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Understanding Neural Mechanisms of Memory in Rapid Recognition of Football Formations

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Introduction

The transition from high school to college football brings a multitude of challenges that a young athlete needs to overcome within the timeframe of a single summer. Commonly, we emphasize the magnitude of the physical demands that come with making this transition, and overlook the substantial mental adjustment that must occur simultaneously to ensure success. This chapter addresses the neural mechanisms of the cognitive processes that take place when a new quarterback is taught how to analyze defensive formations to make play decisions. Through the training process, this information must be consolidated to the point where the athlete is game-ready in the fall. We focus on the stages of learning, the brain mechanisms involved in each, and the human neuroscience technologies that allow us to study these brain mechanisms. Finally, we highlight important challenges, including the effects of stress and the lack of sleep, which must be considered to maximize health and performance.

Learning to Read the Defense

The quarterback lines up and faces a specific defensive formation that will immediately shape how the play unfolds. To understand how one learns to make the necessary split-second decisions in reading the defense, we can break down the learning process into two stages using the classic dual-stage learning model: (1) early/deliberate and (2) automatic (Shiffrin & Schneider, 1977). The deliberate stage always precedes the automatic stage, and is where we would traditionally consider most of the "learning" is taking place. The deliberate stage is defined as a period where the quarterback must exert a high level of concentration to recognize a defensive formation and relies more heavily on consciously holding information in mind (i.e. working memory). In this deliberate stage, the athlete is slow to make the analysis, and commonly makes mistakes. The time a quarterback spends in the deliberate stage is very sensitive as the brain is working hard to consolidate the concepts they are learning, and even the slightest variations in how these skills are taught or how the player takes care of themselves during this period can have a considerable impact on how the athlete performs in a game situation, as we will discuss later in the chapter.

The end-goal of every coach is to get their player to the automatic stage. As the name implies, this stage is defined as a shift towards a more automatic or *unconscious* mode of operation (Shiffrin & Schneider, 1977). The quarterbacks that reach this stage do not need to focus all their attention to read a defense, do not need to rely as heavily on working memory, and can make their analysis quickly and accurately. When competing in high-level athletics, it is important for a player to operate unconsciously. Cognition is not only fast, but they can focus their attention on multiple aspects of the game at once. Attention and working memory are finite resources, and by practicing a skill to the point of automaticity the player is effectively shrinking the amount of mental and neural real-estate it takes to perform that skill.

Measuring the Neural Mechanisms of Becoming Unconscious

A player's progress through the learning stages can be tracked by monitoring distinct changes in the brain that occur in each stage (Chein & Schneider, 2005). Specifically, it is important to measure and understand the neural mechanisms of memory consolidation as it allows us to evaluate healthy versus insufficient learning. Several advances in human neurophysiology allow us to measure the neural mechanisms of learning and memory as they unfold.

Brain activity is commonly measured using two noninvasive neuroimaging methods: Electroencephalography (EEG) and functional Magnetic Resonance Imaging (fMRI). EEG measures the electrical activity of brain cells by placing a network of electrodes on the scalp. With enough (256) channels, we call this dense array or "high density" EEG (dEEG) (Tucker, 1993). When EEG is recorded during a task, small changes in voltage can correlate with specific operations within the task, called an Event Related Potential (ERP) (Figure 8.1).

Small experimental manipulations or changes in behavior can have a measurable impact on ERPs and, as we will soon discuss, can allow us to track learning. The pros of recording EEG is that it picks up brain activity with high temporal resolution, down to one millisecond. However, EEG can be non-specific and records the activity of tens of thousands of brain cells at once. Moreover, due to differences in cell structure in different brain parts, EEG can only record activity from the cerebral cortex (the wrinkled, outer-most layer of the brain). Some of the spatial shortcomings of EEG are made-up for using MRI. Standard MRI (not to be confused with functional MRI) uses a strong magnet combined with radio frequencies (RF) to measure the presence of hydrogen atoms in soft tissue. The brain is made-up of several different types of tissue with very reliable differences in hydrogen, and thus we can tune an MRI to give us a grayscale image of the brain and its tissues (Figure 8.2).

Using some of the same techniques as standard MRI, we can tune the machine to measure oxygen levels in blood vessels after a neuronal event occurs. The brain is constantly being fed oxygen through its matrix of vasculature, and when neurons fire oxygen is stripped from hemoglobin (a protein in red blood cells that carries oxygen) until subsequent cardiac events occur to resupply the brain with oxygenated hemoglobin. fMRI can detect the subtle difference between oxygenated and de-oxygenated hemoglobin while a subject preforms a task, and when we superimpose the map of where oxygen exchange is occurring over a structural image of the brain, we get the

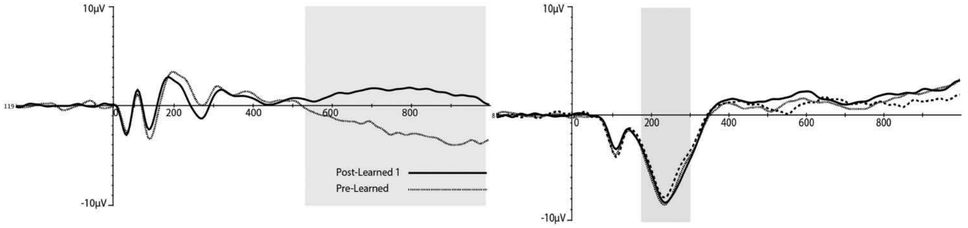

Figure 8.1 Example of Event Related Potentials (ERPs) showing progression of the P300 (left, in red) versus the MFN (right, in blue) over one day of formation analysis training. P300 amplitude significantly increased as learning progressed, whereas the MFN significantly decreased as learning progressed. The amplitude of the MFN is measured in reference to the amplitude of the preceding positive wave (P2).

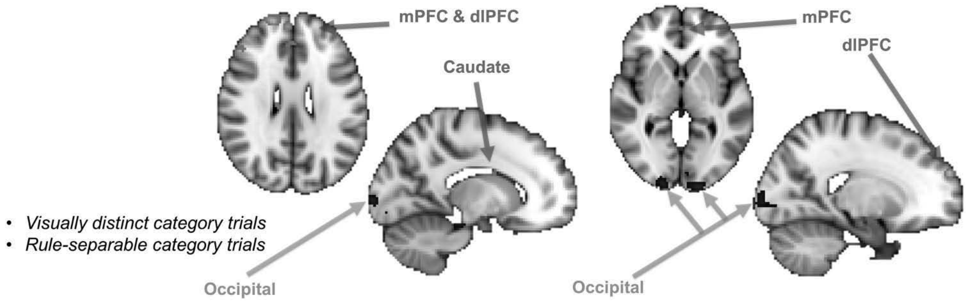

Figure 8.2 Example of functional MRI data (red and blue areas) superimposed on top of structural MRI (grayscale brain images) displaying preferential engagement of multiple memory systems during defensive formation analysis. Visually distinct blitz and goal-line defenses recruited a memory system centered on lateral occipital cortex (blue), whereas visually similar defenses (4-3 and 3-4 formations) relied on a rule-based system that involves several frontal areas and caudate nucleus (red).

classic map of brain activity we are mostly familiar with (Figure 8.2). This map is only limited by the presence of blood vessels, which is luckily very dense, and can image activity in deeper brain regions than EEG. However, blood flow in the brain is substantially slower than the electrical events happening between neurons, and fMRI is stuck measuring activity five to 10 seconds after a neural event has occurred. This makes it difficult for fMRI to tease-apart brain activity that occurs below the approximately seven-second timescale in multifaceted tasks: e.g. if visual analysis of an image, response selection, and feedback evaluation all happen within one second, it can be difficult to analyze activity for each specific subtask. Due to the complimentary shortcomings of both popular neuroimaging methods, our laboratory, like many others, employs both to get the spatial (fMRI) and temporal (EEG) benefits from each modality.

Dual Neural Systems of Memory Consolidation

By looking at how the structures that support memory interact with one another, we can gain insight into how the brain forms, organizes, and retrieves memories within the context of defensive formation analysis. Information about objects and events, and the context or location under which they occurred are processed in two streams in the cerebral cortex (Schneider, 1969). Within this model, the sensory pathways (e.g. primary visual cortex) take information in from the outside world and help us form an initial identification of an event or object, and then send this information up to the parietal lobe (Ungerleider & Mishkin, 1982; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003). We refer to this stream as the dorsal, or "where" pathway. This pathway specializes in the spatial analysis of stimuli, such as how players are configured on the line of scrimmage, and organizes holistic attention that eventually leads to impulsive actions. There is also a second pathway that is responsible for the identification of "what" event or object is being presented, and this information is processed by the ventral limbic system—parahippocampal gyrus, piriform, and entorhinal cortex (with the addition of the amygdala, in humans)—and is referred to as the ventral processing stream (Ungerleider & Mishkin, 1982; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003). Information from both streams converge at the hippocampus, which is a structure situated in the medial temporal lobe (MTL) that plays a key role in organizing input to link memories by their contextual representation (Luu et al., 2011). Once processing commences within the hippocampus, the output returns to the cortical areas from which the inputs originated (dorsal or ventral). In the dorsal pathway an additional structure, the medial prefrontal cortex (mPFC), selects the memory from the hippocampal feedback, whereas the striatum aids in memory selection for the ventral pathway. This feedback structure allows the hippocampus to organize memory retrieval based off "what" occurred or "where" something occurred, and makes it an essential mechanism for memory retrieval. We can now use this model of memory system dynamics/organization as a guide to understand how our athlete's memories are formed throughout the learning process.

Simulating Game Decisions in the dEEG Laboratory

When a new quarterback is working on formation recognition, it is becoming common practice to train them in a classroom environment. This affords coaches the opportunity to control the speed of the game, the formations they are viewing, and record their performance. Luckily for researchers, this environment is easily replicated in an experimental setting. Recently, our lab took 20 novice football players and ran them through a training program that taught them how to identify formations (Morgan, Luu, & Tucker, 2016). Players were shown an array of formations from the quarterback perspective one at a time (Figure 8.3).

On every trial, the participant was asked to either hit a button on a keypad or take no action (Go vs. No Go), which corresponded to a game-time scenario where a player may need to call an audible to switch a play after analyzing the defense (Go) or take no action if a desirable defense is shown (No Go). The participants were given corrective feedback which helped guide their actions or inactions toward each formation. Over three days, we recorded EEG from each participant as their abilities improved, and found two ERPs that accurately reflect the transition from the early/deliberate to the automatic stages of learning. The Medial Frontal Negativity is an ERP that reflects activity from the Anterior Cingulate Cortex (ACC), which is a region that is commonly thought of as the control center of the frontal lobe (Figure 8.1). Frontal brain regions are responsible for higher-level evaluations of a stimulus such as attention, effortful control, performance monitoring, and working memory—all aspects of the deliberate stage. In our study, we found that the MFN was largest when subjects performed poorly on formation recognition in the first day, but as performance increased with practice, the MFN reduced in size. As the MFN was shrinking, we witnessed a sizeable increase in a more posterior ERP termed the P300 (Figure 8.1). The

Figure 8.3 Example defensive formation. The players in white (offense) are held constant in our dEEG study, whereas the players in red (defense) change position from trial to trial. The subject in our study is tasked with learning how defensive formations map onto responses on a keypad.

