their study exhibited a high degree of cortical coherence between the visual and premotor areas of the brain during the early stages of skill acquisition. At that stage, the participants showed a high degree of similarity among different cortical regions of the brain (i.e., as measured by increased coherence or homogeneity of the EEG time series recorded at the different electrode locations). However, relative heterogeneity of regional cortical activity was observed after practice, suggesting that increased specialization occurred in cortical regions. This adaptation would allow for "less" of the cortex to negotiate the task.

In terms of organismic behavior, the physical movements of a great athletic performer, described by sportswriters and adoring fans as fluid, graceful, and smooth, can also be described on another level as efficiently matching motor unit recruitment in an optimal manner with environmental demand and behavioral intention. Furthermore, the adaptive processes that lead to brain or cerebral cortical efficiency may be captured by the phenomenological experiences reported by some athletes. Illustrating this concept is the following quote provided by Zimmerman (1979, p. 40), who reported the psychological state of an NFL running back: "No, even though I'm not thinking, I'm aware of everything. I may run sixty yards without a thought, but when I get to the end zone I can tell you where everybody was and who blocked who. And not just the guys near me but all over the field." One possible interpretation of this quote is that the athlete is experiencing specific and exclusive activation of the relevant visual-spatial resources in a virtually automatic manner to negotiate the movement of the body down the field. This primary task is accomplished while surrounded by a dynamic, potentially distracting multisensory array. It would appear that self-talk and logical analytical processing are minimized (perhaps even actively inhibited) while kinesthetic awareness and any relevant visual-motor generators are allocated and activated.

Hence, the goal of sport psychology as a behavioral science is to measure mental phenomena and attempt to relate these measures to parsimonious theoretical perspectives. In this regard, psychophysiology has been a valuable tool in unobtrusively measuring the psychological correlates of performance in real time, and psychomotor efficiency can provide a useful framework to predict the nature of the brain electrical activity in superior performers.

ELECTROENCEPHALOGRAPHY AND SKILLED PSYCHOMOTOR PERFORMANCE

A large body of empirical evidence for the principle of psychomotor efficiency can be acquired from an analysis of psychophysiological research. A wide variety of studies have examined hemispheric lateralization and regional specificity, cortical event-related potentials (ERPs), and other cortical phenomena obtainable from EEG and cortical-mapping techniques. These measures have been acquired during execution of specific skills across a broad range of behaviors and in the preparatory period just prior to execution of a self-paced task. In addition to the relative unobtrusiveness of psychophysiological measures, they provide an unbiased, objective index of psychological processes. In the first published study of this kind in the sport psychology literature, Hatfield, Landers, and Ray (1984) examined left-hemispheric and right-hemispheric activity in world-class competitive marksmen as they aimed at a target and prepared to execute shots. Hatfield et al. demonstrated that the analytical left hemisphere decreased its activation level during the preparatory sighting phase, whereas the right hemisphere (involved in visual-spatial processing) remained at a relatively higher activation level. In essence, these highly skilled athletes experienced an overall quieting of the forebrain accompanied by a shift in relative hemispheric dominance. Although the specific requirements of rifle marksmanship differ from those of other sports, marksmen are particularly useful for studying such attentive states with EEG technology because they are motionless, yet highly engaged psychologically.

Walter Payton's assertion "I don't know why I did something, I just did it" would seem consistent with the hemispheric shift phenomenon. Although it would appear, on one level, that he thought about "nothing" during a given play (i.e., analytical processing), activation of visual-spatial systems was apparently considerable. The running back position requires the ability to constantly change direction due to the changing environment on the field, and simultaneously requires the ability to allocate the fixed or limited attentional resources to process a wide array of spatially oriented cues. Such a state would enable the athlete to effectively react to changing conditions on the field. Obviously, in the case of skilled performers, it would seem that they would not need to "think about" or analyze their actions (Fitts & Posner, 1967). Such a high degree of skill may minimize engagement in negative or worrisome self-talk as well. The allocation of attention to process only the cues and cognitive activity that relate specifically to the athlete's challenge illustrates the concept of mental/psychological efficiency.

Basic Properties of Electroencephalography

To assist in understanding the available EEG literature, a brief introduction to the measure is provided here. More extensive sources of information are available elsewhere (Coles, Gratton, & Fabiani, 1990; Lawton, Hung, Saarela, & Hatfield, 1998; Ray, 1990). Neural activity in the cerebral cortex produces electrical potentials at the scalp, and the EEG is obtained as a recorded time series of the fluctuating voltages. The placement of electrodes on the scalp conforms to a standard system of locations called the international 10–20 system (Jasper, 1958). The nomenclature of the electrode sites corresponds to the underlying gross neuroanatomy of the brain. The capital letters F, T, C, P, and O, for example, designate scalp placements that correspond to frontal, temporal, central, parietal, and occipital lobes of the brain, respectively.

Functionally, each of the lobes is associated with specific processes. The frontal lobes are associated with higher-order functions such as language, emotion, and motor planning. The temporal lobes house auditory processing and concept formation. The central region mainly involves motor execution. The parietal lobes are associated with sensorimotor function as well as cognition and perception, and the occipital lobes regulate basic visual processes. These cortical locations are further distinguished by subscripts. Sites designated with the subscript letter z are situated on the midline of the scalp (i.e., proceeding from rostral to caudal). Sites designated with numerical subscripts indicate lateral locations. Odd numbers indicate left hemisphere sites and even numbers indicate right hemisphere sites. Higher numbers indicate greater distance from the midline (see Figure 14.2).

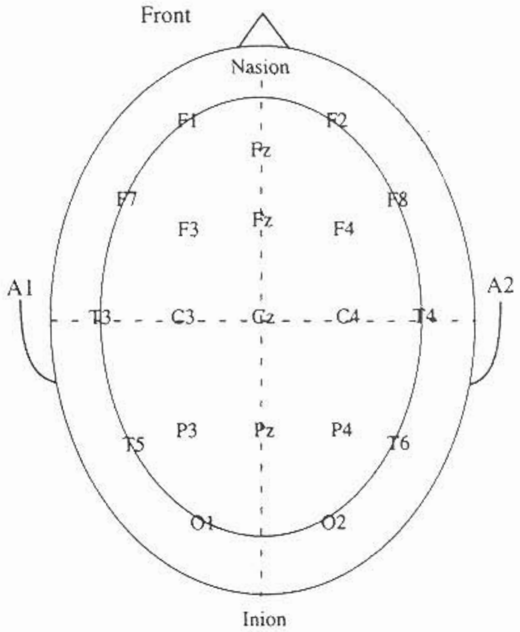

Figure 14.2 International 10-20 standard electrode placements for EEG data collection.

The EEG represents a record or time series of continuously fluctuating changes in electrical potentials across time. The recording represents the instantaneous difference in electrical potentials between two electrodes, with one of the electrodes situated on an area of the scalp overlying the brain and the other placed on a "neutral" or reference area (e.g., the ear lobe or the mastoid). Sometimes, the reference is achieved by linking two neutral sites (e.g., the two ears) to provide an averaged reference. Such a recording convention is termed a "monopolar" record, as only one of the inputs to the amplifier is obtained from an active cortical site (i.e., the other is a reference). At other times, the EEG is recorded in a "bipolar" manner, in that both inputs to the amplifier are obtained from active sites. Bipolar montages are typically employed in clinical applications. When all of the recording sites are commonly referenced to a single active site, the montage is referred to as "referential" as opposed to bipolar (Lawton et al., 1998). The reason for the differential amplification process is based on the concept of common mode rejection or CMR. By employing CMR, any signal that is common to the two recording sites (e.g., active and reference in the case of a monopolar recording) would imply that it is noncortical in origin. Accordingly, it is automatically canceled or subtracted from the records of the two recording channels by the differential amplifier such that the resultant record is considered to represent "true" bioelectrical activity from the cerebral cortex.

The resultant time series, or plot of cortical activity, has two basic properties: frequency and amplitude. In terms of amplitude, the EEG is measured in microvolts or millionths of a volt. The EEG signal typically fluctuates with total or peak-to-peak amplitude smaller than 100 μV. As a consequence, EEG recording requires high levels of amplification, typically with gain factors from 20,000 to 50,000. Additionally, the signal is characterized by a range or spectrum of frequencies from .01 to 50 Hz, although some investigators examine frequencies up to 80 Hz.

The voltage fluctuations of the continuous analog signal are sampled at fixed time intervals, and the rate at which the analog signal is sampled and recorded determines the precision with which the resultant digital time series represents the analog signal. According to a basic principle of digital signal processing called the Nyquist principle (Challis & Kitney, 1991), the analog sample requires a sampling rate that is at least double the highest frequency component of interest to "capture" the range without distortion or aliasing (Newland, 1993; Porges & Bohrer, 1990; Ramirez, 1985).

