From preparation to competition: Examining sleep patterns and neurofeedback in elite level athletes

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I declare that:

a) The thesis is my own account of my research, except where other sources are acknowledged.

b) The extent to which the work of others has been used is clearly stated in each chapter and certified by my supervisors.

c) The thesis contains as its main content, work that has not been previously submitted for a degree at any other university.

Laura E Juliff

A note on formatting and style

This PhD thesis comprises several published research papers. These formatted documents are incorporated into this thesis along with additional text that has been provided to introduce and link the published work. It is hoped that the final amalgamation allows for the development of a cohesive body of research that can be easily followed. The PhD thesis has continuous pagination, which can be seen at the bottom right of each page.

Thesis Abstract

Sleep is a necessity, vital for both health and the majority of biological functions. With the recognised importance of sleep, sleep habits of elite athletes are a popular topic. To date there has been limited research conducted specifically on sleep in athlete populations. Through a series of four studies, the current PhD aimed to enhance the understanding of sleep habits of elite level athletes. The specific purpose of the thesis was to explore sleep behaviour, complaints, and mechanisms within elite level athletes subjectively and objectively during periods of competition, to advance the understanding of the sleep habits in this population. Study One was a cross-sectional questionnaire to identify the occurrence and reported sleep complaints of 283 Olympic and professional athletes prior to important competitions. Study Two objectively and pragmatically monitored four netball state teams via actigraphy through a multi-day national tournament and related findings to final competition standings. Study Three, an observational study, explored the potential physiological, neuroendocrine, and psychometric mechanisms responsible for sleep complaints following a night game. Finally, Study Four examined the effectiveness of a neurofeedback intervention for improving sleep in athletes.

Questionnaires from 283 individual and team sport athletes highlighted that poor sleep is common (64%) the night before critical competitions (Study One). Athletes reported problems falling asleep (82.1%) due to internal factors such as “thoughts about the competition” and “nervousness”. It appeared that whilst sleep disturbances were confirmed by athletes prior to competition, the sleep complaints were predominantly situational and not associated with poor sleep in general. Sleep education therefore requires a situational focus (i.e. night games and competitions). The importance of sleep for athletic performance was demonstrated during a multi-day national netball tournament with increased sleep durations associated with a higher final tournament placing ($r = -0.68$) (Study Two). However, netballers

experienced shorter sleep durations following evening games (7:08 ± 00:45 h) in comparison with afternoon games (7:37 ± 1:06 h). Finding from Study Three provided further support for poor athlete sleep following night games, with reduced sleep durations and efficiencies with early awakenings and poorer subjective sleep ratings reported in athletes after a night-game compared with a time-matched rest day. Athletes with a tendency towards a high trait arousal were more susceptible to sleep complaints following the night game. No differences were observed for core temperature and cortisol measures at bedtime following the night game compared to the time matched control day, despite these two physiological measures postulated to influence sleep.

Based on findings from Studies One, Two and Three, a non-pharmacological sleep intervention of neurofeedback (feedback intervening on the level of the central nervous system using electroencephalography) was developed an examined for its effectiveness in optimising sleep in athletes. Neurofeedback was found to improve overall reported sleep problems measured through the Pittsburgh Sleep Quality Index, increase sleep efficiency, and reduce sleep onset latency in the home environment compared with a placebo group using actigraphy. However, no differences were observed for sleep measures between the neurofeedback and a sham treatment when measured by polysomnography. Despite improvements in subjective measures and sleep onset latency in the home environment further exploration is warranted before neurofeedback is universally adopted in athletes as a treatment modality. Due to learned regulation of specific cortical networks, neurofeedback may however be an alternate modality for specific problematic elite level athletes when traditional behavioural modifications (sleep hygiene) methods are not effective in enhancing poor sleep.

In summary, the current series of studies provides a foundation for understanding sleep in athletes. The results demonstrate sleep disruption is indeed prevalent around competition and may impact competition standings. Despite common assumptions in literature around the mechanistic reasons responsible for night game sleep complaints, trait arousal was found to correlate to poor sleep following night games. In addition, neurofeedback emerged as a potential novel sleep intervention for targeted individuals however further exploration is warranted before it is considered a routine sleep strategy for elite level athletes. Overall, the studies provide useful information that can be used by coaches and staff to develop targeted sleep education to enhance the wellbeing and performance of elite level athletes.