P300 is an ERP which indexes the updating or confirmation of the context under which an action was learned and performed, and is estimated to reflect activity in the posterior cingulate cortex (PCC) and areas surrounding the hippocampus—two regions responsible for the consolidation of memories—amongst several others (Polich, 2007; Luu et al., 2011; Halgren et al., 1995). By combining the dual-stage model of learning with the dual-processing model discussed earlier for memory organization, we can get a clear picture as to why this happens. The early/deliberate stage is responsible for forming the context under which a quarterback learns to recognize a formation and requires controlled processing from frontal regions, whereas the automatic phase marks a reduction in frontal engagement (reflected as a reduction in the need for controlled attention) and an increase in activity from more posterior regions where the context is simply monitored. Put more clearly, the early stage is a time where the brain requires more attentional resources to build-up the contextual blueprint that binds inputs and outputs—where we know the hippocampus plays a large role in associating the two. The lack of context in the early stage leaves little work for the hippocampus to do, but as that context forms with practice, the role of the hippocampus becomes increasingly important to the point where controlled processes are no longer needed and the brain can rely on the object/event recognition system (the ventral processing stream) (Donchin & Coles, 1988; Polich, 2007; Luu et al., 2011). This allows the player to perform the learned action without a substantial cognitive load, and can focus their attention on other aspects of the game.

Implications for Quarterback Training

Within the context of formation analysis, quarterbacks in the early stages of learning are relying heavily on attention and working memory when viewing a defense. They will typically take a considerable amount of time to scan the entire formation and consciously think about the play that counters what is shown. Corrective feedback is given to the quarterback in the form of yards gained or lost as a result of their play calling, and this feedback is critical during the early stages of learning. At the neural level, the anterior brain regions are focusing attention on the most relevant aspects of a scene that lead to success or failure (e.g. how far apart are the players?), and with every trial and error it is interfacing with the hippocampus to generate a small bank of this spatially important data. When a quarterback has had sufficient training, we see that the player no longer needs to scan the entire defense. Instead, they can filter-out the irrelevant aspects of the scene (reducing cognitive load), and quickly peak at the relevant features that garner success and failure. This is measured behaviorally by significantly faster and less variable reaction times than the early stages, along with error reduction. In the brain, our results show that activity has shifted away from anterior regions, and towards the posterior. All the trial and error committed in the early stages of learning has formed an easily accessible database of inputs (formations) and outputs (audible plays). This shift is important as it can be used as a metric during training. Players who report a need to focus attention on a defense could benefit from more analysis drills, whereas a player who reports being unconscious during accurate decision making will only see incremental improvements from the same training.

The anterior-posterior shift observed in our study reflects a well-known phenomenon when a task involves mapping inputs (formations in our example) to a set of corresponding outputs (play selection or button presses) (Shiffrin & Schneider, 1977). In fact, this reliable input/output format is a prerequisite for a skill to reach automaticity, and is an important concept for coaches to understand as they take their athletes through training. Practice sessions must have a concrete set of inputs (with little variation at first) that map onto outputs so that the relay of information from the control processing system (ACC and frontal cortical brain areas) to areas associated with automatic processing (such as the hippocampus or other memory systems) is stable. Unreliable input/output mappings can delay the transition to automaticity, or worse, can contaminate the information that gets into the automatic stream which is the premise for forming bad habits that need to be retrained (Chein & Schneider, 2005). To emphasize this point even more, the introduction of stress into the equation forces athletes to rely on their instincts—that is, they rely on information that comes automatically (Schwabe et al., 2007; Schwabe, Schachinger, de Kloet, & Oitzl, 2010). This is due in part to the modulation of attention, where peripheral attention is incapacitated by stress, and attention becomes more focused (a phenomenon known as "tunnel vision"). This supports the concept of attention being a finite resource.

Recall that a main proponent of the deliberate learning stage is attention, but not for the automatic stage. If a player's ability to focus on multiple aspects of the game is hindered, then they run the risk of stripping attention away from a skill that requires it (in the case that the skill has not be practiced to the point of automaticity). Doing so will certainly lead to errors if the information available to the automatic processing stream is unreliable. In addition, overly focused attention limits the amount of spatial information required by the dorsal ("where") processing stream, and we see disengagement from the dorsal processing stream under stress and a reliance upon the more primitive ventral stream. The brain defaults to relying on actions that are associated with object recognition because this information is readily available. This is the premise for why it is important to practice performing under pressure, as it exposes gaps in a player's current state of training. Quality training regimens will ensure that what comes automatically to a player is the correct action when the pressure of a game-time situation occurs, and that they do not default to an undesirable habit (Schwabe et al., 2007).

Mapping the Appropriate Memory System with Functional MRI

Stress is not the only thing that leads to errors or slow performance during training. As discussed earlier, memories can be broken down into multiple processing streams or memory systems that specialize in different types of memories. Failure to recruit the optimal memory system for processing an incoming stimulus can be detrimental to learning (Maddox, Ashby, Ing, & Pickering, 2004; Zeithamova & Maddox, 2007). In our laboratory, we used fMRI to understand if various types of defensive formations recruit the same or different memory systems. Like our EEG study, 13 participants were trained on how to recognize different defensive formations by pressing a button that corresponds to a play that exploits the defense. However, in this study, we shortened the training to one session, and the different formations were grouped into predetermined categories that reflect some of the most popular formations used in college and professional football. One category of formations corresponded to a goal-line defense (six players on the line of scrimmage and one player in the background, 6-1) and was visually distinct from the other two categories. The two remaining categories were visually similar to each other, with one category having four players on the line of scrimmage and three players in the backfield (4-3), and the other having three players on the line of scrimmage and four players in the backfield (3-4). Twelve total formations were used, resulting in four examples per category (Figure 8.4).

Subjects were instructed to figure out how to place each formation shown into one of the three categories, but they were not given any hints about how to do so. We hypothesized that the goal-line defense would recruit a memory system in visual brain regions that is optimal for making similarity judgments, whereas the two visually alike formations would rely on a rule-based system in the striatum (Figure 8.4) (Kemler-Nelson, 1984; Nosofsky 1986; Smith & Sloman, 1994). In support of our hypothesis, we found that subjects reliably recruited a memory system that is similar to the dorsal processing stream with support from the lateral occipital region (LO). In contrast, subjects relied more on a system similar to the ventral processing stream with engagement from a structure within the dorsal striatum called caudate nucleus, a sub-cortical region that plays a role in rule-application, and mPFC (Figure 8.2). A key take-away from this study is that training football players to recognize defensive formations should not be treated as a unitary phenomenon—the formations simply are not all processed in the

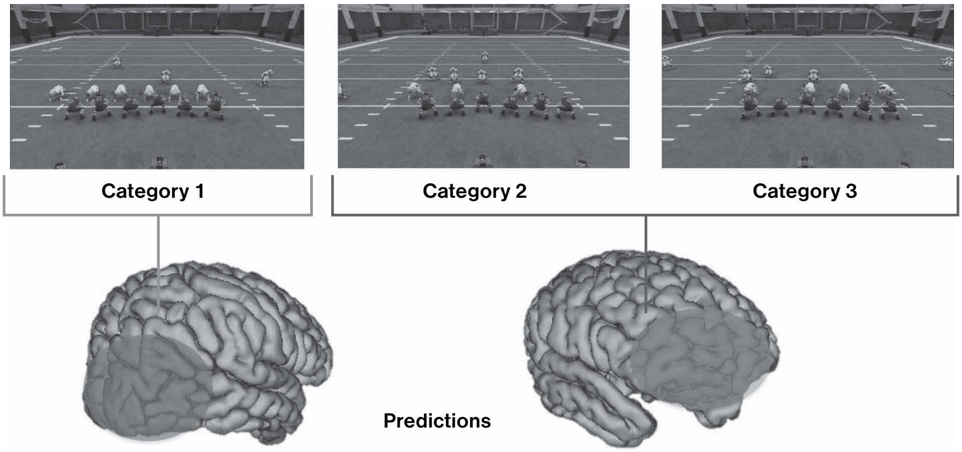

Figure 8.4 [Production: Fix color descriptions] Illustration of predictions in a categorization fMRI experiment. Blue: A visually distinct category should recruit the similarity-based categorization system, centered over the posterior visual regions. Red: Two visually similar categories should recruit the rule-based categorization system, centered over the frontal regions and caudate nucleus (not shown).

same way. In fact, the two memory systems engaged in our study differ in their speed of acquisition, reaction time dependent upon which phase of the learning process they are in, and their flexibility to make accurate responses when shown formations that only partially look like members of a category (Medin & Shaffer, 1978; Smith & Sloman, 1994). Although a person can still accurately categorize a formation with a suboptimal memory system, preliminary results from this study suggest that a mismatch between the formation category and memory system recruited on a single trial (measured by total signal present in each system) results in a higher error rate. These initial results are backed by other research that suggests category/memory system mismatches led to errors, impaired learning, and slow performance (Maddox Ashby, Ing, & Pickering, 2004). Thus, it is important to not only monitor where an athlete is in the learning process, but also where the learning is taking place and whether that system is the one that is going to maximize performance.

The preferential engagement of multiple memory systems has large implications for a quarterback's performance. The two memory systems discussed in our fMRI study are behaviorally expressed in the form of strategies a player uses to identify a formation (Smith & Sloman, 1994). The rule-based memory system is engaged when a player looks at a defense and uses a rule to recognize the formation. In our example, counting the number of players on the line of scrimmage and in the backfield, suffices as a rule. By contrast, the visual similarity system works through a general scanning of a formation and relies on comparing the formation shown to a general idea or exemplar of that formation to determine membership. Although the strategies are similar, using the wrong system can slow them down. To illustrate the point: if a quarterback is presented with a blitz, it will take much longer for the quarterback to count the large number of players on the line versus generally scanning the formation and comparing it to a general concept for a blitzing defense: e.g. "I should count the number of players on the line: 1, 2, 3... 6, that looks like a blitz is coming" vs "I generally see lots of players on the line of scrimmage and I should call an audible to get rid of the ball quickly". However, if the defense has been using two different formations that look visually similar but with different coverages, the quarterback will need to execute the counting rule to detect the subtle visual difference. Relying on a similarity system which works best when between-category variance is high will result in errors when between-category variance is low. Monitoring which system is recruited on a single trial basis can help coaches facilitate the appropriate analysis strategy to maximize performance.

Consolidating Memory with a Good Night's Sleep

If monitoring the brain during training doesn't seem feasible, perhaps the best way to maximize memory efficiency is to ensure that each athlete gets a full eight hours of sleep, because one of the best ways to disrupt memory consolidation and performance is sleep deprivation. Sleep research over the past century has established that memories of a day's experience are temporarily stored in a short-term center during waking hours, and only when someone sleeps does this information get transferred to long-term storage (Jenkins & Dallenbach, 1924; Morris, Williams, & Lubin, 1960; Harrison & Horne, 2000). However, it is not as simple as just falling asleep. Sleep happens in stages where, throughout the night, we oscillate between these different stages (Hobson & Pace-Schott, 2002). The sleep stages are most easily monitored using EEG as they have distinct oscillatory patterns than govern their classification. Perhaps the most widely recognized sleep stage is the period of Rapid Eye Movement (REM) sleep. However, there are also four stages of non-REM (nREM) that are equally important to understand. Stage I nREM is a period of light sleep where one can be awakened easily. Stage II nREM is classified as a time where eye movement stops and body temperature begins to drop. Stage III nREM, or deep sleep, is marked by a slowing heart rate, a further body temperate drop, and the presence of very slow brain waves called delta waves. Interspersed between the delta waves are periods of very fast, but smaller brain waves. Stage IV is commonly referred to as Slow Wave Sleep (SWS), where the brain produces delta waves almost exclusively. After Stage IV, the body enters REM sleep, where the eyes dart back and forth, but the brain activity reflects that of being awake. Sensory input during REM is no longer relayed to the sensory processing centers of the brain by the thalamus, and the body is paralyzed. The clear majority of dreaming happens during REM sleep. A healthy person will spend more time in Stage IV nREM during the early hours of the night, but as the night goes on the amount of REM increases and Stage IV nREM decreases (Figure 8.5). This means that, if an athlete (or anyone, for that matter) is deprived of as little as 2 hours of sleep, they can effectively cut off as much as 40–60% of their time spent in REM. This will become important as we discuss the significance of the sleep stages.