Muscle movements, especially the movements of large muscles, produce electrical signals that can be confounded with EEG. Even small muscular movements including tension in the neck and face can create artifacts. The ability to reduce such unwanted noise is accomplished by means of filtering. Eye movements can also produce large electrical signals that can mask or distort electrical activity from the cortex. Usually, records of eye movement and blinks are recorded simultaneously with EEG in the form of an electrooculogram (EOG). The EOG allows the investigator to identify segments of the EEG record that are accompanied by eye movements or blinks and to either remove the data from further consideration or correct them statistically. Once the "clean" EEG time series has been achieved, it is decomposed into its constituent frequencies by a process termed spectral analysis that is achieved by computing fast Fourier transforms (FFT). The frequencies are grouped according to bands with the traditionally defined categories: delta (1–4 Hz), theta (4–7 Hz), alpha (8–12 Hz) beta (13–36 Hz), and gamma (36–44 Hz). Delta and theta activation has reflected low levels of arousal. Alpha activity relates to a relaxed, conscious state, and beta and gamma activation are directly related to activation. Much of EEG research that has focused on psychomotor performance has examined the alpha and beta bands.

Previously, many studies in this area of research have been confined to an examination of EEG alpha power, which is believed to largely result from thalamic input to the cortex (Lopes da Silva, 1991). Pfurtscheller, Stancak, and Neuper (1996) offered an interpretation of EEG alpha that is useful in relating it to cortical function. In their review, increases in the amplitude of alpha power or event-related synchronization (ERS) are explained as disengagement of cortical structures with a given task or event. Because the EEG electrode senses neural activity over several square centimeters, it is believed that relative inactivity in the involved networks causes them to be more similar and, therefore, more synchronous, resulting in higher amplitude low-frequency recordings. As an analogy, each of the many neuronal columns or assemblies act like the members of a choir singing in unison, such that the volume for a particular passage is loud. Conversely, the size and magnitude of event-related desynchronization (ERD; i.e., decreases in alpha power) reflect the mass of neural networks involved in the performance of a specific task at a given moment. For instance, task complexity increases the magnitude of ERD. In terms of the analogy described above, think of the neuronal assemblies as disjointed members of a choir who are not in unison, such that the volume achieved for a passage is relatively low. Higher levels of alpha power within a recorded time series imply a reduction in cortical involvement in the area of the scalp (brain) from which the recording was obtained and have been referred to by Pfurtscheller et al. (1996) as indicative of "cortical idling." Sterman and Mann (1995, p. 116) offer additional information regarding EEG alpha: "The thalamic generation of localized EEG rhythmic patterns is known to reflect changes in neuronal membrane potentials associated with the attenuation of impulse conduction within a given functional system (Anderson & Andersson, 1968; Kuhlman, 1978; Steriade, Gloor, Llinas, Lopes da Silva, & Mesulam, 1990). Conversely, the suppression of these patterns with task engagement is associated with electrophysiological and metabolic evidence for active processing within these systems (Mazziotta & Phelps, 1985; Pfurtscheller & Klimesch, 1991; Thatcher & John, 1977)."

Neurophysiological Basis of Electrocortical Activation

Initially, psychophysiologists subscribed to the notion that EEG alpha and beta activation were simple indices of relaxation and activation, respectively, and that the two were inversely related. This perspective was first advanced in the early reports of Adrian and Matthews (1934). However, alternative views of the neurophysiological basis of EEG have been advanced, suggesting that the view of Adrian and Matthews may be incomplete (Nunez, 1995; Ray & Cole, 1985; Smith et al., 1999). For example, Ray and Cole proposed that EEG alpha activity indexes attentional demands, whereas beta activity is more related to cognitive processes. This view differs from that of Adrian and Matthews in that alpha and beta are not inversely related; rather, they are indicative of differential processes and may even covary depending on the psychological strategies employed. Furthermore, the attribution of unique psychological processes to different bands within the EEG spectrum has been extended, on a more fundamental level, to unique neurological processes. Specifically, Nunez suggested that alpha power reflects more global cortico-cortico interaction, whereas higher frequencies are more indicative of localized activation, further suggesting the possibility of covariation between differential frequency bands depending on task demands and resource allocation. That is, cortico-cortico interaction refers to communication between different locations within the cortex. However, his position does not rule out the possibility that alpha and beta power can be inversely related in response to a different set of constraints than those that would require covariation.

More recently, Smith et al. (1999) also endorsed the notion that EEG is related to neural communication and networking during skill acquisition and visual-spatial challenge. Specifically, they interpreted increased alpha with skill acquisition as indicative of a change in the neural organization processes that reflect a more refined and task-specific adaptation to demands. That is, specific neural pathways are enhanced while others undergo a pruning process such that the remaining active pathways are those that are specific to the demands. This concept is described by Smith et al. (1999, p. 390):

> Increases in performance accuracy and decreases in reaction times between the beginning and the ending portions of a testing session were accompanied by increased power and parietal alpha and 'frontal midline' (Fm) theta EEG spectral components. The improvements in performance are consistent with prior results from cognitive studies of skill acquisition which suggest that practice yields an increase in the efficiency with which procedural skills operate on information in working memory. The accompanying changes in EEG signals might be related to the neural reorganization that accompany skill acquisition.

Taken together, Nunez (1995) and Smith et al. (1999) provide an alternative explanation for the nature of alpha activation from simple relaxation (Adrian & Matthews, 1934) to that of neural reorganization. Importantly, the reorganization is characterized by both a relaxation of irrelevant resources and an increased allocation of relevant resources and functional pathways. By deduction, Earle (1988) also advanced the position that alpha increases are indicative of relaxation or inhibition of irrelevant resources that may be characterized by the establishment of new and more adaptive pathways. Other researchers have employed functional magnetic resonance imaging (fMRI) to detect changes in specific areas of the cortex during skill acquisition (Elbert et al., 1995). They compared the cortical representation of the fingers of skilled musicians to those of nonmusical controls. Results indicated that cortical representations were related to the level of use, and that these representations were specifically adapted to the current needs and experiences of the individual (Elbert et al., 1995).

In this regard, a well-established principle in the exercise physiology literature has been the specific adaptation to imposed demand (SAID), describing the chronic change that an organism undergoes in response to training. It would appear that this principle is gaining empirical support in the psychophysiological literature as well. Additional support for this notion is offered by Haier, Siegel, Tang, Abel, and

Buchsbaum (1992), who noted reductions in cerebral glucose metabolism in individuals on attainment of a cognitive skill. Such change epitomizes the notion that the brain is characterized by a more efficient adaptive state. That is, the reorganization of neural resources is an adaptive state that provides increased matching between resource and demand resulting in greater efficiency. As stated earlier, this neural change may influence the phenomenological experience of focus, confidence, and peak performance reported by expert performers.

Spectral EEG and Regional Cortical Specificity

As previously mentioned, psychophysiological measurement of the brain in sport performance began with a series of experiments by Hatfield and his colleagues (Hatfield et al., 1984; Hatfield, Landers, & Ray, 1987; Hatfield, Landers, Ray, & Daniels, 1982). Specifically, competitive marksmen were studied to gain insight into cognitive states associated with skilled performance. The use of marksmen for psychophysiological testing was based on the intense level of concentration and psychological engagement accompanied by the minimization of movement. The assessment of hemispheric differences within the brain using electrocortical measurement (EEG) allowed for a contrast between the preparatory state preceding shot execution and known psychological states associated with verbal-analytic and visual-spatial processing. Such an approach established a new paradigm that provided an opportunity to examine the cognitive concomitants of skilled performance in real time in a relatively unobtrusive manner.

Based on a preliminary report by Pullum (1977) that indicated superior marksmanship was associated with an enhanced alpha state, a more stringent psychophysiological assessment was undertaken by Hatfield and colleagues (1982). Specifically, the cortical processes of elite marksmen were examined during the preparatory periods immediately prior to each of 40 shots in the standing position while they aimed at a target at a distance of 50 feet. The results revealed a hemispheric lateralization effect in the brain such that increased alpha power was apparent in the left compared to the right hemisphere, as the time to trigger pull approached. These results were replicated and extended by Hatfield et al. (1984) with a different group of elite marksmen performing the same task. Using a referential montage with a common vertex reference, their results indicated that increased alpha power was observed across three successive 2.5-s epochs over all electrode locations (left [T3] and right [T4] temporal and left [O1] and right [O2] occipital). In other words, the cortex was becoming progressively "quieted." In addition, hemispheric differences in the temporal region were observed with increased alpha power at T3, and relative stability was found at T4 across the three successive 2.5-s epochs leading up to trigger pull. To highlight changes in hemispheric dominance across the epochs, an alpha ratio for the homologous temporal leads (i.e., T4/T3) was computed (see Figure 14.3). A significant decrease in the magnitude of these ratios was observed up to the trigger pull, indicating decreased alpha power in the right hemisphere. Further, this effect was found to be consistent across the four blocks of 10 shots.