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Table of Contents

Abbreviations

AASM	American Academy of Sleep Medicine
ADHD	Attentional deficit hyperactivity disorder
Ag/AgCL	Silver chloride electrode
ANOVA	Analysis of variance
AWI	Awakening index
BFB	Biofeedback
cm	Centimetres
CAR	Cortisol awakening response
CI	Confidence interval
CMJ	Countermovement jump
CNS	Central nervous system
DSI	Disturbed sleep index
ECG	Electrocardiogram
EEG	Electroencephalograph
EMG	Electomyography
EOG	Electrooculogram
FFT	Fast fourier transform
GABA	y-aminobutyric acid
h	Hours
HPA	Hypothalamic-pituitary-adrenal axis
Hz	Hertz
kg	Kilograms
kV	Kilovolts
m	Metres
Min	Minutes
ms	Millisecond
NFB	Neurofeedback
ng/min	Nanogram per minute
nmol/L	Nanomoles per litre
NREM	Non-Rapid eye movements
PSAS	Pre-sleep Arousal Scale

PSG	Polysomnography
PSQI	Pittsburgh Sleep Quality Index
QEEG	Quantitative Electroencephalogram
REM	Rapid eye movements
RNAs	Ribonucleic acid
rx	Spearman's correlation coefficient
s	Seconds
SD	Standard deviation
SE	Sleep efficiency
SMR	Sensorimotor rhythm
SOL	Sleep onset latency
SPT	Sleep period time
SWS	Slow wave sleep
TIB	Time in bed
TST	Total sleep time
ug/dL	Microgram per decilitre
VLPO	Ventrolateral preoptic nucleous
WASO	Wake after sleep onset
$\chi2$	Pearsons chi-squared test
Yr	Years

List of Tables

List of Figures

List of Articles Submitted for Publication

Juliff L.E, Halson, S.L., & Peiffer, J.J. Understanding sleep disturbance in athletes prior to important competitions. Journal of Science and Medicine in Sport. 2014;18(1):13-8. Doi: http://dx.doi.org/10.1016/j.jsams.2014.02.007

Juliff L.E, Halson, S.L., Hebert, J., Forsyth, P.L., & Peiffer, J.J. Longer sleep durations are positively associated with finishing place during a national multi-day netball competition. Journal of Strength and Conditioning Research. 2016. Doi: 10.1519/JSC.0000000000001793.

Juliff L.E, Peiffer, J.J., & Halson, S.L. Night games and sleep: physiological, neuroendocrine and psychometric mechanisms. International Journal of Sports Physiology and Performance. 2016. In – Press.

Juliff LE, Peiffer JJ, Hegg J, Fuller K, Chan V, Marijke, & Halson SL. Optimising sleep in elite athletes using neurofeedback. 2016. Prepared for submission Dec 2016 BJSM

Other non-first author manuscripts from this thesis:

Fuller K.L, **Juliff L.E**., Gore, C.J., Peiffer, J.J, & Halson, S.L. Software thresholds alter the bias of actigraphy for monitoring sleep in team-sport athletes. Journal of Science and Medicine in Sport. 2017. http://dx.doi.org/10.1016/j.jsams.2016.11.021

CHAPTER ONE

Introduction

1.1 Introduction

Sleep is a basic requirement of human health and is critical for athletic performance[1, 2]. Sleep restriction can negatively influence cognitive[3] and psychomotor performance[4], mood[5], motivation[6, 7], immune and hormonal function[8] as well as exercise performance[3, 8, 9]. For athletes, reductions in performance due to sleep restriction, may influence competition outcome[10-12]. Despite the influence of poor sleep quality on athletic performance, research in the area remains limited with majority of information anecdotal or from non-sport individuals (i.e. shift workers and patients with sleep pathology)[6, 11, 13, 14]. Sleep is highlighted as the single best recovery strategy available to an athlete due to its restorative and physiological effects[1, 10]; yet, the majority of recovery research has focused on techniques such as hydrotherapy, compression garments, massage and nutritional interventions with sleep frequently overlooked[1, 15]. Sleep durations obtained by adults in the general population are well understood[17], however, much less is known in regards to elite level athletes[1]. Recent sleep research conducted on Australian athletes indicates athletes on average obtain 6.5 hours per night, well below the recommended 8 hours[16, 17].