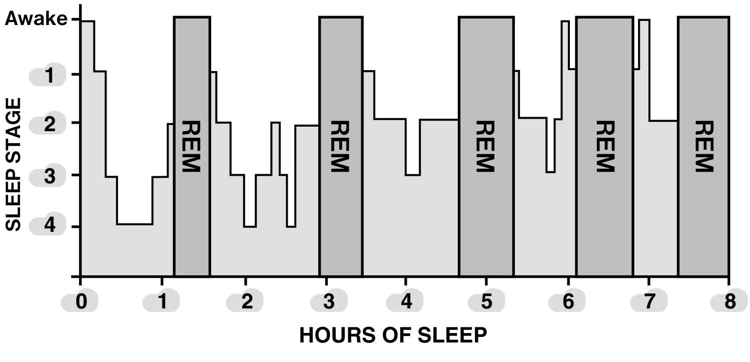

Figure 8.5 Illustration of sleep stages during an eight-hour night. Throughout the night, the body oscillates through four nREM sleep stages and a single REM stage. In the later hours, the amount of time spent in REM sleep increases, while the time spent in deep sleep (stages III and IV nREM) decreases.

A growing body of evidence suggests that slow-wave sleep (SWS) (stages III and IV nREM) is responsible for the consolidation of declarative memories, which is the type of memory we associate with things such as explicit facts (Plihal & Born, 1997; Harris & Horne, 2000). Studies have shown that time spent in SWS can predict learning outcomes on a memory task the next day. More recently, the literature further specifies that not only is the time spent in SWS important, but the phase alignment of the slow oscillations and sleep spindles within this stage can also predict performance (Molle & Born, 2011). This means that, even if an athlete is getting a full eight hours of sleep, it is the brain activity during those hours that have an important role in subsequent performance the next day.

Perhaps even more jarring, Stage II nREM sleep spindles in the last two hours of sleep (hours seven and eight) are closely tied to motor memory consolidation (Laventure et al., 2016). This has profound implications for the sports domain, as motor memory is a key aspect of any formal sport, and if an athlete is woken up early to go to practice (cutting their sleep to six hours), the coach could be inadvertently hindering their brains ability to form connections in motor memory pathways.

The significance of REM sleep and its vivid dreams has long been debated. Several findings suggest that REM is important to emotional integration (van der Helm et al., 2011). This would imply that fully integrating the emotional significance of training and performance challenges may be impaired if sleep is limited, because REM is the main stage that suffers from too little sleep. Furthermore, other evidence suggests that creativity in problem-solving is impaired if REM is disrupted (Cai, Mednick, Harrison, Kanady, & Mednick, 2009). Is creativity important to the quarterback's effective gameplay decisions? On the one hand, we might think that with adequate automaticity the quarterback's decisions are already made, and no creative problem solving is required. On the other hand, the creative mental skill of many quarterbacks is impressive, as they not only understand the intentions of the defense, but they select play options and executions that cause those intentions to be lead the defense in the wrong directions. In any sense, it is clear to see why, perhaps above and beyond any monitoring of memory system function during training, we allow them to sleep for as long as the body requires.

Future Directions

Future research in our lab will focus on using the information discussed in this chapter to improve the learning process. By using fMRI and dEEG, we will continue to classify neural signatures to track the learning process, along with the preferential engagement of multiple memory systems to consolidate and recall these memories efficiently. Our work will move toward understanding how memories are consolidated through sleep, and whether there is a way to enhance an athlete's time spent in the stage(s) of sleep most conducive to transferring relevant information to long-term memory. In addition, we will begin to develop tools (such as brain stimulation devices) to facilitate activity in the optimal memory system for categorizing a specific formation to prevent memory system/stimulus mismatches that lead to poor performance. Our long-term goal is to provide teams with an avenue to augment their training by measuring how their players are progressing through the program at the neural level, and use that information to develop tailored interventions to bring all players up to the desired skill level. This could give teams a competitive edge in a domain where it is common to see several teams in a division utilizing the same or similar strength training programs. Importantly, bridging sports and neuroscience represents a prime example of how brain research can have a positive impact beyond the traditional laboratory experiment.

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9

Psychologically Mediated Heart Rate Variability during Official Competition

Ambulatory, Ecological Investigations of the Heart Rate Deceleration Response with Implications for Quantifying Flow

Roland A. Carlstedt

Ambulatory sport psychophysiology involves the continuous instrument-based monitoring, observation, and analysis of mind-body-technical performance of athletes during real training and competition. It is particularly important to the study of athletes where research findings should have a high degree of ecological validity, meaning acquired data must be procured from and reflect conditions encountered in the context of sport-specific situations and actions (Fahrenberg & Myrtek, 1996; Carlstedt, 2012). For example, it is not sufficient to assume that shifts in relative brain hemispheric activation that were observed in an experimental situation will transfer to the playing field without measuring brain functioning during real competition. Or, it cannot be assumed that an analysis of heart rate variability (HRV) in vitro will be predictive of an athlete's autonomic balance during real competition (de Geus & van Doornen, 1996; van Doornen, Knol, Willemsen, & de Geus, 1994; Carlstedt, 2012). Ultimately, replicable and predictive psychophysiological response tendencies that are observed during real competition will help better explain the role or impact of mind-body variables in the peak performance equation.

While the value of ambulatory psychophysiological assessment has been recognized, it is still a relatively unexplored and underused procedure in Sport Psychology, despite the fact that many of the central constructs and theories of sport performance have physiological and psychophysiological components (Heil & Henschen, 1996; Taylor, 1996). For example, Yerkes and Dodson' s (1908) Inverted-U Theory proposes that a curvilinear relationship exists between physiological reactivity and performance, whereby increases in reactivity results in incremental improvement in performance, but only to a certain point, after which excessive reactivity disrupts performance. The psychophysiological concomitants of the Inverted-U-Theory are delineated in Duffy's (1972) description of activation theory and include increasing levels of HR, BP, muscle tension, skin conductance, and desynchronization of EEG alpha activity. In extending the Inverted-U Theory to account for individual differences in physiological reactivity, Hanin' s (1980) Zone of Optimal Functioning theory is also based on similar physiological markers of activation or intensity. Catastrophe Theory, the most recent postulate of intensity, similarly alludes to physiological processes (Hardy & Fazey, 1987). This theory advances the idea that cognitive anxiety mediates the effects of physiological arousal on performance (Hardy & Fazey, 1987).

Unfortunately, many of the physiological measures these theories allude to have not been operationalized beyond the theoretical. Little is known about the psychophysiological functioning of athletes during actual competition. Attempts to delineate physiological functioning during real competitive are rare with the field of Sport Psychology still relying on imprecise operationalizations of key physiological components of sport performance. This is illustrated in Taylor's (1996) view of intensity, which he refers to as

> the most critical factor prior to competitive performance because, no matter how confident, motivated, or technically or physically prepared athletes are to perform, they will simply not be able to perform their best if their bodies are not at an optimal level of intensity, accompanied by the requisite physiological and psychological changes.
>
> *(p. 75)*

In viewing Taylor's notion of intensity, one must ask, what do "confident" and "motivated" mean? Also, what is an "optimal level of intensity," and what are "requisite physiological" and "psychological changes" that accompany intensity?

These questions have yet to be answered. Without studying the effects and impact of physiological and psychophysiological processes on performance, assumptions about intensity or states of activation and performance remain speculative.

The ultimate goal of ambulatory psychophysiology in sports is to establish performance relationships that have a high degree of ecological validity as well as to establish ways of testing the efficacy of interventions and replicating laboratory data that have implications for performance. To date, the use of ambulatory psychophysiology in studying performance has been neglected, despite the potential it holds for deriving data that may be vital to the credibility of many of the theories and interventions in sport psychology. In the following study, relationships between psychological factors (for traits and behaviors comprising the Athlete's Profile [AP] model of peak performance, see Carlstedt, 2012), and psychophysiology (using heart rate variability as predictor and outcome measures) and performance were investigated using methods in ambulatory, ecological assessment.

Background and Review of the Literature

Heart Activity: An Ideal Measure of Psychological Performance

Research has revealed significant interactions between the cardiovascular, the central nervous system, and the somatic nervous system (Andreassi, 1995). One line of research has established relationships between cardiac activity and reaction time (RT), with Lacey and Lacey (1964); Obrist, Webb, and Sutterer (1969); and Webb and Obrist (1970) reporting decreased heart rate (HRD) during the fixed foreperiod of simple RT experiments. It has also been shown that greater magnitudes of HRD are related to faster RTs (Lacey, 1967). It has been suggested that HRD represents a preparation to respond when an individual expects a significant stimulus (Andreassi, 1995). Another line of research has focused on power spectral density analysis (PSD) or spectrum analysis of heart rate variability (HRV) to assess sympathetic versus parasympathetic influence on the heart (i.e., autonomic balance; Akselrod et al., 1981; Jorna, 1992; McCraty & Watkins,1996; Porges & Byrne,1992). As a sensitive, noninvasive test of autonomic nervous system (ANS) function, spectrum analysis of HRV has been used in clinical settings to investigate stress-related disorders, such as hypertension and cardiovascular disease (McCraty & Watkins, 1996). Clinical research has found that lowered HRV is associated with aging, depressed hormonal responses, and increased incidence of sudden death (Malik & Camm, 1995). In addition, spectrum analysis of HRV has shown that depression, panic disorders, anxiety, and worry affect autonomic function, and can reduce the protective influence parasympathetic activity exerts on the heart (Malik & Camm, 1995).

The Theory of Critical Moments (see, Carlstedt, 2012) predicts that negative constellations of AP factors (hypnotic susceptibility/absorption/subliminal attention, neuroticism/subliminal reactivity, and repressive coping/subliminal coping) that have been shown to drive physiological hyper-reactivity and resulting clinical complaints in patients can disrupt motor/technical and psychological performance in athletes (Taylor, 1996; Wickramasekera, 1988). By contrast, it is predicted that athletes who possess ideal constellations of AP factors are more likely to reach their zone of optimal functioning and maintain peak performance, especially during critical moments of competition. Since both physiological reactivity and autonomic balance are reflected in spectrum analyses of HRV, and HRD, cardiac activity is a valuable measure of physiological reactivity (intensity), emotions, attention, and mediator of outcome in athletes (Akselrod et al., 1981; Tiller, McCraty, & Atkinson, 1996; McCraty, Atkinson, Tiller, Rein, & Watkins, 1995; Carlstedt, 2012).

HRV can be viewed as the window into mind-body interactions. In addition to reflecting physiological reactivity and emotions, heart activity has also been found to be an important measure of attention and cognitive activity (Sandman, Walker, & Berka, 1982). In reviewing the literature, Sandman et al. (1982) concluded that heart rate (HR) and blood pressure (BP) were the physiological parameters that best differentiated the cognitive-perceptual process. Their observation was based on the Lacey's (1964; 1967) investigations that discovered that HR decreased during tasks demanding attention to the environment and increased during tasks requiring mental concentration (or, rejection of the environment). This phenomenon has been explained on the basis of brain-heart interactions whereby HRD has been found to release the cortex from the inhibitory control of the baro-receptors, as reflected in fast-frequency (i.e., beta waves in the 23–38+ Hz range) electroencephalographic (EEG) activity (23–38+ Hz EEG activity has been associated with vigilant or attentive behavior; Lindsley, 1969; Sandman et al., 1982). Conversely, heart rate acceleration (HRA) has been shown to stimulate baro-receptor activity and thereby inhibit cortical activity. This is reflected in slower wave EEG (8–12 Hz) that has been associated with decreased perceptual processing (Sandman et al., 1982; Wolk & Velden, 1987).