Collectively, these results suggested that right-hemispheric processing became increasingly important over the time to trigger pull while a progressive decrease in left cerebral activation was noted. This finding was interpreted as a reduction of verbal-analytic processes such as self-talk while visual-spatial processing was enhanced. To further support this interpretation, elite marksmen were also presented with two known psychological challenges: arithmetic calculation and verbal comprehension to engage the left hemisphere, and matching geometric forms and Moonie faces to engage the right. Similar to the Rorschach test, Moonie faces are vague stimuli that require increased perceptual processing to assemble the image of a face. The hemispheric dominance associated with shooting was more similar to that associated with the right-hemispheric tasks than for those observed in response to the left-hemispheric tasks (Hatfield et al., 1984). Furthermore, the dominance

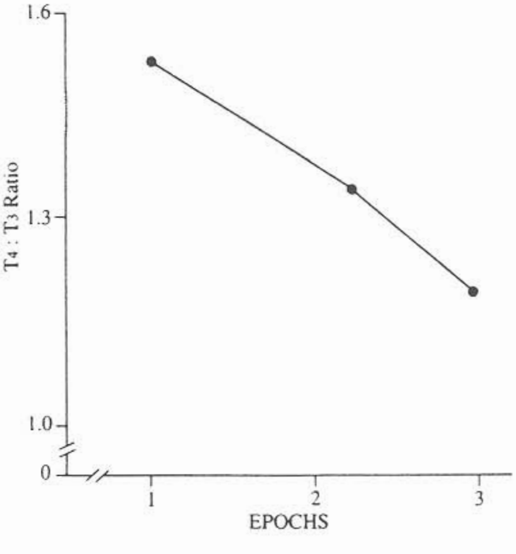

Figure 14.3 Changes in EEG alpha activity ratios (T4:T3) over successive epochs. Decreasing ratios indicate a trend toward relatively greater right-hemispheric processing.

effect evoked by the shooting task was remarkably lateralized even in comparison to the right-hemispheric tasks. Figure 14.4 illustrates this finding.

Corroborating the findings of Hatfield et al. (1984), Rebert, Low, and Larsen (1984) assessed central, temporal, and parietal hemispheric asymmetry during visual-spatial challenge. EEG activity was assessed during 10-s epochs preceding an error using the video game *Pong*. Their results showed a progressive increase in right-hemispheric dominance at the temporal and parietal regions and an opposing left-hemispheric dominance in the central region. During the time between rallies, when the brain was not actively challenged, alpha power was relatively undifferentiated between hemispheres in all regions. The results suggested that psychomotor performance of a visual-spatial task (e.g., video game rallies, shooting) preferentially engages the right hemisphere as decreased alpha power (i.e., ERD) was found in the right compared to the left hemisphere. Figure 14.5 illustrates the results obtained by Rebert et al. The hemispheric differences were most pronounced in the temporal region (Hatfield et al., 1984; Rebert et al., 1984) and appeared to lessen posteriorly. That is, decreased lateralization was evident in the parietal region (Rebert et al., 1984) and altogether absent from the occipital region (Hatfield et al., 1984). Collectively, these findings suggest that EEG recordings during performance are sensitive to the specific cognitive challenges involved with the task. Such regional specificity may be similar in kind to the metabolic and musculoskeletal resources that are differentially engaged in different types of motor performance (McArdle et al., 1986) and may contribute to the experience of a focused state.

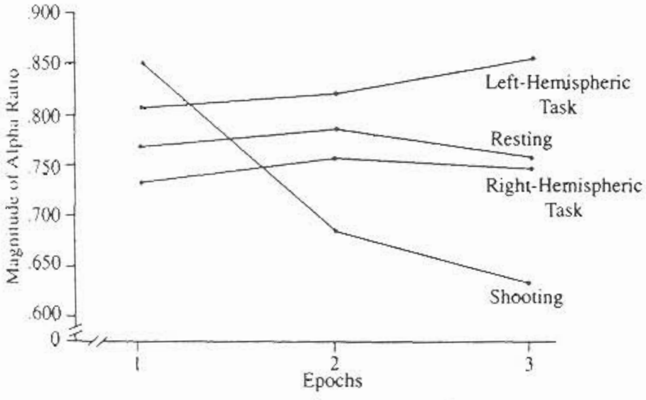

Figure 14.4 Relative changes in EEG alpha activity ratios (T4:T3) over successive epochs for four different cognitive-demand conditions.

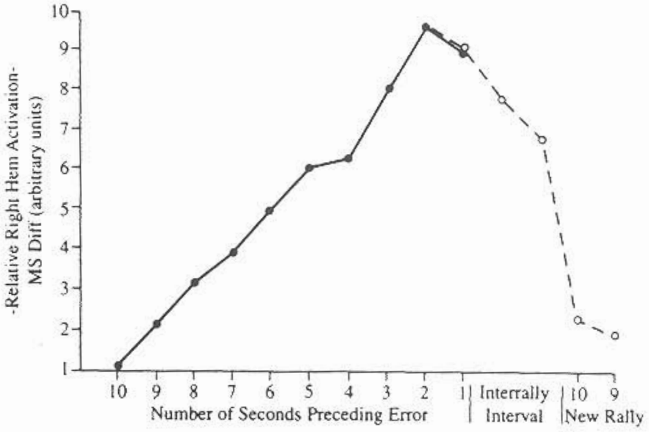

Figure 14.5 Changes in EEG alpha power asymmetry during *Pong* rallies and interrally intervals recorded from temporal leads.

Crews and Landers (1993) extended the finding of differential hemispheric engagement during psychomotor performance using another closed motor task, the golf putt. Again, a relative increase in left-hemispheric alpha power was noted during the preparatory period leading to the golf putt. This finding was accompanied by relative stability of the right hemisphere. Furthermore, there was a significant decrease in left-hemispheric beta I activity (i.e., 13–20 Hz), whereas no change was observed in the beta II band (i.e., 21–31 Hz). These results can also be interpreted as a reduction of verbal-analytic processes in a highly skilled population, not only because of increased alpha power in the left hemisphere, but also due to the ipsilateral decrease in beta power. Hatfield et al. (1984) similarly reported a relative reduction of beta power in the left compared to that in the right hemisphere in elite marksmen.

EEG Spectral Differences in Expert-Novice Paradigms

In an attempt to ascertain the changes in electrocortical activity that accompany skill development, comparative analyses between highly skilled and true novice shooters were conducted by Haufler, Spalding, Santa-Maria, and Hatfield (2000). When compared with the highly skilled marksmen, who were characterized by relative automaticity (Fitts & Posner, 1967), novices were predicted to be more effortfully and verbal-analytically engaged during the preparatory aiming period. To test this hypothesis, the participants were provided shooting, verbal, and spatial challenges. The latter two tasks were administered in a manner similar to that used by Hatfield et al. (1984) to achieve psychological inference of the mental state during sharpshooting. Specifically, it was hypothesized that novice performers would exhibit relatively higher left hemispheric activation while preparing to shoot and would evidence an EEG activity profile more similar, with regard to alpha spectral power, to that observed during the execution of the verbal task. In sum, decreased alpha power was expected in the left relative to the right hemisphere during shooting, an effect opposite that expected in the expert performers.

Consistent with expectations, novices, when compared to highly skilled marksmen, showed reduced levels of alpha power (10–11 Hz) in the left hemisphere and increased levels of beta and gamma activity. However, no such differences were observed in the right hemisphere. These results imply that the true novices were less efficient in their resource allocation to accomplish the task. No such group differences were observed for the verbal or spatial tasks that were equally novel for both groups. Furthermore, in novices, a similar level of right hemisphere alpha power was noted for both the shooting and the novel spatial challenge. Interestingly, skilled marksmen showed higher alpha power across all sites relative to that observed in the novices; this effect was particularly noticeable at the T3 site. Again, such a finding suggests an increase in efficiency for experts with specific activation in the cortical area that would appear most relevant to the task demands.

Additional comparative research, also with highly skilled marksmen and noncompetitive shooters as participants, was conducted by Janelle et al. (2000) to examine differences in specific engagement of resources based on skill level. This research was also guided by the hypothesis that less-skilled shooters would exhibit differential hemispheric dominance and activation relative to that observed in highly skilled marksmen. Specifically, noncompetitive less-skilled shooters were predicted to show decreased alpha power in the left hemisphere compared to highly skilled marksmen.

Findings were in opposition to the stated hypotheses, as increased alpha power across both hemispheres was found in the less-skilled group. One possible interpretation of this finding is that the less-skilled participants were unable to actively engage the relevant cortical resources to the same degree as the experts. When considering the notions of Pfurtscheller et al. (1996), the less-skilled shooters may have been characterized by a relative degree of cortical idling, as they may have lacked the requisite experience to focus on the task-relevant cues. According to the notion of psychomotor efficiency, one would expect increased alpha power to be displayed in the more highly skilled group. However, the lack of support may be explained by the nature of the less-skilled athletes. These athletes were not at the novice stage of skill, as was the group examined by Haufler et al. (2000), and it is possible that they had progressed beyond the stage characterized by effortful processing. A "high" level of alpha power would be consistent with such a post hoc explanation. Furthermore, the results revealed an increased level of hemispheric lateralization in the highly skilled marksmen. Specifically, Janelle et al. (2000) noted increased alpha (i.e., 8–12 Hz) and beta (i.e., 13–20 Hz) power in the left hemisphere of the experts concomitant with a relative decrease in alpha and beta power in the right hemisphere as compared to the less-skilled. Therefore, the magnitude of difference in band power between the two hemispheres was greater than that observed in the noncompetitive shooters (see Figure 14.6). This latter finding may imply an increased level of hemispheric specificity (i.e., specialization) in the highly skilled marksmen, suggesting a more efficient match between neural resource allocation and task demand.