In elite athletes, numerous factors can negatively impact sleep and result in total sleep deprivation or sleep disruption, both which can compromise athletic performance[6, 18, 19]. Diet[6], environmental and body temperatures[10], changes in altitude[6], anxiety[6], pain[10], apprehension and psychological stressors[11] have each been indicated to impact sleep[18, 19] and are common factors experienced or manipulated amongst elite athletes[20]. For instance, within a large cohort of German athletes 65.8% reported experiencing poor sleep in the night(s) before an important competition with nervousness and thoughts about the upcoming competition given as the primary factors for the poor sleep[20]. Athletes who travel for competition may be at additional risk of experiencing sleep disturbance due to time zone changes, jet lag, unfamiliar surroundings (bedroom) and stress of travel and noise[6, 8]. In light of this information, a greater understanding of an athlete's sleep prior to competition is necessary for optimal preparation and performance both in and out of competition[3, 8, 9].

Sleep is a complex phenomenon regulated by several regions of the brain through modulations of neurotransmitters and neuropeptides that control daily cycles of wakefulness and sleep[21, 22]. Moruzzi et al[23] confirmed two distinct influencers of sleep within the brain; 1) the ascending arousal system in the hypothalamus promoting wakefulness and 2) sleep active neurons in the ventrolateral preoptic nucleous (VLPO)[24]. Interactions between the ascending arousal system and sleep active neurons act much like a "flip flop switch" turning on and off periods of sleep and wakefulness[24]. Stressful events can stimulate neurotransmitters (norepinephrine and epinephrine) of the ascending arousal system triggering the release of cortisol, collectively causing a disruption of the sleep-wake cycle[25]. More specifically, within seconds of a stressful episode the adrenal glands release epinephrine and norepinephrine to the bloodstream creating a 'flight or fight response'[26]. This response results in complex interactions between endocrine and nervous systems ultimately resulting in the pituitary gland releasing adrenocorticotrophic hormones, which act to up regulate the release of cortisol[26]. Elevated cortisol levels are associated with decreases in health and athletic performance and due to the metabolic properties of cortisol, high concentrations are likely to make sleep incompatible[27, 28]. Cortisol and catecholamines can be elevated in athletes via numerous factors such as sleep deprivation[26], anxiety[26, 28], exercise[28], and athletic competitions[28] that may ultimately disrupt the sleep-wake cycle.

Very little evidence exists examining the neurophysiology of sleep in athletes. Despite increases in cortisol levels reported during tennis[29], volleyball[30], wrestling matches[31], triathlon[32], judo[33], and women's football competitions[34], no research has examined the impact of cortisol and catecholamine levels (ascending arousal system) following exercise on subsequent sleep. Studies within civil servants[25] and patients with sleep pathology[35] have identified that increased urinary catecholamines and increased psychological arousal both result in poor sleep. However, the effects of cortisol cannot be determined from these studies[36]. Exploration of the neurophysiological responses of athletes during competition and the possible impact of the arousal system on sleep is therefore necessary to understand the optimal conditions to allow restorative sleep in this population.

There are a variety of non-pharmacological means an athlete can partake in to promote sleep enhancement[37] including; relaxation techniques[10], skin warming[38], hydrotherapy[10], napping[39], sleep hygiene education[40], neurofeedback[41] and bio-feedback[41]. With a long history for treating insomnia[42], the use of bio-feedback as a non-pharmacological therapeutic treatment and as a research tool is increasing[43]. Using instruments that provide information related to indices such as; muscle activity, skin temperature, electrodermal activity, respiration, heart rate, heart rate variability, blood pressure, brain electrical activity, and blood flow, bio-feedback enables an individual to learn and gain voluntary control over physiological and psychological functions[43-45]. This technique has been successfully used to treat insomnia[41]; thus, bio-feedback may provide a useful tool within elite athletes who experience poor sleep.