Galin (1974) maintains that heart activity is more useful than EEG for analyzing attentional processes, because EEG represents only activity at the dorsal convexity of the brain but does not reflect activity in deep medial brain areas such as the hippocampus and the amygdala. Pribam and McGuiness (1975) have proposed that the hippocampus and amygdala (deep, medial brain areas) play an important role in attentional processes.

Not surprisingly, attention and cognitive activity play central roles in the anecdotal literature and research of sports performance (Gallwey, 1974; Waller, 1988). As might be expected, attention (e.g., focusing on the ball) is considered a desirable psychological state, whereas cognitive activity (e.g., thinking about winning during a point) is thought to disrupt sport performance. For instance, Gallwey (1974), in his classic book *The Inner Game of Tennis*, advocates letting things flow, or happen naturally, by focusing on the ball and warns of thinking too much about the consequences of hitting the ball. These notions appear to have found acceptance, with Ravizza (1977) reporting that 95% of the athletes he surveyed believed that thinking hinders performance. In addition, Waller (1988) reported that reduced levels of cognitive activity were experienced by athletes during peak performance episodes.

Since HRV has been shown to reflect many psychological states (e.g., attention & cognition), its importance to externally validating predictions from the TCM is highlighted. It is an ideal measure for operationalizing psychological constructs that have yet to be defined beyond anecdotal conjecture in sports (e.g., attention, cognitive activity, physiological reactivity, or intensity).

Given that there have been no studies on psychologically mediated HRV during real competition, research exploring the dynamics of AP-brain-heart interactions and their effects on performance is presented here. In extending research on HRD and HRV to the field, this study investigates some cardiovascular concomitants of constellations of AP factors during actual competition, in this case, official tennis tournament matches.

Heart Rate Variability/Heart Rate Deceleration: A Primer

In order to understand how HRV can reflect psychological processes (e.g., AP factors) and performance, it is necessary to review how the heart responds to autonomic nervous system activity.

HRV represents the net effect of parasympathetic (vagus) nerves, which slows HR, and the sympathetic nerves which accelerate it (Porges & Byrne, 1992). At rest, both parasympathetic and sympathetic nerves remain tonically active, with vagal effects being dominant (McCraty & Watkins, 1996; Obrist, 1981). Stimulation of the vagus nerves slows the heart. This slowing occurs almost immediately, within one or two heart beats after its onset. After vagal stimulation ceases, HR quickly returns to its previous level. An increase in HR can result from a reduction in vagal activity. Therefore, sudden changes in HR are initiated by parasympathetic activity (Lacey & Lacey, 1978). Increases in sympathetic activity cause HR to rise above the intrinsic HR level produced by the sinoatrial node. After sympathetic stimulation begins, there is a delay of up to five seconds before a progressive increase in HR occurs, which reaches a steady level in 20–30 seconds (McCraty & Watkins, 1996). The slowness of HR response to sympathetic stimulation is contrasted to vagal stimulation that produces immediate HR deceleration (McCraty & Watkins, 1996).

Blood Pressure, Baro-receptors, and HRV

Blood pressure (BP) regulation is of primary importance to cardiovascular function. The factors that control BP also regulate HRV (McCraty & Watkins, 1996; Obrist, 1981). Short-term regulation of BP is achieved through an intricate system of pressure-sensitive baro-receptors located throughout the heart, aortic arch, and the carotid artery (Lacey & Lacey, 1978; Obrist, 1981). Afferent impulses (i.e., signals transmitted to the brain) from the baro-receptors travel via the glosso-pharyngeal and vagal nerves to the vasomotor centers in the medulla oblongata where they regulate sympathetic nervous system (SNS) transmissions to the heart and blood vessels. Some modulation of parasympathetic nervous system (PNS) transmission also occurs in the medulla oblongata (Obrist, 1981; Porges & Byrne, 1992). Baro-receptors regulate HR, vasoconstriction, venoconstriction, and cardiac contractility to maintain BP (Obrist, 1981).

The regulation of BP by baro-receptors is hypothesized to differentially facilitate or inhibit cortical activity and attentional efficiency (Lacey & Lacey, 1978). Specifically, elevated HR and BP are thought to inhibit cortical activity, thereby decreasing attention, whereas HR deceleration and lowered BP are thought to facilitate attentional processes (Lacey & Lacey, 1978; Sandman et al., 1982).

In summary, ANS (sympathetic and parasympathetic) activity along with afferent signals from the baro-receptor produce the beat-to-beat changes that characterize HRV (Obrist, 1981; Porges & Byrne, 1992).

Measures of HRV

Time and frequency domain measures are used to analyze HRV (Leiderman & Shapiro, 1962; Akselrod et al., 1981). The most common method for obtaining these measures is to plot the sequence of time intervals between the R-waves of the heart period (HP; such data can be obtained using ambulatory HR monitoring equipment, e.g., Holter & Polar systems). The resulting graph of heart rate changes (i.e., HRV) is called a tachogram (Andreassi, 1995). The tachogram reflects the ANS mediated HRV signal and beat-to-beat changes in HR (Andreassi, 1995; McCraty & Watkins, 1996).

With both methods, the time intervals between consecutive R-waves of the HP are first calculated (Andreassi, 1995). Thereafter, HRV measures of interest are delineated and analyzed accordingly (e.g., HR deceleration or PSD analysis).

Time Domain Measures

Time Domain Measures of HRV reflect changes in heart activity that occur within a single cardiac cycle (i.e., HP, or inter-beat interval [IBI], and are expressed in milliseconds; [ms] Andreassi, 1995). Time domain measures of interest include heart rate deceleration (HRD) and, to a lesser extent, heart rate acceleration (HRA). HRD is the progressive slowing of one or more successive IBIs (i.e., HR slowing from R-wave to R-wave of the HP). For example, IBI ms values of 555, 560, 570, 575, and 580 reflect HRD between four IBIs (increasing values reflect a longer HP, or slowing of the heart; Andreassi, 1995). By contrast, IBI values of 580, 575, 570, and 565 reflect HRA between three consecutive IBIs (decreasing IBI values indicate a shorter HP or acceleration of the heart).

Time domain measures of HRV have been used to study RT, task performance, complex motor activity, perception, mental imagery, attention, motivation, emotion, and operant conditioning of HR (Carriero & Fite, 1977; Elliott, 1974; Elliott, Bankert & Light, 1970; Hahn, 1973; Jennings & Wood, 1977; Lacey & Lacey, 1974; Lang, Levin, Miller, & Kozak, 1983; McCanne & Sandman, 1976; Obrist, Howard, Sutterer, Hennis, & Murrell, 1973; Schell & Catina, 1975).

Frequency Domain Measures

Frequency domain measures refer to power spectral density (PSD) or spectrum analysis measures of HRV (McCraty & Watkins, 1996). PSD shows how the power of heart activity is distributed as a function of frequency (McCraty & Watkins, 1996). The PSD of HRV is obtained by filtering and extracting the different frequency components of HRV that are discernible in the tachogram. The HRV power spectrum contains three main frequency ranges: (1) very low frequency (VLF, 0.033–0.04 Hz); (2) low frequency (LF, 0.04–0.15 Hz); and high frequency (HF, 0.15–0.4 Hz; Akselrod et al., 1981; Malik & Camm, 1995). The HF range reflects rapid changes in beat-to-beat variability (i.e., HRV) that are caused by parasympathetic or vagal stimulation (Akselrod et al., 1981; Malik & Camm, 1995). The VLF range is thought to reflect predominantly sympathetic stimulation (Akselrod et al., 1981; Malik & Camm, 1995). The LF range reflects both a mixture of sympathetic and parasympathetic stimulation of the heart (Akselrod et al., 1981; Malik & Camm, 1995). The LF/HF ratio is used to quantify the overall balance between the sympathetic and parasympathetic systems and is a measure of special interest in this study (Malik & Camm, 1995).

Frequency domain analysis of HRV (i.e., PSD or spectrum analysis) provides reliable measures of the effects stress and emotions exert on autonomic function. To date, PSD analysis of HRV research has been limited mostly to clinical and organizational settings (McCraty & Watkins, 1996; Jorna, 1992; Myrtek, Bruegner, & Mueller, 1996). It has not been used to analyze continuous psychologically mediated HRV during official sports competition (Carlstedt, 2012).

Heart Rate Variability Research

The presented study is based on two lines of research. The first is traced to Lacey & Lacey's (1964; 1978) seminal investigations of cardiac deceleration (HRD) in the simple reaction time paradigm. The second line can be traced to Akselrod's et al. (1981) mathematical quantification of the physiologic mechanisms of beat-to-beat HR fluctuations, or spectrum analysis of HRV. Research of HRD and spectrum analysis has been numerous, although interest in HRD has waned over the years (due to time consuming methods and analytics that are required to accurately isolate HRD trends over time), while interest in spectrum analysis of HRV has been increasing. This is also attributable to the fact that psychologically mediated HRD is no longer disputable, and spectrum analysis, which is more relevant to clinical, educational, and work place issues and can be derived and analyzed using user-friendly hard-and software (Andreassi, 1995; Sandman et al., 1982).

Although there is literature on HRD research in sports, it has been limited to static, non-action types of sports such as shooting, archery, and golf (Hatfield, Landers, & Ray, 1984, 1987;

Boutcher & Zinsser, 1990). Other than this author's long line of HRD investigations (Carlstedt, 2012) this cardiac response has not been studied ecologically, during real competition or in action sports where little is known about the effects of cardiac deceleration, especially during critical moments. Furthermore, no studies of have investigated HRD in athletes as a function of AP factors and other psychological measures. There also, are no previous studies on spectrum analysis of psychologically mediated HRV in athletes during official competition.

HRD Research

HRD research falls into two categories. (1) Mechanistic studies are investigations that have detailed the properties of HRD within experimental variations of the simple RT paradigm. These studies have demonstrated the existence of HRD. Simple RT time and choice RT paradigms are presented in some detail to illuminate components of the simple RT model that have been adapted to the presented study and other investigations of HRD in sports. (2) Performance studies have investigated the effects of HRD on performance. These studies have associated HRD with differential RT and task performance, both in the laboratory and structured sport experiments.

Mechanistic Studies of HRD

HRD has been demonstrated in a variety of studies, with Lacey and Lacey (1964) being the first to show that HR decreased in response to an imperative (i.e., imminent or impending) stimulus. The Laceys' work introduced the simple RT paradigm in which subjects were required to press a key after the appearance of a ready signal (a green circle in a display box), hold the key down until the imperative signal (a white cross) was superimposed on the green circle, and respond as quickly as possible to the white cross, by releasing the key. The so-called fixed foreperiod, or time offset, between the time of initial key depression and the presentation of the imperative signal lasted four seconds. Results of this study showed a progressive slowing of the heart (i.e., HRD), from the time of the ready signal (i.e., pressing the key) to when the imperative signal was presented (as reflected in the lengthening of successive IBIs prior to the imperative signal).

In an extension of their original research, the Laceys (1978) measured HP as a function of time in which the imperative stimulus was presented in the cardiac cycle. They found that the magnitude of HR deceleration during the fixed foreperiod depended on where in the cardiac cycle the imperative stimulus was presented. If it occurred early (4th decile) in the cycle, deceleration was significantly greater than if the imperative signal came late (10th decile) in the cycle.

The Laceys (1970) also reported anticipatory slowing (i.e., HRD) in experiments requiring self-initiated responses (choice RT paradigm). For example, subjects having a prior knowledge of the onset of a significant stimulus tended to exhibit increasingly greater heart rate slowing (HRD) as the time of voluntary motor response approached.