Although the cross-sectional studies comparing experts and novices are informative, they are problematic in the sense that the observed group differences in spectral power may be due to a number of competing explanations beyond those of a neurocognitive nature. For example, any differences in the morphology of the skull (e.g., skull thickness) as well as any differences in cortical neuroanatomy (e.g., orientation of the gyri and sulci) between the groups could

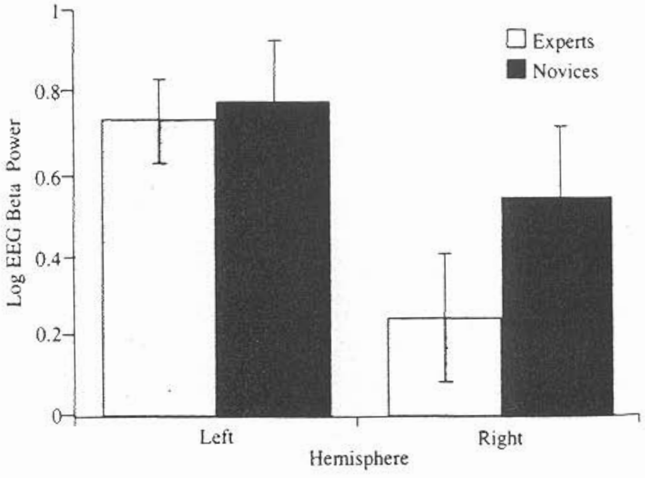

Figure 14.6 Group × hemispheric interaction for EEG beta spectral power for expert and novice marksmen.

affect the amplitude or power of the derived spectral content. Moreover, the few studies that have been reported in the literature of EEG change in association with skill development (i.e., intervention studies) are brief in training duration, typically involving repeated trials within only one session (Buşk & Galbraith, 1975; Etnier, Whitwer, Landers, Petruzzello, & Salazar, 1996).

In an attempt to overcome these problems, Landers and his colleagues (1994) conducted a longitudinal investigation with beginning-level archers who participated in a semester-long physical education class. Results showed that novice archers significantly increased alpha power in the left hemisphere during a 14-week performance training course such that increased cerebral asymmetry was observed at the posttest compared to the pretest (see Figure 14.7) as performance improved. These findings strongly suggest that EEG asymmetries as related to psychomotor performance are learned patterns, and that they may facilitate task-specific environmental transactions. Although a comparative control group was not formed in the study, the results appear to provide support for enhanced cortical efficiency because the increased synchronization in the left hemisphere would imply a reduction in irrelevant processing (e.g., verbal-analytical) along with a maintenance of right-hemispheric visual-spatial involvement.

In a similar attempt to causally relate electrocortical activity with performance, Landers et al. (1991) used an EEG biofeedback intervention with pre-elite archers to facilitate skill acquisition and improve performance outcome. Experienced archers were placed in one of three groups: correct biofeedback (i.e., greater left hemisphere slow potential negativity), incorrect biofeedback (i.e., greater right hemisphere slow potential negativity), and a no-feedback control. Results showed that the correct feedback group significantly increased shooting accuracy from pre- to posttest (as measured by the score achieved over 27 shots). The incorrect group decreased performance, and the control group showed no change after one 45- to 75-minute session of biofeedback training (Landers et al., 1991). Additionally, the incorrect feedback group revealed increased beta power in the right hemisphere in the 13–31 Hz range, whereas the other two groups showed no such effect. This heightened power observed in the right hemisphere may be interpreted as more effortful processing or reduced efficiency compared to the other two groups. Figure 14.8 illustrates this finding.

Intrasubject Variability in EEG and Performance Outcome

In another investigation of electrocortical responses of skilled athletes (i.e., elite archers), Salazar and his colleagues (1990) found support for the hemispheric asymmetry effect reported in the literature with golfers (Crews & Landers, 1993) and marksmen (Hatfield et al., 1984). Twenty-eight elite archers completed 16 shots in one of four conditions: normal archery shooting with 14–22-kg bow at full draw; holding the bow at full draw while looking at the target; holding a 2-kg bow while looking at the target; and rest. EEG was monitored at sites T3 and T4 during the final 3 seconds of the aiming period. The four comparative conditions were created to ascertain the relative influence of the physical exertion involved in the task, as opposed to the neurocognitive processes, on the

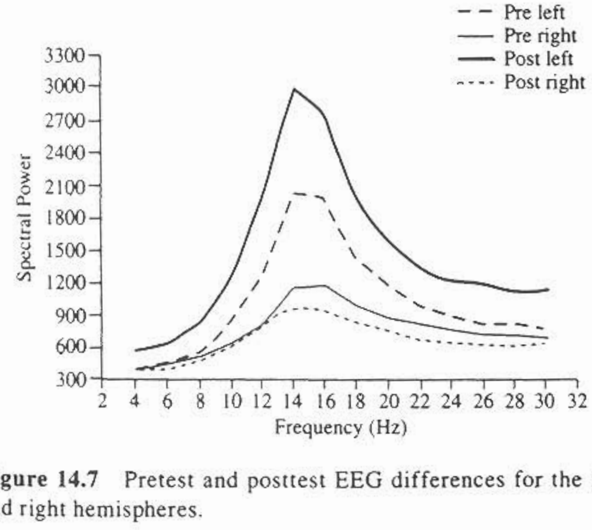

Figure 14.7 Pretest and posttest EEG differences for the left and right hemispheres.

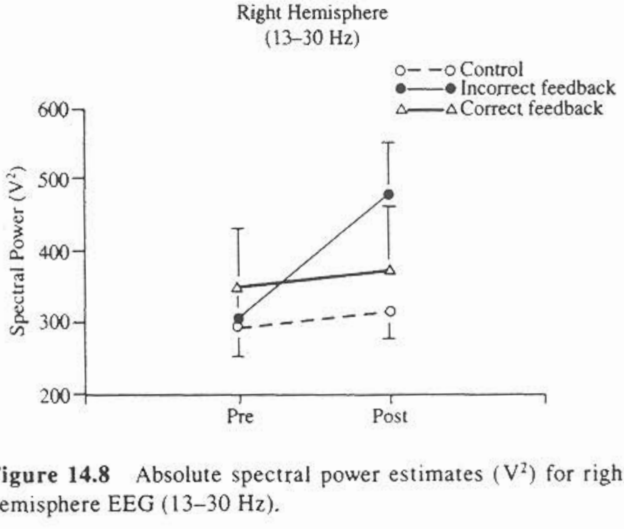

Figure 14.8 Absolute spectral power estimates (V^2) for right hemisphere EEG (13–30 Hz).

recorded EEG. Across all conditions, a significant difference in hemispheric power was noted in the final second prior to arrow release such that the left hemisphere exhibited significantly higher levels at 10, 12, and 24 Hz, whereas relative stability was shown in the right hemisphere over the 3-s aiming period. Worth noting is that the highest level of synchronization of spectral power was observed during the condition characterized by the highest level of ecological validity. Interestingly, this condition represented the situational challenge to which the participants were most adapted. Furthermore, the observed EEG differences were associated with performance variability (i.e., comparison of the four best and worst shots), again supporting the concept that lateralization levels may affect performance levels. The findings indicated increased power in the left hemisphere at 6, 12, and 28 Hz for the worst shots compared to that observed for the best (Salazar et al., 1990). No such performance-related differences in EEG power were noted in the right hemisphere. Although one would expect from the preceding discussion that higher levels of alpha power would be associated with better performance, the heightened levels associated with poorer performance might be indicative of excessive synchronization. That is, the relatively inactive left hemisphere may have been inappropriately disengaged. Salazar et al. caution that the lack of spatial resolution in this investigation (i.e., only two recording sites) precludes definitive insights as to the neurocognitive basis for the observed findings.

Using a denser electrode array to characterize intraindividual differences in electrocortical activity with greater spatial resolution, findings similar to those of Salazar et al. (1990) were obtained by Hillman, Apparies, Janelle, and Hatfield (2000). Using a within-subjects design, EEG alpha and beta activity assessed during the preparatory period prior to executed and rejected trials were compared in highly skilled marksmen. Shot rejection trials referred to those when the shooter would aim his or her rifle at the target and then withdraw without firing a shot. EEG was measured at sites F3, F4, T3, C3, C4, T4, P3, and P4 with a referential montage employing the vertex (i.e., Cz) as the common active site. Based on the model described by Hatfield et al. (1984), Hillman et al. (2000) hypothesized that decreased alpha power in the left hemisphere would accompany the rejected shots. More specifically, they predicted that left hemispheric dominance would characterize the preparatory period prior to shot rejection. As such, they subscribed to an interference model positing that relative left-hemispheric activation would be incompatible with the execution of the task.