Neurofeedback (NFB) is a specific form of biofeedback, which makes use of electroencephalography (EEG; recording of electrical activity on the scalp). This feedback intervenes on the level of the central nervous system[41] and enables an individual to recondition and retrain the brain[46]. During training, EEG is recorded and the participant receives instant feedback (auditory and/or visually) on the cortical activity of their brain. The goal of this technique is to normalise the functioning of the brain by inhibiting and/or reinforcing specific frequency bands[47]. Traditionally, there are four types of brainwaves that differ according to frequency; 1) delta (0.5-4 Hertz), 2) theta (4-8 Hertz), 3) alpha (8-12 Hertz) and 4) beta (13-20+ Hertz)[48]. The most widely used NFB protocols include either the enhancement of the sensorimotor rhythm (SMR; 12-15 Hertz) or the modulation of the theta/beta ratio[46]. There are many clinical applications of NFB, however, in a remarkably short time NFB has evolved into the most widely researched intervention in sport psychophysiology[46, 49, 50]. Different NFB protocols have demonstrated positive effects on creativity, intelligence, memory, reaction time tasks and sleep[46, 49]. In a study of seventeen insomnia patients Cortoos et al.[41] found that by applying a NFB protocol focusing on increasing SMR, which is associated with sleep improvement, and inhibiting theta power and a high beta power brainwaves associated with arousal, participants experienced greater objective and subjective sleep changes as well as a significant increase in total sleep time[41]. While successful in insomnia patients this treatment may have positive influences in athletes, as athletes are likely to demonstrate physiological hyperarousal responses and stress symptoms following heavy training periods or prior to competitions.

1.2 Purpose of the Study

The effects of sleep disturbance on performance and health has been acknowledged, however, only a small number of studies have investigated sleep problems specific to athletes and their effects around critical competition times[20, 51, 52]. This thesis comprises four studies that aimed to; subjectively examine the sleep patterns of Australian athletes prior to important competitions (Study One); objectively examine sleep within elite level netball athletes during a national competition (Study Two); measure the neurophysiology of athletes prior to and following night games to assess their impact on sleep (Study Three); and examine the influence of neurofeedback training within elite level athletes as an aid to increase sleep (Study Four). Findings from the series of studies will assist the Australian sports science community and coaches through a greater understanding of the sleep habits of athletes around competition and the effectiveness of a novel sleep intervention, neurofeedback. Ultimately these studies will support the optimisation of sleep in athletes with the potential to enhance recovery and provide the greatest chance of athletic success.

Research Questions

This thesis attempted to address the following research questions:

Study One: Understanding Sleep Disturbances in Athletes Prior to Important Competitions.

1. Do Australian athletes experience sleep disturbances prior to important competitions? If so what are the particular sleep problems, reasons, and consequences for the sleep disturbance?
2. Are sleep disturbances reported by athletes global (i.e. every-day) or competition specific?

Study Two: Longer Sleep Durations are Positively Associated with Finishing Place During a National Multi-Day Netball Competition.

1. How do athletes sleep during a tournament style competition?
2. Do any sleep differences exist based on final competition standings (top and bottom finishing teams)?
3. Do athletes have reduced sleep durations and efficiency following night games compared to afternoon games in the tournament?

Study Three: Night Games and Sleep: An Exploration into Physiological, Neuroendocrine and Psychometric Mechanisms in Team Sport Athletes.

1. Do athletes experience worse sleep following a night game compared to a rest day?
2. Are the commonly hypothesised mechanisms reported for poor sleep following night games (core temperature[53], psychometric measures[51], cortisol[53, 54], and adrenaline and noradrenaline[51, 54]) associated with reduced sleep variables?

Study Four: Optimising Sleep in Elite Athletes Using Neurofeedback.

1. Does a neurofeedback intervention enhance sleep variable (actigraphy and polysomnography) in athletes compared to a sham group?