The simple RT paradigm and variations thereof (e.g., choice RT paradigm) lend themselves well to studying HRD in settings where persons are waiting to respond to a stimulus including prior to certain sport-specific tasks (Edwards & Alsip, 1966; Heslegrave, Ogilvie, & Furedy, 1979; Nowlin, Eisdorfer, Whalen, & Troyer, 1970; Surwillo, 1971; Walter & Porges, 1976). For example, in measuring heart activity as a function of task demand, the Laceys (1968) measured HRD during a six second interval prior to the foreperiod, for six seconds of the foreperiod, and for six seconds after the response. In tennis this would amount to a player waiting six seconds prior to entering the ready position to receive serve, after which six more seconds pass before the ball is served (stimulus presentation-response), followed by action lasting six seconds (time period from when the serve was returned to when the point ends). Similar intervals occur in golf, baseball, softball, and basketball, sports that were investigated in Study 1 (below). The Laceys' original mechanistic studies of HR deceleration have been replicated numerous times (e.g., Webb & Obrist, 1970). In essence, replication investigations support the hypothesis that HRD is a species-wide response, in anticipation of an imperative stimulus.

Performance Studies of HRD

The mere fact that HRD has been empirically validated as a species-wide response is of minor importance to athletes if HRD cannot be linked to within- or between-subject differences in performance. Thus, if HRD does not distinguish good from poor performance, why should it be studied? This question is in part answered by performance studies of HRD which suggest that within- and between-subject differences in HRD are associated with differential task performance and level of skill. For example, Wang and Landers (as cited in Boutcher & Zinsser, 1990; original source unavailable), Landers et al. (1994) and Salazar et al. (1990) comparing highly and moderately skilled archers, reported HRD in both subject groups prior to shooting (i.e., in the preparation phase before arrow release). In addition, they found differences in HRD between groups. Although both groups exhibited HRD patterns, highly skilled archers demonstrated significantly greater HRD in comparison to lesser skilled archers, during the aiming phase.

In a similar study involving golf, Boutcher and Zinsser (1990) replicated the basic findings of Wang and Landers. In a comparison of elite and beginning golfers during putting, they also reported individual differences in HRD-performance effects. Specifically, they showed that both elite and beginning golfers exhibited significant HRD compared to baseline HR, prior to putting. In addition, elite golfers were found to experience significantly slower HR than beginning golfers immediately before, during, and after the ball was putted. Hatfield et al. (1984) also reported that elite rifle shooters exhibited HRD prior to shooting. Although this study did not differentiate performance proficiency, it did provide evidence in support of previous electrophysiological and neurocardiologic explanations of psychologically mediated HRV (e.g., Armour, 1994; Lacey & Lacey, 1978; McCraty & Watkins, 1996; Sandman et al., 1982). These researchers reported that increased right hemispheric EEG activity was concomitant to HRD prior to shooting. This finding is in line with previous research associating HRD with increased cortical activity (as observed in increased EEG alpha activity (Lacey & Lacey, 1978; Sandman et al., 1982). The authors proposed that elite marksmen have developed attentional focus to the extent that they are unconsciously capable of reducing cognitive activity in the left hemisphere (i.e., left half of the brain). Left hemisphere cognitive activity has been associated with the disruption of motor performance (Hatfield et al., 1984; Langer & Imber, 1979).

The above studies are important because they clearly establish that the magnitude of HRD during self-paced sports is associated with a performer's level of skill. They provide evidence that HRD is not only a species-wide physiological response, but that it also reflects individual differences in athletic ability. However, they did not investigate within- or between-subject differences in HRD as a function of personality traits or behavioral measures (e.g., AP factors/constellations). Recent research by Hassmen and Koivula (2001) showing that anxiety can disrupt HRD trends supports the TCM hypothesis that personality and behavioral factors can affect physiological responding and should be considered in all psychophysiological research.

HRD I: A Case Study of HRD during Official Tennis Matches: Hypotheses

Hypothesis 1: Total HRD

Hypothesis 1 predicted that HRD patterns during tennis matches would resemble deceleration trends observed in previous research of self-paced sports. For example, it was hypothesized that during the pre-action phases of matches, IBIs would progressively lengthen (i.e., become slower) up to the point when action commences.

Hypothesis 2: HRD and Successful Performance

Hypothesis 2 predicted that more and greater magnitudes of HRD would occur in a match that was won compared to a match that was lost.

Spectrum Analysis of HRV

A spectrum analysis of HRV was performed for exploratory purposes to determine if differences in heart rate variability existed between matches.

Participant

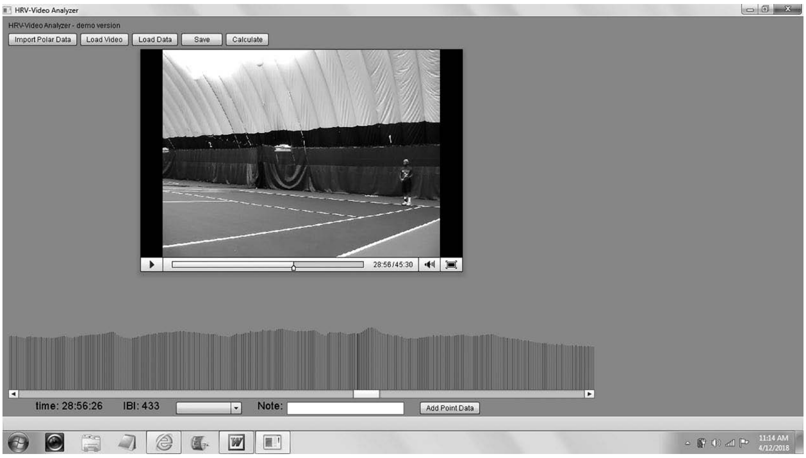
This study involved a 16-year-old male who was a nationally ranked tennis Player. He was assessed on AP factors and found to have the constellation High Absorption, Medium Neuroticism, and Low Repressive Coping. It should be noted that this is considered a relatively negative constellation in the context of critical moments of competition (TCM).

Research Design

The study used a single-case/repeated measures design and was carried out during an official USTA tennis tournament. The player's heart activity was monitored using ambulatory cardiac monitoring instrumentation during his first, second, and third round matches. Since the goal of this study was to establish differences in HRD and HRV between matches that were won and lost, Match 1 (won) was compared with Match 3 (lost). Match 2, which was won, was not analyzed since it was played on the same day as Match 1. All the matches were videotaped in their entirety. Performance measures in the matches were obtained using qualitative and quantitative methods of content analysis. The exploratory nature of this field study precluded the manipulation of variables.

Instrumentation

Heart activity was recorded using a Polar Heart Rate Monitoring system consisting of a noninvasive wireless and telemetry system to transmit heart signals from a chest strap (housing electrodes) to a wrist-watch for data storage. Data is then transferred to a computer by an interface for analysis. IBIs of each HP were extracted using Polar HR analysis software. HRD and HRA epochs were delineated in the context of downtime before and between points, pre-action preparation, and action using a special developed application that synchronized the match time line video with the Polar derived HRV/HRD-IBI (Figure 9.1).



time: 28:56:26 IBI: 433

Figure 9.1 Heart rate deceleration analysis app.

Video Analysis

Matches were video-taped using a Sony camcorder. Tapes of the matches were time coded using a Sony video-editing system to establish a timeline between match events and heart activity.

Procedure

This study was carried out at an official USTA men's tennis tournament in central California. Prior to the tournament the subject was familiarized with the Polar equipment. This involved learning how to start the receiver (wristwatch) and how to read its data display. A practice session was also carried out in which it was established that the equipment would not hinder the player's stroking ability and mobility. Upon arriving at the tournament venue, preparation to carry out the study commenced. The Sony camcorder was placed on a platform overlooking the court on which the player's matches would be played. A computer station for receiving data was set up in the club house. Approximately 10 minutes before the beginning of the first match, the subject was fitted with the Polar chest strap. The wristwatch was attached to the player's left arm. The player was instructed to start the watch immediately prior to the first point. The camcorder was started just prior to the end of the warm-up session before the match. These procedures were repeated prior to both matches.

Methods and Analysis of Data

The heart activity-performance time line was calibrated from the time on the videotape when the watch was started. That time was compared with the heart activity time-line of the watch to discern HRD trends prior to, during, and after action. Videotapes of the two matches were analyzed to obtain performance data. HRD and HRV data were extracted using computer generated data sheets that sequentially listed all IBIs stored in the watch. A questionnaire was used to debrief the subject. The purpose of this questionnaire was to obtain self-report feedback on the player's perceived psychological state during the matches.

Statistics

T tests were used to analyze the HRD data. They were performed on pre-action interbeat intervals within and between matches. The exploratory spectrum analysis generated descriptive data on HRV between matches. Tests for the difference between two proportions were carried out to examine between match differences in HRV.

Results

Match Outcome

The player won Match 1 by a score of 6-4, 6-1. He lost Match 3 6-0, 6-1 (the score of Match 3 is the second worst score possible in a best of three set match).

Self-Report of Psychological State during Matches

The player reported that he was very attentive in Match 1 (5 on a 5-point Likert like scale) and not very nervous (2 on a 5-point scale). He further described himself as very motivated, and confident of winning every point in the match (4 on a 5-point scale). The player also mentioned not having "much respect for the game of his opponent." During changeovers, the player stated that he visualized how he would play the upcoming game, something a player who is high in the AP factor absorption would be likely to do and benefit from. In general, the player reported highly positive emotions and cognitive activity in Match 1.

As would be expected, the player described vastly different emotions prior to and during Match 3. He reported a high degree of nervousness (4 on a 5-point scale) and a low level of attention (2 on a 5-point scale) during Match 3. He also stated that after being unable to make his best shots throughout the match, "negative thoughts" tended to dominate. He frequently thought about losing, lost motivation (1 on a 5-point scale), and eventually resigned himself to being defeated.

This feedback is highly consistent with what would be expected to occur in an athlete having an AP factor constellation of high absorption, medium to high neuroticism, and low repressive coping, especially once performance becomes disrupted during competition.

Qualitative Observations

The first match was won easily. At no time was the player in danger of losing control of the match and appeared motivated as well as psychologically stable throughout. Besides remaining both calm and attentive (high absorption) from beginning to end, the player conveyed the impression that he had confidence in his technical abilities and was not afraid to attempt difficult or risky shots. The first match was routine in nature and he was obviously better than his opponent from a technical standpoint. Critical moments did not emerge in this match, with the average criticality level for all points being between 1 and 2 (lowest rating on a 1–5 criticality scale). Consequently, potential negative manifestations of his AP factor constellation did not emerge. The player appeared to benefit from his high intrinsic level of absorption since the overall level of stress associated with this match was low. This facilitated focus on the task at hand as opposed to internal cognitions that might have emerged to disrupt performance during a more demanding match. Essentially, potential manifestation of the player's neuroticism remained dormant, allowing for full absorption in the tasks at hand.

The player's behavior and performance in the third match visibly contrasted with that of the first. In facing the number one seeded player, a 31-year-old veteran of the professional tennis tour, he appeared nervous from the beginning of the match. His agitation was reflected in poor movement and technique, which resulted in numerous unforced errors. The player also displayed displeasure with his performance by frequently chiding himself. These emotional displays stood in stark contrast to the calmness he exhibited in the first match. However, after it became apparent that the match would be very difficult to win, the player reverted to a state of emotional indifference, indicative of an athlete who is resigned to losing.