Contrary to expectations, the comparison of the EEG during the preparatory periods that preceded shot execution and rejection revealed increased alpha and beta power for the latter. Moreover, the increased power for rejected shots was observed at all regions, with the greatest power at the temporal sites and the least power at the central sites. Furthermore, this effect interacted with time, as increased power was observed for rejected shots while power remained stable during executed shots (i.e., the magnitude of difference increased as the time to trigger pull approached; see Figure 14.9). These results are consistent with the cortical idling explanation advanced by Pfurtscheller et al. (1996). That is, prior to shot rejection, the marksman may have failed to engage the relevant cortical processes to the extent that they were recruited prior to execution. The ERD

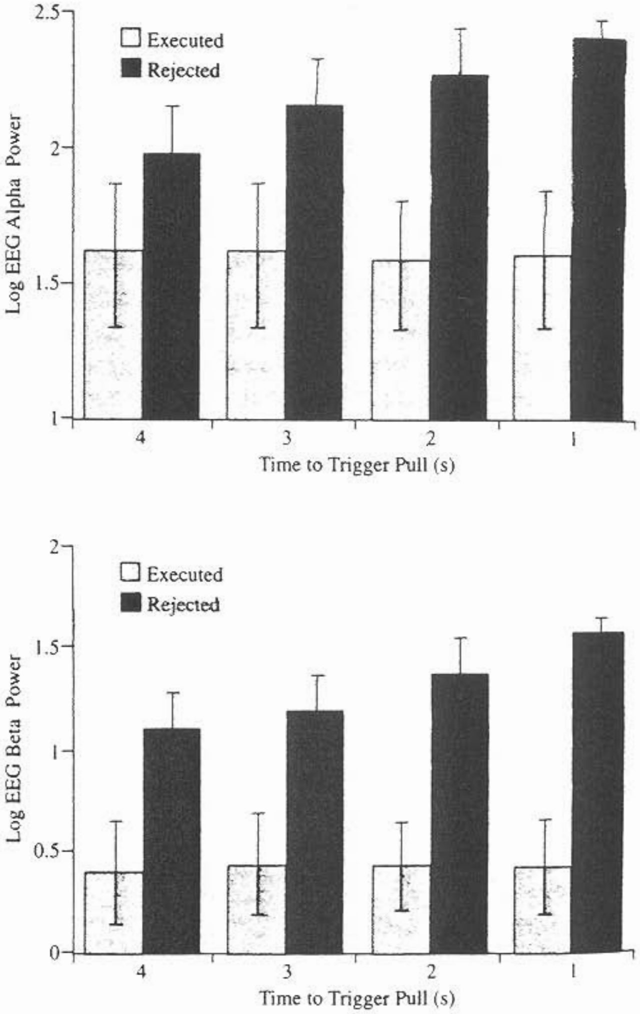

Figure 14.9 Alpha and beta spectral power for the trial type × epoch interaction.

noted in the "successful" state would imply greater engagement of the relevant resources in cortex with challenge.

Failure to appropriately engage task-relevant resources during the performance of a novel task has also been observed in research beyond psychomotor performance. For example, Earle (1988) measured alpha power in temporal and parietal regions in individuals engaged in visual-spatial problem solving and noted increased alpha power in those individuals who experienced greater difficulty negotiating the task. He also contended that the increased alpha power was due to a failure to activate task-relevant neural resources. Taken together, the results of Janelle et al. (2000), Hillman et al. (2000), and Earle are consistent with the notion that less-experienced individuals, or skilled individuals who are not in an ideal performance state, fail to efficiently allocate task-specific neurobiological resources as they struggle with task demands.

Affective Correlates of Psychomotor Skill

Previous investigators have confined their assessment of the electrocortical correlates of skilled performance to the cognitive and motor domains. However, Saarela (1999) attempted to extend the psychophysiological assessment of this state to the affective domain by manipulating time pressure with skilled marksmen who were given varying amounts of time to complete a regulation shooting match in the standing position. That is, marksmen were given the regulation 80 minutes to complete 40 shots. They also experienced a temporal perturbation such that they were required to complete an additional round of 40 shots in half of the time it actually took them to complete the first round. To assess the emotional states associated with these conditions and their relationship to performance, Saarela measured frontal asymmetry (i.e., F3, F4), an established index of affect (Davidson, 1988). Davidson and colleagues (Davidson, Ekman, Saron, Senulis, & Friesen, 1990) have provided evidence that relative left frontal activation (i.e., decreased alpha power at F3 relative to F4) is associated with approach-related behaviors and pleasant affect, and relative right frontal activation (i.e., decreased alpha power at F4 relative to F3) indexes withdrawal-related behaviors and unpleasant affect. Saarela et al. hypothesized that increased right frontal dominance would be found as a result of temporal perturbation along with a deterioration in performance compared to the nonstressed condition. Their findings indicated that marksmen did exhibit greater right frontal activation (i.e., reduced alpha power at F4) in conjunction with poorer performance under temporal stress relative to that under normal shooting conditions in which relative left frontal activation was observed (Saarela et al., 1999). Moreover, a strong correlation was noted between frontal asymmetry and performance outcomes in the hypothesized direction. Accordingly, the approach orientation associated with the nonstressed shooting condition can be considered an active engagement with the task or high degree of focus that may explain the superior performance. Conversely, the temporal perturbation influenced the emotional state and subsequent performance in a negative direction. Importantly, the prefrontal area, which is involved in the emotional state, is also intricately related to the motor control centers of the brain (Bear, Connors, & Paradiso, 1996). Therefore, the variability in affect could potentially cause variability in the motor pathways, resulting in alterations in the quality of performance.

In an attempt to further assess the influence of emotional states on performance, Kerick, Iso-Ahola, and Hatfield (2000) examined frontal asymmetry in novice shooters by providing them with false feedback. That is, positive feedback was manipulated to generate psychological momentum that was hypothesized to enhance task engagement or approach-related behavior. Alternatively, negative feedback was hypothesized to decrease task engagement. Although the differences in frontal asymmetry were not significantly different, a trend was found in the hypothesized direction. Because the performers were at the novice stage of skill, the failure to achieve significance may have been due to the inherent variability in the cognitive-affective processes associated with the preparatory state. From a speculative point of view, the variability of a beginning performer may be due to inconsistent allocation of neural resources. Furthermore, such inexperienced individuals may not have efficiently adapted to meet task demands (Smith et al., 1999). That is, they may be struggling effortfully to negotiate the challenges, a style that could contribute to their lack of consistency in negotiating the challenge and concomitant cortical activity.

Event-Related Potentials and Skilled Motor Performance

Beyond the information provided by examination of the EEG spectral domain, ERPs offer an additional tool in understanding performance, as they are indicative of specific temporal processes. Coles et al. (1990) defined the ERP as a manifestation of brain activities that occur in preparation for or in response to discrete events. That is, ERPs represent cortical activation that is time-locked to a specific stimulus. Additionally, ERPs are derived from the average of multiple responses to increase the signal-to-noise ratio.

Generally, ERPs are measured in terms of the direction of peak amplitude (i.e., positive or negative) and latency of the cortical waveform. For example, a positive peak that occurs approximately 300 ms after stimulus presentation would be referred to as P3.

In the field of sport performance, a number of investigators have used such measures to study attentional processes in the moments leading up to the execution of a self-paced motor performance. Konttinen and Lyytinen (1992) reported their findings from examination of slow potential (SP) negative shifts (recorded from sites Fz, C3, C4, and Oz) in national-level marksmen and nonpracticed participants. SPs refer to a specific type of ERP that indexes slow shifts in cortical activation related to stimulus processing. Increasing negativity was observed across the sites prior to trigger pull, implying an increasing level of "readiness" to execute the shot. The less successful shots were preceded by a significantly larger shift at the Fz site. Based on these data, Konttinen and Lyytinen theorized that the level of arousal preceding the poorer shots was excessive, and a more economical cortical activity profile was associated with superior performance.

In a subsequent investigation, Konttinen and Lyytinen (1993) reported the individual variability of SP activity in skilled sharpshooters during the 7.5-s preparatory period prior to trigger pull. Recording of SP activity was obtained from the midline (Fz, Cz, Pz) and central lateral (C3, C4) sites. Konttinen and Lyytinen hypothesized that individual marksmen would evidence consistent SP profiles that were reflective of an overlearned automatic cognitive and attentional strategy. Furthermore, individual differences were hypothesized to exist among marksmen, suggesting unique adaptations to the challenge of sharpshooting. The results were consistent with their hypotheses. Importantly, intrasharpshooter variability occurred between high- and low-scoring shots. These findings suggest that variability in electrocortical activity, which underlies the psychological approach, influences performance outcome (see Figure 14.10).