2. Are athletes able to demonstrate a learned effect of their EEG activity after fifteen neurofeedback sessions?

CHAPTER TWO

Literature Review

2.1 Introduction

Sleep has been attributed to having an essential role in human health, vital for physical and cognitive performance and wellbeing[2, 55, 56]. As such, most humans require large amounts of sleep with approximately one third of human life spent in a state of sleep[57]. Despite the biological necessity for sleep, prevalence of acute sleep deprivation is not uncommon within the general population and athletes[2, 58]. Beyond the basic health benefits of sleep[6, 59], within an athletic population, sleep is described as an important recovery strategy due to its physiological and restorative effects[10], so much so that adequate sleep has been labelled as a 'new frontier in sport performance enhancement'[1, 60]. Regardless, to date a paucity of research exists focused on sleep in athletes with most recommendations developed from sleep data on shift workers and patients with sleep pathologies such as insomnia[13, 14]. Greater research into sleep and sleep habits of athletes is essential to understand not only the general sleep habits of athletes but the effects exercise and competition has on subsequent sleep and performance, with the intention of optimising sleep quality and quantity in athletes[9]. Furthermore, with the banning of selective sedatives and restrictions and warnings on the use of other sedatives for athletes, alternative strategies to facilitate effective sleep are needed. Therefore, the exploration of non-pharmacological interventions to prevent unwelcome sleep loss in athletes would be beneficial. The purpose of this literature review is to outline the theoretical basis regarding the importance of sleep and identify current sleep research in athletes in order to establish and define key areas for new understanding and knowledge in the area.

2.1.1 Sleep

The sleep-wakefulness cycle is described as one of the main discernible biological circadian rhythms; natural fluctuations of physiological and behavioural processes occurring over a 24-h period in the human body[8, 61]. The circadian rhythm of sleep is evident through alertness associated with daylight and an increasing propensity to sleep occurring during the dark part of a 24-h day[13, 61]. In addition to the circadian drive for sleep a homeostatic mechanism exists in humans where an increasing need for sleep arises after a period of wakefulness[52, 61].

Currently, eight hours of sleep per night is recommended for healthy individuals; however this perspective is derived mostly from statistical averages, thus may be too simplistic[17, 62]. Therefore sufficient sleep may be defined as sleep that is followed by a spontaneous awakening leaving one feeling alert and refreshed[63]. With much debate surrounding the optimum amount of sleep essential for recuperation and performance, what is agreed upon is that sleep is highly individual in nature[9, 10, 13]. This is likely to influence current research as although recommendations based on averages may be suggested, ultimately sleep needs to be reviewed on an individual basis, not as one recommendation fits all.

In order to understand the complexities of sleep, there has been a continued increase in sleep related research. Despite the increase, the function of sleep remains unclear[36]. Based on observations of the body and brain during sleep deprivation studies, it is hypothesised that the brain has a chance to 'turn off' and repair neuronal connections during sleep[3, 63]. This concept is reinforced when considering the function of sleep at a neurometabolic, somatic and cognitive level[64]. Waking imposes a metabolic and neural cost to the nervous system that on a neurometabolic level is restored in the subsequent sleep period[10]. Somatically, sleep is associated with several purposes such as the restoration of tissue and of the immune and endocrine systems[20, 64]. While cognitively, sleep plays a role in memory, learning and synaptic plasticity[10, 64]. What is known is that sleep is a complex, precisely regulated process consisting of periods of synchronised cortical activity[63]. The events in the brain are accompanied and coordinated with physiological changes in the rest of the body. These physiological changes create a network of programmed physiological activities each night in order for neural, metabolic and cognitive restoration and repair from prior wakefulness[63]. The specific oscillations and morphological changes in the brain and body allow for the identification of specific sleep stages[60].

2.1.2 Sleep Stages

Over a 24-hour period, the human body continually cycles through states of wake and sleep[6]. The fluctuation of sleep states enables the body to recover and renew from prior wakefulness enabling an individual to awaken feeling fresh and alert[8, 65]. During sleep, the detection of sleep stages is achieved through identifying changes in electrical activity in the brain (Figure 2.1). Specifically, brain electrical frequency also commonly known as brain waves (delta 0-3.99H_z; theta 4-7.99H_z; alpha 8-13H_z; beta 13+H_z) and amplitude (the strength of the electrical signal) change during each sleep stage (discussed below)[6]. Approximately every 90 minutes during a night of normal sleep, the brain oscillates between two main sleep stages; non-rapid eye movement sleep (NREM) and rapid eye movement sleep (REM) (Figure 2.2), with approximately 75% of total sleep time spent in NREM[66].