Although points in Match 3 only averaged about 3 points on the criticality scale, it should be noted that the player lost all criticality level 5 points. This was to be expected on the basis of his constellation of AP factors whereby it appeared that the player's medium level of neuroticism emerged under the stress associated with Match 3 to drive excessive physiological reactivity. The heightened stress and resulting physiological hyper-reactivity in Match 3 (as reflected in decreased HRD) coincided with the player's self-report of negative intrusive thoughts. In the presence of high level of neuroticism, such cognitions are the kind that people high in absorption tend to ruminate on during times of increased stress. Consequently, the player's increased ability to focus on tasks at hand, an ability associated with high absorption (which was exhibited in Match 1) shifted from sport-specific tasks to internal negative thoughts in Match 3, leading to poor performance. The fact that the player was low in repressive coping allowed for the unmitigated interaction of absorption-neuroticism. In accord with predictions from the TCM, the player's low level of repressive coping and high absorption made him especially vulnerable to negative intrusive thoughts associated with neuroticism that are more likely to occur during critical moments of competition.

Match Statistics

The subject committed 10 unforced errors, 16 forced errors, and hit 16 winners in the first match. Forced errors are considered unavoidable and a result of an opponent's forcing shot. Thus, a winners-to-unforced errors ratio of 16:10 is consistent with matches that are well played and won. By contrast, the subject committed 28 unforced errors, three forced errors, and hit four winners in Match 3. The low winners-to unforced errors ratio of 1:7 reflects a match that was poorly played and lost, and underscores the above qualitative observations. Conversely, statistics from the first match support the contention that the player was psychologically in control of his game in Match 1.

HRD and HRA Phases

There were 51 usable (for HRD analysis) pre-action phases in Match 1 and 27 in Match 3. Pre-action phases were identified in the videotapes of the matches. These phases corresponded with clean heart activity data extracted from the computer analysis data read-out (with in artifact tolerance range). Pre-action phase with excessive artifact were eliminated from the analysis. It should be noted that although artifact corrections can be made, doing so can also impact the ability to isolate HRD trends accurately.

In contrast to previously cited laboratory research, in which a pre-specified number of IBIs were studied prior to action, a field study cannot predict in advance how many IBIs will occur prior to action. Thus, the number of IBIs prior to each action phase was variable. In Match 1 there were 283 decelerating IBIs prior to the 51 action phases, or a mean of 5.55 IBIs per pre-action phase. There were 112 decelerating IBIs prior to 27 action phases in Match 3, or a mean of 4.15 IBIs per pre-action phase.

Hypothesis 1

An examination of all pre-action IBIs in Match 1 and Match 3 revealed HRD in all IBIs prior to action. The presence of HRD in the IBIs prior to action supported the hypothesis that HRD trends during tournament tennis would resemble HRD that was observed in previous laboratory and field studies (Figure 9.2).

……….HRD<<<<<<<<<<.HRA>>>>>>>>>>>>>>

I_I_I_I_I___I____I______I____I__I__I_I_I_I_I_I_I

pre-action…………………I action.........................

Figure 9.2 Sample selection of pre-action, action, and post-action IBIs in Match 1. Notice that the IBIs become progressively longer, leading up the response IBI. Thereafter the IBIs become progressively shorter during the action phase. After action ceases, the IBIs again become longer in the post-action recovery phase. Longer IBIs indicate a slowing of the heart. Shorter IBIs indicate an acceleration of the heart or a shorter and faster heart period.

Hypothesis 2

Hypothesis 2 was tested by comparing various combinations of IBIs in pre-action phases of Match 1 and 3. The following IBI combinations were examined to determine if greater magnitudes of HRD would be evident in a match that was won compared to a match that was lost: (1) the difference in the rate of HRD between all IBIs prior to action in Match 1 compared to Match 3 (Figure 9.2); (2) the difference in the rate of HRD between the last IBI prior to action in Match 1 compared to Match 3; Figure 9.3; (3) the difference in HRD between the 2nd to last IBI and the next to last IBI, compared to the difference between the next-to-last IBI and last IBI prior to action, in Match 1, compared to Match 3.

The following significant effects in support of Hypotheses 2 were found: (1) total IBIs prior to action in Match 1 compared to Match 3 revealed more pre-action HRD in Match 1 than in Match 3 (mean IBI = 6.79 vs. 5.57; $p = 0.05$; (2) HRD in IBIs prior to the last IBI before action in Match 1 compared to Match 3, revealed more HRD in match 1 (mean IBI = 6.37 vs. 5.42; $p = 0.085$); (3) the next to last IBI, compared to the last IBI prior to action in Match 1, revealed significant HRD between the last 2 IBIs (mean = 11.67; $p = 0.008$); (4) the next to last IBI, compared to the last IBI prior to action in Match 3, also revealed significant HRD between the last two IBIs (mean = 8.67; $p = 0.079$; Figure 9.3); and (5) the IBI decelerative trend between the 2nd to last IBI and the next to last IBI, and the next-to-last IBI and the last IBI prior to action in Match 1, compared to Match 3, revealed more HRD in Match 1 (mean = 3.86 vs. −1.67; $p = 0.037$)

Although a comparison of the next-to-last IBI with the last IBI prior to action in Match 1 with Match 3 did not reveal significant differences (mean= 11.67 vs. 8.67; $p = 0.16$) more HRD did

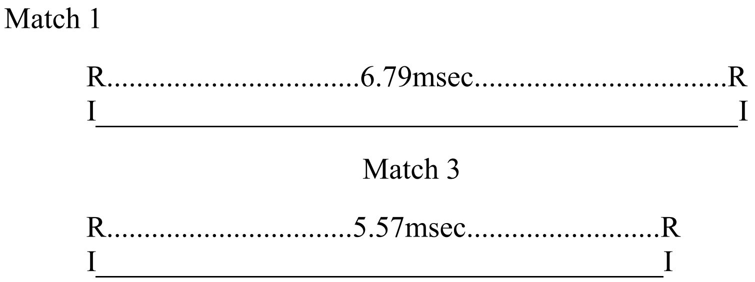


Figure 9.3 Mean rate of heart rate deceleration for all IBIs prior to action in Match 1 compared to Match 3 ($p < 0.045$).

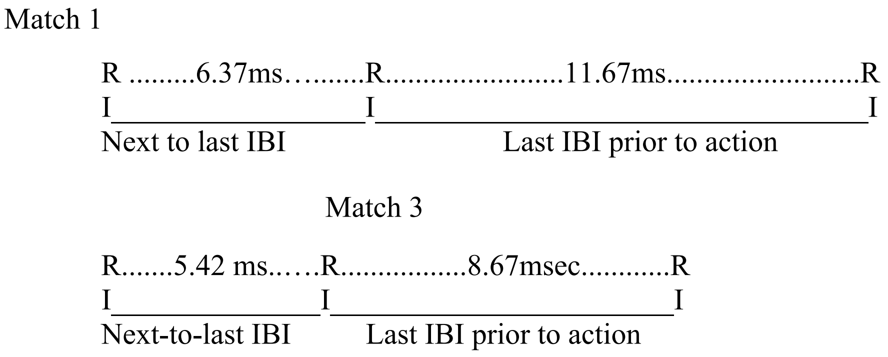


Figure 9.4 Mean difference of the rate of heart rate deceleration between the last IBI prior to action compared to the next-to-last IBI in Match 1 ($p < 0.008$) and mean difference of the rate of heart rate deceleration between the last IBI prior to action compared to the next-to-last IBI in match 3 ($p < 0.079$).

occur in the last IBI prior to action in Match 1. This is important in the context of within-match performance, where significant HRD in the last IBI prior to action was demonstrated (Figure 9.4).

Spectrum Analysis of HRV: Exploratory Data

A spectrum analysis was performed to determine if matches could be distinguished on the basis of autonomic nervous system activity.

The spectrum analysis of Match 1 revealed the following values: (1) 5-minute total power = 1573.4 (power in the band <0.40 Hz); (2) 5-minute VLF = 1378.6 (power spectrum range from 0.0033 to 0.04 Hz); (3) 5-minute LF = 180.6 (power spectrum range from 0.04 to 0.15 Hz); and (4) 5-minute HF = 14.3 (power spectrum range from 0.15–0.4 Hz; (5) LF/HF = 12.7). Spectrum analysis of Match 3 revealed the following values: (1) 5 minute total power = 2288.7; (2) 5-minute VLF = 2094.5; (3) 5-minute LF= 174.6; (4) 5-minute HF = 19.6; and (5) LF/HF= 8.9.

Discussion

The results of this study showed that varying magnitudes of HRD preceded action phases during both tennis matches. These findings were the first to demonstrate HRD during official action-sport competition. Moreover, the general hypothesis of this study, which predicted more HRD would occur prior to action phases in a match that was won compared to a match that was lost, was supported. Although both matches were marked by progressive HRD leading up to action, Match 1 showed significantly greater HRD in all configurations of IBIs prior to action. A particularly noteworthy finding was that the last IBI prior to the action response was significantly longer than the IBI preceding the action response (i.e., more HRD) in Match 1 compared to Match 3. This finding is consistent with studies by Lacey and Lacey (1978) and Jennings and Wood (1977) that reported the greatest amount of HRD in the last IBI prior to the presentation of a stimulus. In addition, when comparing the last the IBIs prior to action in Match 1 with those of Match 3, it was found that HR slowing was significantly greater between IBI 2 and IBI 1(last IBI prior to action) in Match 1 than between IBI 3 and IBI 2 in Match 3. These data also replicate studies reporting that successive IBIs, prior to the imperative stimulus, become progressively slower as the time of response nears (Jennings & Wood, 1977; Lacey & Lacey, 1978).

It should be noted that significant HRD occurred both within matches and between matches. However, this study marks the first time that significant within-subject differences between HRD and performance outcome have been reported. Previous research has focused either on between-subject differences in performance, or did not report significant within-subject results as a function of performance (Boutcher & Zinsser, 1990; Nowlin, Eisdorfer, Surwillo, 1971; Whalen, & Troyer, 1971).

This study also marks the first time that HRD has been demonstrated at higher HR levels. For example, in previous research, HRD was observed in the 70–90 bpm range, whereas in this study, HRD occurred at levels as high as 150 bpm (Boutcher & Zinsser, 1990). This is noteworthy since experiments of operant conditioning of HR have only been successful in slowing HR below resting baseline or slightly elevated HR (McCanne & Sandman, 1976). Although the HRD observed at higher HRs in this study could be attributed to the exercise recovery response, this is only a partial explanation since HRD here resembled HRD trends in other laboratory and field studies (Obrist, 1981; Boutcher & Zinsser, 1990). These trends were thought to be mediated by constellations of AP psychological factors.

The results of the spectrum analysis indicate that, in general, there was more sympathetic activity in Match 1 and more parasympathetic activity in Match 3. This is reflected in the LF/HF ratio of each match (LF/HF ratio = 12.7, in Match 1, vs. 8.9, in Match 3). Although parasympathetic predominance was evident in Match 3, it is pointed out that VLF, which is also thought to reflect sympathetic activity, was higher in Match 3 than in Match 1. Since there are no norms for, or studies of, spectrum analysis during tennis or any sport, there is much room for interpretation and speculation when analyzing these results. Thus, the results of spectrum analysis can only be addressed in the context of the comprehensive data of this study.

The results of this study become more meaningful when interpreted in relationship to the diametrically opposed performance and outcome of the two matches. These extreme differences are reflected in quantitative performance data (e.g., match score and statistics) and qualitative impressions of the match (i.e., psychological performance) and are consistent with the player's constellation of AP factors. The player's self-report of experiencing major differences in attention, emotions, self-confidence, cognitive activity, and reactivity between matches suggest that his AP factors impacted the above measures, HRD, and performance.