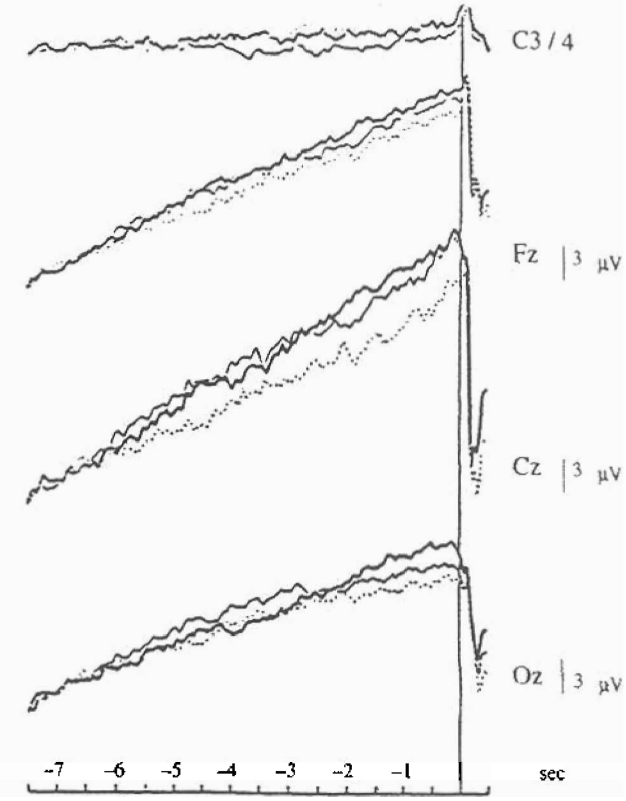

Figure 14.10 The grand averages from the SP calculated across high (687 trials), medium (716), and low (724) score shots. The time window is −7500 to 1500 ms.

In an attempt to more clearly relate cortical activity to behavior, Konttinen, Lyytinen, and Era (1999) used a psychobiomechanistic approach to explain differences in sharpshooting performance. Specifically, they compared elite (i.e., Finnish Olympic team) and nonelite (i.e., nationally ranked but without international competitive experience) shooters in terms of SP activity (Fz, C3, C4 sites) and postural sway behavior. Participants fired 200 shots in the standing position on an indoor 18-meter range and were instructed to hold the aiming period for at least 7 to 8 seconds prior to the trigger pull to provide a constant time period for SP recording. SP positivity was predicted to be heightened prior to poorer performance compared to more accurate trials. This increase would imply elevated psychomotor effort to inhibit irrelevant motor activity and override the SP negativity associated with arousal regulation and visual-spatial processing (i.e., a less efficient state; Konttinen et al., 1999). The results revealed that the elite group showed a reduction in the amplitude of body sway that coincided with a reduction in frontal positivity, and the nonelite group evidenced a different association between the cortical and biomechanical variables. That is, both the amplitude of sway and sway velocity in the anteroposterior plane were related to lateralization in SP central negativity. It is remarkable that such differences emerged in light of the approximation in skill level between the two groups. These results are consistent with the principle of psychomotor efficiency in that superior performance was characterized by decreased cortical effort (as indicated by the reduced amplitude of SP positivity), which, in turn, resulted in reduced sway behavior in the elite group.

In the broader context of attention (i.e., within the reactive task domain), a number of investigators have examined how individuals shift attention in dynamic, fast-paced, and unpredictable environments. The implications for this research are paramount to sport, as athletes are often challenged with a complex visual-spatial array in which they must focus on relevant cues while preparing for the unexpected. Attentional flexibility has been described as the ability to quickly disengage, move attention, and then engage attention again on different aspects of a task. It has been empirically assessed through the use of Posner's (1980) cued attentional paradigm. According to Posner's paradigm, an individual must react to one of two imperative stimuli (i.e., choice RT) preceded by a directional warning stimulus (i.e., an arrow pointing to the left or right of a visual display). The imperative stimulus (S2) follows a warning stimulus (S1) that either correctly or incorrectly cues the subject as to the position of the imperative stimulus that is about to appear. Higher levels of attentional flexibility are characterized by a reduction in attention cost concomitant with an equivalent or greater attention benefit. Attentional cost is defined as slower RT to an imperative stimulus that is preceded by an invalid cue (relative to an uncued RT), and attentional benefit is defined as faster RT in response to an imperative stimulus preceded by a valid warning cue relative to noncued stimuli. This view of attentional flexibility is referred to as location shift. Alternatively, some investigators prefer the term attentional flexibility to refer to the ability to quickly vary or shift the span of visual attention from a focal to a diffuse mode and vice versa (Eriksen & Yeh, 1985). Accordingly, attention is conceived as a "scarce" processing resource that can vary from uniform distribution over the entire visual field to highly focused concentration. When spatial information is provided, the system switches to its focused mode, thus concentrating all resources on a circumscribed area, and processing is allocated to objects falling within the focused area.

In studies of athletic populations, a number of investigators have provided behavioral evidence (i.e., as operationalized by RT) that athletes are characterized by greater attentional flexibility than nonathletes. Castiello and Umilta (1992) compared the RTs of volleyball players to nonathletes. Their results showed that attention benefit did not differ between the two groups, but that attention cost was smaller in the athletic group, thus providing support for the notion that athletes have greater attentional flexibility from the location shift perspective. Conversely, the results of other studies have shown that both attention benefit and cost were smaller in athletes compared to nonathletes (Nougier, Ripoll, & Stein, 1989; Nougier, Stein, & Azemar, 1990; Nougier, Stein, & Bonnel, 1991).

In an attempt to resolve the contradictory findings, the cued attention paradigm (Posner, 1980) has also been used to study attention benefit and cost with ERPs (Hillyard, Luck, & Mangun, 1994; Mangun & Hillyard, 1991; Mangun, Hillyard, & Luck, 1993; Van Voorhis & Hillyard, 1977). Use of this paradigm may provide an opportunity to determine some aspects of the covert strategic neurocognitive processes. Because the paradigm is presented visually, occipitally recorded visual ERPs can be recorded from participants as they negotiate the challenge. The amplitude of constituent components (i.e., P1, a positive waveform component that occurs approximately 70–110 ms after stimulus presentation, and N1, a negative component that occurs approximately 125–170 ms after the stimulus) can then be used as indices of attention allocation. Investigators (Eimer, 1994; Hillyard et al., 1994; Mangun & Hillyard, 1991) have found that the amplitudes of both P1 and N1 were greater in response to the imperative stimulus in the valid cueing condition. Although the neuroanatomical source of N1 is not clear, its maximal amplitude distribution over the posterior area of the brain, and its sensitivity to the cueing effect, make it an ideal candidate for studying attentional flexibility. Therefore, one would expect that the amplitudes of P1 and N1 would show a similar pattern of attentional benefit and cost to that indicated by RT. According to the location shift perspective, a person with greater attentional flexibility would exhibit a similar or greater amplitude enhancement under valid cueing conditions relative to the neutral condition, whereas the amplitude reduction under invalid cueing conditions would not be as severe.

Hung, Santa-Maria, and Hatfield (1999) administered Posner's cued attention task to determine attention flexibility and motor preparedness in 15 table tennis players and 15 nonathletes. Table tennis players were hypothesized to have greater attention benefit and reduced attention cost compared to nonathletes. The variables were measured by means of RT and ERPs (i.e., P1, N1, and the contingent negative variation, CNV). The CNV is an SP wave that is defined between a fixed S1–S2 interval (e.g., a warning and imperative stimulus, respectively). ERPs were recorded from scalp sites C3, C4, O1, and O2 to obtain visual ERPs from the occipital sites and a lateralized CNV recorded from the central sites over the motor cortex. The amplitude of N1 was used as an index of visual attentional resource allocation, and the amplitude of the CNV served as an index of the magnitude of resources allocated to motoric preparedness. Their results revealed that the athletes were faster in terms of RT and were characterized by an inverse N1 cueing effect (i.e., amplitude of N1 to the invalid condition was greater than in the valid condition). Interestingly, this result suggests that the table tennis players directed their limited attentional resources to the less likely location in order to prepare for the unexpected. The reactive-task athletes were also found to have greater motor preparedness, as indicated by greater amplitude of the CNV prior to movement initiation. As such, it may be that skilled psychomotor performers adopt specific strategies to optimize speeded behavioral responses in uncertain or ambiguous situations by allocating attention to the lower probability event while motorically preparing for the event associated with the higher expected probability. Such an adaptation would appear to be ideally suited to the minimization of maladaptive responses to unexpected challenges.

Electrocortical Activity and the Quiet Eye Period

To better understand electrocortical differences between skilled and unskilled psychomotor performance in a convergent methodology, gaze behavior has been studied concurrently with EEG recording based on the underlying assumption that the eye is a "window to the brain." Of specific interest has been the "quiet eye period," which has been hypothesized to index the time needed to organize the visual parameters prior to task execution (Vickers, 1996a, 1996b; Vickers & Adolphe, 1997). Vickers (1996a) explained the quiet eye period by incorporating the work of Posner and Raichle (1991), who postulated the involvement of three critical neural networks. These include the posterior (i.e., orienting) and anterior (i.e., executive) attention networks, as well as one for the coordination of the anterior and posterior systems, the vigilance network. The orienting network directs attentional resources to the most critical environmental cues for the planning of responses. The executive attention network is involved with the recognition of specific cues that relate to goal achievement. Once the pertinent cues have been identified, the vigilance network maintains focused attention. Accordingly, longer quiet eye periods allow performers to extend programming duration for specific targets without disruption from other environmental cues. In line with this view, the quiet eye duration indexes the organization of critical neural networks necessary for optimal control of visual attention.