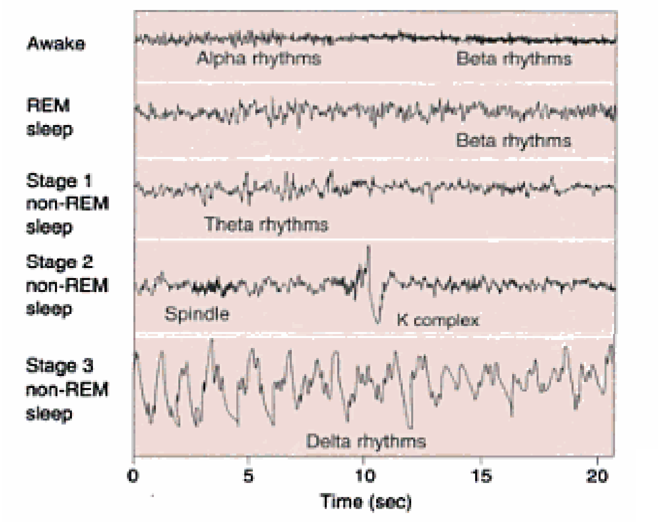

Figure 2.1. Electroencephalography (EEG) rhythms that characterize each sleep stage[66].

Within NREM sleep, three progressively deeper sleep stages (i.e. stage 1, 2 and 3) exist[5]. Stage one 'bridges the gap' between waking and sleeping and is characterised by diminished responsiveness to external stimuli[6]. Approximately 50% of total sleep time is spent in stage two and while 'deeper' than stage one, is not classified as restorative[6]. Stage three is commonly referred to as either delta, slow wave sleep or deep sleep[6, 8, 67]. For the purposes of this literature review, the term slow wave sleep (SWS) will be used to represent stage three. Comprising approximately 15-20% of total sleep time, SWS is electrically characterised by low frequency, high amplitude delta waves as a result of minimal cerebral cortex activity[6, 14]. Furthermore, parasympathetic activation results in a decrease (circadian daily lowest) in heart rate, blood pressure, core temperature, respiratory rate and energy utilisation[6, 8, 67]. On the contrary, growth hormone secretion is highest during SWS which importantly aids in neural and peripheral cellular restoration[8, 68]. Following progression through each of the four NREM sleep stages, a period of REM sleep occurs.

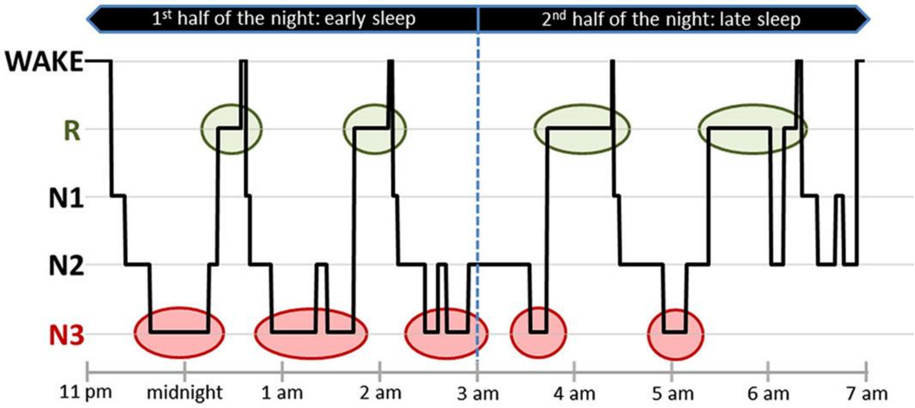

Figure 2.2 Represents a night of human sleep illustrating the cyclical nature of sleep from non-rapid eye movement sleep (NREM) to rapid eye movement (REM) sleep[69].