Of these factors, attention is considered by many to be the most central to performance since it is directly related to observing and processing environmental stimuli (Boutcher & Zinsser, 1990). Relative to the findings of this study, it was hypothesized that this player's level of attention was mediated by his constellation of AP factors negatively exerting their effects on cognitive activity and disrupting HRD in the match he lost.

In Match 1, AP factors may have potentiated vagal activity and resultant greater HRD prior to action. This could have increased attention by limiting competing sensory feedback such as negative intrusive cognitions from reaching the left-frontal lobes of the brain (seat of rumination; Sandman et al., 1982; Carlstedt, 2012). In essence, limiting superfluous and disruptive feedback to the left-frontal lobes prevents sensory flooding from diverting attentional resources away from a significant stimulus (Klemm, 1996). Consequently, heart-brain feedback loops marked by increases in HRD may have facilitated attention in Match 1 by efficiently taking in stimuli that was significant, and excluding stimuli that was potentially disruptive (intake-rejection hypothesis; Lacey & Lacey, 1964). These dynamics were thought to occur because of the positive influences of high absorption in Match 1 that allowed for optimum focusing.

Paradoxically, although HRD was significantly greater in Match 1, this match was marked by less total parasympathetic activity. This may be attributable to an overall higher level of sympathetic activation during action phases of the match, indicative of motivated performance and greater intensity. Thus, levels of sympathetic activity associated with greater motivation, activation, and energy expenditure in Match 1 may have skewed the spectrum analysis data to under-reflect the parasympathetic activity associated with increased HRD and attention (Jorna, 1992; McCraty, Barrios-Choplin, Rozman, Atkinson, & Watkins, 1996; Porges & Byrne, 1992).

Match 3 was marked by a major decrease in overall performance and HRD. Self-report indicated that the player was more nervous, less motivated, and less attentive in this match. In addition, the player reported a loss of confidence and a sense of helplessness as the match progressed. He also admitted to frequent negative cognitions. Thus, it was hypothesized that negative intrusive thoughts associated with the player's increased levels of neuroticism interfered with attention during pre-action phases of Match 3 by diverting focus away from (external) sport-specific tasks toward disruptive (internal) cognitions. Since negative cognitive activity has been associated with decreased attention, it was posited that focus on internal thoughts prior to action disrupted the priming of neuronal networks responsible for initiating motor responses and HRD, leading to more errors in Match 3 (Klemm, 1996; Ravizza, 1977; Waller, 1988). The player's tendency to fixate on negative intrusive thoughts was believed to have been facilitated by his high level of absorption.

Match 3 was marked by more parasympathetic than sympathetic activity. Since it was believed that losing a match would be marked by greater emotion, stress, and hyper-reactivity, the data on spectrum analysis from Match 3 were surprising. However, since the player revealed that after recognizing that the match could not be won he became more relaxed, it was to be expected that parasympathetic activity would increase. Thus, it was hypothesized that the stress and effort associated with a difficult match was attenuated once the subject gave up hope of winning, leading to increased parasympathetic activity in Match 3.

The fact that performance and outcome between matches were highly incongruous suggests that HRD is not only a species-wide physiological response to an impending stimulus, but that it also varies as a function of specific tasks, performance demands, and psychological factors (e.g., AP factors). This contention is based on a comprehensive evaluation of the data. Although initial p values were set at <0.10 for this exploratory study, most HRD effects were demonstrated to be significant at $p < 0.05$, with the most important effect being significant at $p < 0.008$ (next-to-last IBI, compared to last IBI in Match 1), and $p < 0.038$ (comparing last three IBIs in Match 1 to Match 3). Even though statistical procedures and their results can be broadly interpreted to suit a particular hypothesis, the quantitative results of this study lend additional support by extreme differences in match scores, performance statistics, data on content analysis, and self-report feedback (Denzin & Lincoln, 1994; Gall et al., 1996). Consequently, there was a high degree of qualitative certainty that HRV effects in this study were not random.

It can be argued that, since an athlete's constellation of AP factors does not change over time (i.e., it is stable and trait-like), it should have the same impact on performance regardless of match outcome. However, one is again reminded that AP factors are not static. Constellations of AP factors are dynamic and predicted to impact performance the most during critical moments of competition by mediating physiological responses and subsequent motor performance. Since HRD has been shown to reflect physiological reactivity, attention, and cognitive activity, the changes in HRD that were observed between matches having highly incongruent performance and outcome may have been mediated by AP factors. The player's self-report between matches supports this interpretation since it was consistent with theoretical conceptualizations of AP factors and how they can impact performance and physiology. These dynamics were also quasi-validated in the context of the observed HRD trends.

Although this investigation involved only one athlete, single case studies have an important advantage in that a person serves as his or her own control. Such control is particularly important in psychophysiological studies. Consequently, changes in physiological response tendencies across diverse conditions in the same individual may very likely reflect psychological influences. Single-subject ambulatory psychophysiological field studies such as this one also can have a higher degree of ecological validity than laboratory studies involving a larger population (Gall et al. 1996; Myrtek et al., 1996) making them more useful for exploratory and validation purposes.

HRD II: Toward a Global Physiological Biomarker of Psychological Performance during Critical Moments of Competition: Assessing Zone or Flow States

Since the psychophysiological approach to the assessment of critical moments can be laborious, a quick, efficient, and reliable method for assessing global psychological performance is needed. An emerging method that I am developing involves monitoring and analyzing heart activity over the course of an entire competition since it appears to be the physiological measure that best illuminates mind-body interactions. It is also the only measure that can be reliably monitored during actual competition in a relatively non-intrusive manner, making it ideal for assessing psychological performance during critical moments of competition.

While it has been established that HRD reflects heightened attention during competitive moments that are preceded by a mental preparation phase, it has yet to be determined to what extent HRD occurs over the course of an entire competition independent of mental preparation phases (i.e., during action phases). Consequently, in this exploratory study, a tennis player's heart activity was monitored during an actual match to not only isolate HRD trends prior to action, but also delineate global heart activity over an entire competition.

Participant and Procedure

A German amateur Men's 35 division ranked tournament tennis player's heart activity was monitored during the first round of tournament competition using a Polar cardiac monitoring system. The player was assessed for AP factors and cerebral laterality prior to the match and found to be high in absorption, high in neuroticism, and low in repressive coping. He was also shown to be relative right brain hemisphere predominant on the basis a line-bisecting test. His cerebral laterality score was consistent with high neuroticism and low repressive coping (relative left hemispheric hypo-activation and increased right hemisphere's activation). The player's constellation of AP factors made him psychologically vulnerable during critical moments of competition.

The player's heart activity was monitored continuously but not synchronized to specific competitive events. Set statistics included points played, pre-action points, and action moments. Afterward, the match data were transferred from the Polar device into HRV and HRD software for analysis.

Analysis of the Data

Previous research (Carlstedt, 1998) indicates that "true" heart rate deceleration, as distinguished from heart rate slowing due to diminishing metabolic demands, consists of an uninterrupted linear progression of at least four but less than 15 inter-beat-intervals (e.g., 468, 473, 480, 487). A HRD trend is considered to be over whenever its linearity is broken by an accelerating IBI (e.g., 468, 473, 465). Linear HRD trends of four or more IBIs were isolated and interpreted in the context of previous research, the TCM and set statistics (post-hoc).

Match Result and Set Statistics

The player lost his first round match 4-6, 7-6, 6-1. For the purpose of this analysis, Set 1 was compared with Set 3, which were highly incongruous in outcome and HRD trends. Set 1 consisted of 60 points, 60 pre-action preparation moments and 360 action moments (X = 6 strokes per point). Action moments are defined as strokes (hitting the ball) occurring during the course of a point including the serve or return of serve. Set 3 consisted of 35 points, 35 pre-action moments, 175 action moments (X = 5 strokes/pt).

These results were blind to me (not known) until after the heart activity data were analyzed.

Heart Rate Deceleration Trends

The Y axis of the histogram depicts the number of HRD trends listed on the X axis. Considering that both sets consisted of only 95 points it is obvious that HRD occurred in excess of actual pre-action moments (preparing to serve or return serve). However, when one considers the amount of strokes (action moments) that correspond to each point (competitive moment) most of the HRD trends can be accounted for (Figure 9.5).

In Set 1 there was an average of six strokes per point or a total of 360 action moments within the 60 points. In Set 3 there were 175 action moments within the 35 points played. When analyzing HRD trends without being able to precisely synchronize them with competitive events, it is important to rely on previous investigations for guidance. Since most studies of HRD in sports and in the laboratory have revealed HRD trends of at least four IBIs, trends of 3 IBIs were eliminated from the analysis. Very short HRD trends (≤3 IBIs) were considered random, superfluous, or irrelevant to performance and thought to occur mostly during phases of movement not having a direct effect on preparation or sport-specific task (e.g., walking to get into position, walking to the bench).

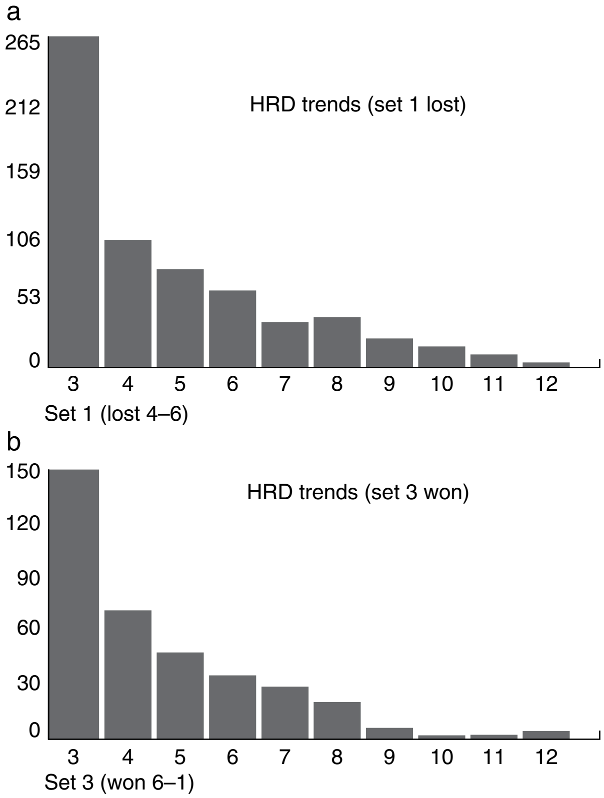


Figure 9.5 Set 1 (lost 4–6) Set 3 (Won 6–1).

HRD trends of 4, 5, and 6 IBIs were considered relevant to performance, leading to a preliminary theory attempting to explain their presence during action, something that has not previously been considered or thought possible. Because of their high prevalence and inability to explain HRD during action on the basis of 2 and 3 and 8 or more linear IBI sequences, I hypothesized that HRD trends of 4, 5, and 6 IBIs had to have occurred primarily during action moments in which technical, tactical or physical performance was consistent with or exceeded normative performance standards. These magnitudes of HRD trends are thought most likely to occur during action moments when an athlete does not experience negative psychological influences (e.g., AP mediated negative intrusive thoughts). Instead, they are hypothesized to reflect psychophysiological micro-events during action phases in which baro-receptor activity regulates flow of blood to the brain to facilitate task performance. I predict that athletes who are in control of mind-body processes (free from negative intrusive thoughts) will exhibit HRD not only prior to the initiation a sport-specific task (e.g., preparing to putt) but during action moments as well (e.g., shooting at a goal while moving). By contrast, athletes who experience negative intrusive thoughts during action will exhibit excessive or extra HR (heart rate acceleration; Blix, Stromme, & Unsinn, 1974) exceeding metabolic demands that can disrupt motor performance or technical skills. When this occurs, baro-receptor activity permits more blood flow to the brain, activating cortical areas that should normally remain dormant during motor performance.