From a behavioral perspective, Vickers (1996b) and colleagues (Vickers & Adolphe, 1997) have found differences in quiet eye duration based on skill level in both open (e.g., volleyball) and closed (i.e., basketball free throw shooting) sports. Furthermore, Janelle and colleagues (2000) examined the relationship between EEG and quiet eye duration in highly skilled and less-skilled shooters. The specifics of their methods and the design employed were described in an earlier section of this chapter. Experts showed longer quiet eye duration and reduced alpha and beta band power compared to the less-experience shooters. Additionally, lower levels of alpha and beta power were observed in the right hemisphere of the experts, indicative of superior organization of the visual-spatial parameters needed for effective performance. Subscribing to the framework provided by Nunez (1995), the reduced EEG power may imply decreased cortico-cortico communication, which, in turn, may imply reduced activation of irrelevant neural pathways. These findings suggest a more focused state from both measurement perspectives, in that longer quiet eye duration and decreased spectral power in skilled marksmen may relate to quiescence of irrelevant neural activity. The pruning of irrelevant resources may provide an opportunity for more pronounced involvement of task-specific neural activation and the observed activation pattern may underlie greater attentional focus.

In sum, multiple psychophysiological measures reveal different patterns of cortical activity based on expertise. That is, the combined measures (e.g., EEG, ERPs, quiet eye) have enabled investigators to index elite performance, compare skill levels (i.e., expert-novice), and observe differences within individual performance states. Collectively, these studies have attempted to address the differences in cognitive strategies associated with different levels of skill and during different performance states.

NEURAL PROCESSES AND THE MOTOR SYSTEM

With regard to motor control and performance, the efficient allocation of neural resources at one level (i.e., cognitive, affective, and attentional) would appear to be intimately related to the organization and quality of efferent motor outflow. Specifically, integral interactions occur between the higher association areas of the brain, such as the prefrontal cortex and the motor loop (Bear et al., 1996). Higher cortical structures, such as the parietal cortex and the prefrontal area, are directly involved in initiating the signal sent to the motor cortex to "launch a movement." Once the signal leaves the higher cortical structures, it is sent to the basal ganglia that act on the thalamus to trigger the motor cortex. The signal is then sent from the motor cortex via the corticospinal tract to the relevant skeletal muscles (Bear et al., 1996). Hence, task difficulty and effortful cognitive processing may have a strong negative influence on the quality and consistency of the resultant movement by increasing the "noise" input to the motor loop. Conversely, a skilled athlete performing a familiar task would be expected to exhibit decreased noise in the motor loop, which may result in increased quality and consistency of movement (see Figure 14.11).

To illustrate this concept, the example of a place kicker faced with a critical situation in the final moments of a critical football game is provided. In this situation, the opposing team usually calls a time-out to make the athlete "think too much" and overly analyze the challenge with which he is faced. In a sense, the brain of the athlete could be characterized as busy or "noisy" in the cognitive-affective domain. This altered psychological state may then cause disregulation (i.e., excess activation or alteration in the sequencing of events) within the motor loop (Kandel & Schwartz, 1985). Accordingly, the activation of the involved agonistic muscles (hip flexors) and the attendant coordination of the antagonists (gluteal and upper hamstring groups) may also be disregulated, resulting in an alteration of the kinematics of the motion involved in the actual kick. Such processes may underlie the following real-life occurrence: "With only eight seconds on the clock and a chance to tie the game, Mowrey ensured instead that he will be remembered as a copycat killer of Seminole hopes. When Florida State had a chance to beat the Hurricanes in Tallahassee last year, Gerry Thomas saw his last-second kick sail wide right too. New goat, same result" (Murphy, 1992, p. 14).

Of interest to sport psychologists is the question of how elite athletes coordinate cognitive and motor functions to produce the optimal movements required for their sport. To understand this, the organizing principles associated with skilled movement must first be understood. One theoretical perspective that relates well to the principle of psychomotor efficiency for explaining the control and coordination of movement is that of dynamical systems. The dynamical systems perspective views movement as the result of many control parameters, including the interaction of neural maturation and physical growth. Thelen, Kelso, and Fogel (1987) believe that it is this interaction, along with the intrinsically self-organizing properties of the sensorimotor system, that produces movements that are appropriate within the context of the prevailing environmental conditions.

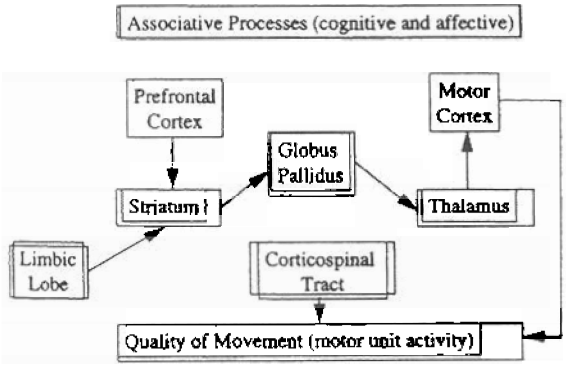

Figure 14.11 The influence of cognitive-affective processes on the motor loop.

Bernstein (1967, p. 185) stated that "motor acts demand the most precise intercorrelations of a multiplicity of muscles acting together and of the entire interconnected musculature, with uncontrollable external and reactive forces making up the variable force field in which a movement is carried out." He proposed that coordination of movement was a process of mastering the redundant degrees of freedom of the moving organism and that this process converts the system from a multivariable system into a more simplified one. Rather than having each element of the movement controlled by the CNS, a relationship is formed among the various elements of the system to constrain the vast complexity or degrees of freedom. Gel'fand, Gurfinkel, Fomin, and Tsetlin (1971) view the function of the nervous system in a similar manner. They emphasize the principle of "least interaction": that a system works expediently in some external environment if it minimizes its interaction with that environment.

Considering the role of the CNS, this principle means that minimal input is needed by the higher centers for movement production while control is shifted to lower centers. Thus, the complexity or degrees-of-freedom problem presented to the cortex was solved by apportioning relatively few responsibilities to the executive level and many to the lower levels of the CNS, whose activity the cortex regulates. Therefore, the forming of movements becomes more automatic as opposed to requiring cognitive effort, allowing for the execution of motor skill in an efficient manner. It would appear that there is abundant evidence to support the notion that the organizing principle of neurocognitive efficiency extends to the periphery as well. In this regard, the next three sections of the chapter concern the efficient regulation of muscular, cardiovascular, and metabolic activity in higher-ability individuals or participants in research characterized by lower levels of emotional arousal. This generalizability to the periphery relates to the concept of the mind-body link that was illustrated in Figure 14.1.

Electromyographic Correlates of Psychomotor Performance

In addition to electrocortical activation, the measurement of electrical activity within specific muscles has been useful in understanding the psychological states associated with skilled performance. Weinberg (1978) used EMG and the Sport Competition Anxiety Test (SCAT; Martens, 1977) to determine how high and low state/trait anxiety, under success or failure feedback conditions, affected the expenditure of neuromuscular energy on an overarm throwing task. EMG was measured from both the biceps and triceps brachii, antagonist muscle groups of the upper arm. These measures were obtained to assess the quality of neuromuscular activation. Results revealed that high trait-anxious subjects, before and after feedback, activated more motor units than the low-anxious subjects before, during, and after the throw. Presumably, individuals who move in a certain manner over time develop a neuromuscular pattern, which is reflective of their cognitive interpretation of the situation. Further, the highly anxious participants viewed the performance situation as threatening; therefore, their movement patterns reflected this by being constrained and inhibited. In terms of positive feedback presented to the participants, Weinberg stated that "the important point is that a successful experience helped high-anxious subjects become more efficient in their quality of movement" (p. 59). Again, this finding supports the interactive relationship between mental and physical efficiency.

EMG has also been used to study the preparatory state associated with large-muscle gross motor performance. Brody, Hatfield, Spalding, Frazer, and Caherty (2000) measured integrated EMG activity and force in 15 strength-trained men during maximal isometric actions of the biceps brachii, with the elbow in a position of 90°, immediately following 20-s periods of mental preparation, reading aloud, and mental arithmetic. Bipolar recordings of EMG were obtained from the agonistic and antagonistic muscles involved in the task. The reading aloud and mental arithmetic conditions were employed as attentional distractions. Perceived arousal and attentional focus ratings for the mental preparation conditions were significantly greater than those obtained for reading aloud and mental arithmetic, which were undifferentiated. However, perceived effort, average biceps and triceps EMG, and maximal force did not differ across the conditions. These findings indicate that relatively stable neuromuscular adaptations were achieved in trained individuals that are robust to attentional perturbation. Of course, such activation and force-production stability may not occur in relatively inexperienced individuals for whom the alterations in emotional state (i.e., psyching vs. calm) may result in drastic performance alterations.

Cardiovascular Psychophysiology

In addition to the cortical influence on the voluntary nervous system and subsequent neuromuscular activity, the brain is intimately interconnected with the autonomic nervous system. This interrelationship has been extensively examined during psychomotor performance in the cardiovascular domain. Early research by Landers, Christina, Hatfield, Daniels, and Doyle (1980) revealed that elite marksmen fired their shots between heartbeats, an effect not found for less-experienced shooters. Remarkably, of the 400 shots executed by the 10 elite marksmen examined in this study (i.e., each took 40 shots from the standing position), only 6 shots coincided with ventricular contraction (Landers et al., 1980). This phenomenon, which was unconscious to the performer, seemed to serve as an adaptive influence by decreasing reverberatory movement associated with ventricular ejection and enhanced quality of performance.

Research by Hatfield et al. (1987) revealed that, in addition to a top-down perspective, the activity of the heart may also influence the activation level of the cortex. Specifically, they noted an overall chronotropic pattern (i.e., faster heart rate) during the 3-second period preceding the trigger pull that followed a phasic heart rate response, characterized by a preliminary acceleration followed by the deceleratory phase. Framing this work within the broader context of basic psychophysiology may be useful for understanding the significance of the changes in cardiac activity. Accordingly, Lacey and Lacey (1978) postulated that cardiac deceleration facilitated sensorimotor efficiency by increasing the sensitivity of the CNS to environmental stimuli. In their words, cardiac deceleration was related to "intake of environmental stimuli." Alternatively, cardiac acceleration was associated with "environmental rejection" and internal cognitive elaboration (Lacey & Lacey, 1978). Therefore, a circular regulatory process was posited in which the orientation of attention influences cardiac activity that, in turn, facilitates the attentive processes (and, eventually, the performance outcome).

Hatfield et al. (1987) did, in fact, provide evidence that cardiac activity is related in an influential manner to cortical activity during skilled psychomotor performance. Specifically, they tested a centralist model maintaining that cortical activity (i.e., EEG alpha power) would influence subsequent cardiac activity (i.e., heart rate), versus a peripheralist model that held that cardiac activity would influence subsequent EEG activity. Findings supported the peripheralist model such that heart rate activity during the periods preceding trigger pull was related to the subsequent EEG alpha power during the later epochs just prior to trigger pull (Hatfield et al., 1987). This finding suggested that skilled performance is associated with a complex integrated systems adaptation that aids in arousal regulation—one that may help to shape the specific pattern of cortical activation in the highly skilled performer.

Fenz (1975) also studied the relationship between autonomic arousal and psychological state during a high-risk activity, sport parachuting. In the classic work of Fenz and Epstein (1967), two groups of parachuters that were equally experienced but differed in skill level were monitored during the events leading up to the final altitude prior to sky diving. Specifically, heart rate (in beats per minute, bpm) progressively climbed from the time they arrived at the airport until they entered the aircraft. However, the groups exhibited a divergent heart rate pattern from the time they entered the aircraft until they reached final altitude. Poorer performers continued a progressive increase in cardiac activity (reaching a mean above 120 bpm), whereas the superior performers revealed a cardiac deceleration pattern during this same period (mean of approximately 90 bpm; Fenz & Epstein, 1967). Subscribing to Lacey and Lacey's (1978) intake-rejection model of attention, the divergent cardiac patterns were also associated with different psychological profiles. Fenz observed that superior jumpers were more externally focused and task-oriented, whereas the less-skilled jumpers were characterized by excessive cognitive rumination, thoughts of fear, and general rejection of the environment. In this manner, the task-oriented or intake perspective of the superior performer was considered to influence cardiac deceleration, which would, in turn, facilitate performance by increasing sensorimotor efficiency or the processing of task-relevant cues. Again, on a different level of analysis than that conducted by Hatfield et al. (1987), the adaptive regulation of arousal seems to be characterized by a complex interactive system.

In another illustration of the significance of efficiency within psychophysiology, Porges and colleagues (Porges, Doussard-Roosevelt, Stifter, McClenny, & Riniolo, 1999) have extensively researched the role of the vagus nerve (i.e., the tenth cranial nerve responsible for the majority of parasympathetic outflow) in behavioral transactions with the environment. They determined that vagal tone (i.e., as indexed by heart rate variability) is involved in adaptive coupling between the brain and the metabolic state of the organism. This coupling may manifest itself as an efficient transaction between the nervous system and the environment when metabolic activity of the organism is matched to environmental challenge.

PSYCHOLOGICAL STATES AND METABOLIC EFFICIENCY

Reviewing the concepts presented thus far, it becomes obvious how influential physical efficiency is in determining the outcome of a performance. It is also important to note that physical efficiency, in many instances, may be achieved as a result of being mentally efficient. There is a constant interaction between the psychological and physiological domains such that the effects of one on the other may be beneficial or destructive. W. Morgan (1985) reviewed a number of studies that supported the influence of psychogenic factors on physiological and metabolic factors during exercise. Additionally, T. Williams, Krahenbuhl, and Morgan (1991) administered the Profile of Mood States (POMS) to moderately trained runners performing at 50%, 60%, and 70% of VO_2 max to examine the effects different mood states had on running economy. Collectively, findings demonstrated that those who experienced mood states that were low in negative affect had a lower oxygen consumption rate for a given amount of work.

Hatfield et al. (1992) also conducted a study to determine how cognitive orientation influences physiological economy. They attempted to determine whether there was a causal influence of the association and disassociation strategies as originally noted in endurance athletes by W. Morgan and Pollock (1977). Interestingly, W. Morgan and Pollock determined that elite U.S. distance runners tended to focus on their bodily efforts during competition, whereas less accomplished runners tended to block out or disassociate the effort associated with exertion. Hatfield et al. reasoned that biofeedback, a strategy that can help one to attenuate physiological responses, appeared similar in principle to such associative strategies and disassociation was similar to distraction. Therefore, in a controlled laboratory setting, they examined whether physiological feedback (ventilatory effort and EMG activity) and distraction (a coincident timing task) would differentially affect the physiological economy of competitive distance runners performing immediately below ventilatory threshold. Daniels (1985) had earlier established the importance of running economy to performance outcome in endurance athletes. The results revealed a measurable effect on ventilatory effort (V_E/VO_2) for the biofeedback condition as compared to the distraction and control (i.e., no manipulation) conditions, although oxygen consumption did not differ. That is, during the feedback condition, the runners were able to maintain a similar oxygen consumption level while breathing a reduced volume of air. These findings lend strong support to the interactive relationship between mental and physical efficiency by showing how a specific cognitive strategy (i.e., associative) may alter the physiological state. It is possible that such an effect could result in a more physically efficient performance.

FUTURE RECOMMENDATIONS

Several key concerns should be addressed in future performance psychophysiological research. Technologically, most EEG research has involved only two to four electrode sites. One such development that may advance our understanding of the psychology of performance is increased spatial resolution. To date, up to 256 electrode locations have been employed to measure electrocortical activity. Although such detailed resolution may be excessive for many of the questions in performance psychology, denser electrode arrays are needed to capture the activity of the brain in a more representative manner. Another concern in this area of research is the lack of consistency in recording strategies across studies. The diversity of methodologies in kinesiological psychophysiology is problematic. Specifically, different referencing strategies (e.g., linked ears, averaged ears, vertex) can alter the spectral estimates that are derived from the recorded EEG waves. Although the specific reference used in a given study will be determined on the basis of the question being addressed by the investigators, it would seem that some reasonable degree of standardization would result in greater comparability of results across studies.

Also of concern when studying the psychology of skilled psychomotor performance is the lack of consistency in the labeling of the participants as "skilled" and "unskilled" or "expert" and "novice." It would appear problematic that different investigators assign different levels of ability to categories that are characterized by the same name. In other words, skilled performers in one investigation may not be similar in ability to those who are labeled skilled in another study. It would be helpful, when possible, to describe skill in terms of absolute behavioral criteria as opposed to the relative rankings of the groups that are included in a given study. Subscription to such an approach would resolve possible contradictions that may emerge in the results of various studies.

Finally, it would appear of major importance for future studies to determine cognitive activity from EEG by employing experimental designs that incorporate appropriate comparison conditions. In this regard, the participants should be challenged with "known" psychological tasks so that the recorded time series can then be compared to those that are obtained during psychomotor performance. Such a strategy will allow for reasonable cognitive inferences so that the psychophysiological recordings can be related to higher-level psychological functioning.

CONCLUSIONS

Generally, the psychophysiological measures that have been used in performance psychology are sensitive to both intersubject and intrasubject differences. That is, expert and novice as well as skilled and unskilled performers exhibit different electrophysiological profiles. Further, performance variability within participants is also associated with specific patterns of psychophysiological activity. These physiological distinctions have been observed in both the cognitive and affective domains and, importantly, have been associated with performance state.

Efficiency of psychomotor performance may provide a conceptual framework within kinesiological psychology to guide both research efforts and interventions employed by applied sport psychologists. The acquisition of skilled performance may undergo an adaptive process that prunes task-irrelevant processes, resulting in a more economical or efficient allocation of neural resources. Such processes may contribute significantly to the phenomenological experiences or psychological states that are central to this area of research. Because the integration of motor control and psychological processes occurs in the brain, the psychophysiological level of measurement holds promise for understanding how cognitive-affective factors influence the quality of motor behavior.

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