When comparing HRD trends of 4, 5, or 6 IBIs between sets, we observe that Set 1 contained 240 such trends out of 360 action moments. This suggests that 120 action moments were devoid of HRD. In Set 3 there were 155 HRD trends of 4, 5, or 6 IBIs and 175 action moments. Although we cannot be certain that these HRD trends corresponded to action moments it is highly probable that they did, since lower and higher magnitude HRD trends are most likely to occur during other competitive and non-competitive moments. As previously noted, HRD trends of 2 or 3 IBIs are most likely to occur in a random fashion, accompanying walking, slight movements or resting, whereas HRD trends of 7, 8, 9, and 10 IBIs have been shown to occur when preparing for action. Since it is unlikely that a linear trend of 4, 5, or 6 progressively slowing IBIs will occur randomly, action moments can be best accounted for on the basis of HRD trends of these magnitudes, with the ratio of HRD trends of 4–6 IBIs to total action moments being a potential index of psychological performance during action moments of competition (action moments/HRD trends = PPPQ-Phrd [Psychological Performance Proficiency Quotient-Psychophysiological Index/HRD]) in this study.

Using this formula, the player's PPPQ-Phrd was 0.667 in Set 1 and 0.889 in Set 3. This means that in Set 1 it is probable that 120 action moments were not accompanied by HRD, suggesting compromised technical, tactical and/or physical performance when HRD did not occur. By contrast, in Set 3 it is probable that this player experienced HRD during action moments approximately 89% of the time or 155 out of 175 action moments. A PPPQ of 0.889 is very high and may reflect a level of psychophysiological functioning associated with a zone or flow-like state.

Pre-action moments were also analyzed on the basis of HRD trends. In Set 1 there were 75 HRD trends of 8, 9, or 10 IBIs, 15 more than actual pre-action moments. In Set 3 there were 40 HRD trends in this range, five more than there were points or competitive moments (pre-action phases). In the context of my preliminary TCM-HRD-action theory, whenever a range of HRD trends associated with a specific type of competitive moment exceeds the amount of actual pre-action competitive moments or action moments, one can assume that technical, tactical, and physical performance were relatively free from negative psychological influences (intrusive thoughts) during those periods. Conceptually consistent occurring HRD during any competitive moment is thought to increase the probability that motor performance will not be disrupted. Thus, in this match the player appeared to be psychologically in control during all preparation or pre-action phases as reflected in a 1:1 or greater ratio of competitive moments to HRD trends (8, 9, or 10 IBIs) in both sets.

Toward the Quantification of Zone or Flow States using HRD

As previously mentioned, to date, most research has only documented HRD during non-action phases of laboratory experiments where it has been observed that HRD occurs prior to the initiation of an action response. Since it also has been observed that any movement occurring prior to responding disrupts the linear trend of consecutive slowing IBIs (HRD), few if any attempts have been made to study HRD in the context of action or during movement, as one would expect movement to disrupt HRD during sport-specific action tasks. The effects of movement on HRD was elucidated by Obrist (1968), leading to the cardiac-somatic concept which essentially contends that HRD is more a function of heart-muscle than heart-brain interactions. However, Lacey (1964) took exception to the cardiac-somatic concept, attributing HRD more to attention and the orienting response as opposed to somatic quieting.

Thus, when interpreting HRD in the context of the TCM and sports, I hypothesize that HRD can occur during action moments of competition regardless of level of heart rate, metabolic demands, and muscular/motor activity during a sport-specific task, since attentional and other cognitive components of focusing and orientation toward a stimuli during action, very likely involve similar cortical and cardiovascular processes and interactions observed when focusing or orienting in a more static or non-action situation. For example, when a tennis player is involved in an intense rally or a basketball player is trying to get open to shoot a jump-shot, although having to maintain cardiac-output associated with high metabolic demands, he or she is still expected to experience a brief episode of HRD (micro-HRD) when positive psychological processes involved in the initiation of a sport-specific action are manifested (e.g., attention, strategic planning).

Since it has clearly been demonstrated that HRD occurs prior to action when focusing on a stimulus (hole in golf, ball toss in tennis, hoop in basketball), it is reasonable to expect that HRD will occur even at high levels of heart rate. Such a micro-psychophysiological moment is hypothesized to occur unconsciously or subliminally. If this moment is of the positive kind, free from negative psychological influences (e.g., intrusive thoughts), the linear heart rate acceleration that normally occurs with increased metabolic demands during intense action will briefly be interrupted precisely prior to the commencement of action (hitting a tennis shot while on the run, or kicking a soccer ball, etc.). This temporary "freeze" in heart rate acceleration is thought to facilitate neurophysiological processes underlying optimum motor control, including the baroreceptors and ensembles of neuronal units that function to block other "intrusive" neurons from interfering with performance (functional disconnection syndrome associated with high repressive coping). Relative to the TCM, the probability of achieving such a homeostatic peak performance state is more likely during innocuous routine action moments when psychological stress is minimal. However, once critical moments occur, depending on an athlete's constellation of AP factors, an athlete will be more or less likely to experience a disruption of the delicate balance between the heart and brain.

Athletes possessing an ideal constellation of AP factors (high or low hypnotic susceptibility/subliminal attention [HS/SA], neuroticism/subliminal reactivity [N/SR], and high repressive coping/subliminal coping [RC/SC]are less likely to be affected by negative intrusive thoughts during critical moments as reflected in HRD, even during action phases of competition). By contrast, athletes possessing less than ideal constellations of AP factors (high HS/SA, high N/SR and low RC/SC) are more likely exhibit increases in HRA that exceed metabolic demands and that will disrupt motor performance during critical moments.

Anecdotal notions such as "loss of concentration," "just do it," and being "in the Zone" can be explained on the basis of and are hypothesized to be reflected in HRD trends, whereby remaining focused and free from intrusive thoughts is associated with micro-HRD trends of 4–6 IBIs during action phases and greater magnitude HRD trends (six or more IBIs) during preparation phases prior to action. It is hypothesized that so-called zone or flow states can be quantified on the basis of HRD trends, whereby consecutive HRD trends proportionate and appropriate to a specific competitive moment (action phase = 4–6 IBIs, preparation phase, six or more IBIs) will be an objective physiological marker of peak psychological or flow performance. Being in the zone or a flow state would be determined on the basis of a physiological measure (HRD) that correlates highly with successful technical and statistical performance outcome measures as well as self-report.

A Zone or Flow experience might look like this:

Return of serve: 450 ms, 455, 468, 475, 488, 492, 495 (HRD), action phase: 467, 460, 445, 430, 423, 410, 400, 390, 378 (HRA), 385, 399, 403, 410 (micro-HRD prior to stroke), 391, 380, 370, 360, 345 (HRA), 366, 378, 382, 390, 399 (micro-HRD prior to stroke), 376, 369, 360, 355, 345 (HRA), 362, 366, 376, 384, 390 (micro-HRD), point ends.

In this point, we observe one pre-action preparation phase marked by a linear HRD trend of 6 IBIs (remember, increasing value reflects longer heart period or cardiac cycle, i.e., HRD) followed by an action phase. The action phase is delineated on the basis of commencement of a HRA trend (decreasing values, shorter heart period/cardiac cycle) consisting of nine linear accelerating IBIs. HRA occurs as a function of increasing metabolic demands associated with running to the ball. After the 378 IBI, notice that there is a one decelerating IBI (385) followed by three more slowing IBIs. Another HRD trend starts with IBI 366 and 362. These are micro-HRD trends that are thought to reflect psychological influences involving strategic planning, priming of neuronal ensembles responsible for technical-motor action occurring at the millisecond level, long enough to maintain focus on the task at hand, but short enough so as not to disrupt cardiac output necessary to fulfill metabolic demands. Thereafter, HRA resumes until the next shot of the point occurring at IBI 366 and again at 362. This heart activity sequence depicts the hypothesized order of HRD and HRA acceleration trends during competitive moments of a tennis match. The observed trends are consistent with what research has revealed regarding HRD trends during preparation phases prior to the initiation of action and what is hypothesized to occur during actual action phases of competition. Approximations or variations of the above cycle are hypothesized to occur repeatedly whenever an athlete is in a zone or flow state.

Competitive moments and episodes consisting of appropriate HRD and HRA trends, like the above, that are sustained over the course of longer periods of time during competition are hypothesized to reflect optimum psychological performance or being "in the Zone." It is expected that greater technical and physical performance will occur during phases of ideal heart rate variability (HRD-HRA) along with subjective feelings of well-being and mastery, and in many instances will coincide with a winning performance. Once a series of ideal HRD trends comes to an end, it is predicted that a zone or flow state will also cease.

TCM-AP factors play an important role in the HRD-Zone/Flow equation. Consistent with the TCM, it is expected that HRD trends are more likely to be disrupted during critical moments of competition in athletes possessing less than ideal constellations of AP factors and vice versa.

Although the HRD-Zone/Flow model needs to be further investigated, a preliminary analysis of heart activity data from this match is promising and suggests that HRD may indeed be the marker of psychological performance.

The TCM-HRD-action theory evolved from observing HRD trends in athletes, mostly tennis players over the course of actual tournament competition and practice. Repeatedly, an analysis of heart activity revealed trends of HRD that could not be explained merely on the basis of metabolic demands or in the context of the cardiac-somatic concept, especially since many of these trends were observed to occur at high heart rate during action phases of competition, something that was not thought possible.

An fMRI study of golfers by Ross et al. (2003) suggests that cortical "quieting" occurs more frequently in skilled golfers compared to less skilled golfers. Fattaposta et al. (1996) also found more cortical effort expenditure in non-athletes attempting to learn a task never previously engaged in compared to expert marksmen. I hypothesize that reductions in cortical activity is marked by less blood perfusion in ensembles of neurons associated with specific motor activity and preparatory cognitions in expert or successful athletes. This reduction in cellular blood flow to specific neurons is regulated by baro-receptors that also induce concomitant heart rate deceleration that is seen in peak performance. By contrast, in novices or even skilled athletes who are disrupted by intrusive thoughts, more cellular blood profusion is predicted to occur as a function of less baro-receptor control over regional cerebral blood flow (rCBF) resulting in heart rate acceleration or lessened heart rate deceleration.

Directions for Future Research

Future research must delineate the general HRD observed during competition more precisely. Should it be determined that HRD is unequivocally associated with performance and affected by psychological factors (AP factors), interventions can be designed to help athletes manipulate their HR in the desired direction. Since HR biofeedback has been successfully demonstrated both in the field and in laboratory studies, it is plausible that this mental training method could be used to enhance the psychological performance of athletes (Fahrenberg & Myrtek, 1996; Ludwick-Rosenfeld & Neufeld, 1985; Weiss & Engel, 1971). Since this study also demonstrated that within subject HRD varied situationally, individualized norms for HRD should be derived through future research. A large-scale study should be implemented to determine if HRD can be used to distinguish and assess level of ability, attention, motivation, and activation in athletes and equivocally determine to what extent AP factors affect this cardiovascular response.

Although the results of the spectrum analyses in this chapters first study were only revealing at the macro-level, spectrum analysis of HRV still holds much potential for assessing states of activation in athletes. Spectrum analysis could be used to establish individual norms for activation and reactivity in athletes and to establish parameters of physiological reactivity beyond the hypothetical (Hanin, 1980; Hardy & Fazey, 1987; Taylor, 1996). Doing so would have major implications with regard to preparing athletes for competition. In addition, spectrum analysis could be used to better discern to what extent specific psychophysiological processes are active during certain phases of competition (e.g., levels of attention, cognitive activity, autonomic nervous system activity). Such research could lead to a better understanding of how cognitive activity, and hence psychological variables, facilitates or disrupts motor performance during action phases of competition.

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