Approximately 90 minutes after sleep onset, during the normal sleep cycle, the brain transitions from NREM to Stage R sleep (REM) with greater durations of REM sleep obtained during successive sleep cycles[6]. Described as "an active, hallucinating brain in a paralysed body"[66], the brain during Stage R displays similar brain wave patterns (i.e. low-amplitude, high-frequency) to those observed during wakefulness[8]. However, blocking of the cortico-spinal pathways by the brain stem results in total muscle relaxation during which time myofibril restoration occurs[8]. Concurrently, up-regulation of sympathetic activity increases brain temperature, heart rate, cerebral blood flow and brain protein synthesis[6]. This process plays an important role in the formation of memories; the transcription of messenger RNAs involved in protein synthesis and has been suggested to be critical for memory consolidation and persistent forms of brain plasticity in vitro and vivo[70, 71]. Furthermore, during REM it is believed dreaming occurs[66]. Overall, it is evident throughout a night's sleep there are distinct neural and physiological changes that take place enabling researchers and clinicians to measure or indirectly identify specific sleep stages, which are of scientific and clinical interest.

2.1.3 Sleep Measurement

Within the literature, sleep is regarded as a biological necessity[6], thus techniques are necessary to help researchers and clinicians quantify sleep in all populations. There is no direct measure of sleep; however through a variety of measures information regarding sleep stages, duration and efficiency can be assessed[2, 72]. These techniques include; measures of electrical activity in the brain via electroencephalography (EEG), eye movements via electrooculogram (EOG), muscle activity via electromyograms (EMG), heart rhythms via electrocardiogram (ECG), activity monitors, heart rate, behaviour, temperature and subjective sleep diaries[2]. Each method of sleep measurement has both advantages and disadvantages and will be discussed below[73].

The combination of sleep data collected simultaneously through 30 second epochs of EEG, EOG, EMG, and ECG is termed polysomnography (PSG) and is considered the 'gold standard' measure of sleep, primarily used for assessing sleep disorders[72]. Through this technique, information on sleep staging (i.e. stages 1 – 3 and stage R), sleep latency (time taken to fall asleep); total sleep duration, and the number of arousals from sleep can be obtained throughout a night[73-75]. Whilst an accurate measure of sleep, the large time commitment for PSG collection and analysis (scoring each 30 epoch of an entire sleep study) makes this technique inconvenient for long-term and regular/routine monitoring[74].

Due to low cost, ease of administration and non-invasiveness, wrist activity monitors (actigraphy) have emerged as a popular research and clinical sleep assessment tool[73, 74, 76]. These small devices can store several days and nights of data before downloading to a computer[77]. The ease of capture allows users to monitor multiple participants over consecutive nights in any environment; for an athlete this means the ability of capturing home or away at competition[77]. As an alternative to PSG, actigraphy indirectly measures sleep and wakefulness through the assessment of movement by a piezoelectric accelerometer and the use of specifically defined algorithms to score sleep into either low activity periods classed as sleep or high activity periods scored as wakefulness[73, 75]. The use of algorithms to quantify the actigraphy data has significantly reduced the time necessary to analyse sleep as the requirement for manual interpretation and scoring is greatly reduced[73]. Importantly, the accuracy of actigraphy has been documented through epoch-by-epoch comparisons to PSG with agreement rates of 78-95%[76, 78]. Higher correlations are observed with healthy participants rather than sleep pathology patients and when subjective data (sleep diaries) are combined with actigraphy data for estimates in total sleep time (also known as sleep duration; amount of actual sleep time in a sleep episode; equal to total sleep episode less awake time) and sleep efficiency (the ratio of the total time spent asleep in a night compared to the total amount of time spent in bed).[73, 78]. More recently, the validity of actigraph watches has been examined in athlete populations with a study concluding actigraphy monitors are a "valid alternative to PSG for measuring sleep in athletes"[79]. Specifically the results indicated that overall agreement rates between PSG and actigraphy monitors were very high (81-90%) and comparable to rates previously reported in other populations[79]. In addition, the reliability of actigraphy has also been demonstrated within literature with an ICC range of 0.84-0.99 found dependant on the sleep variable measured[80]. Of note the, inter-scorer reliability in the study was better than that typically reported for polysomnography which ranges from 80% to 98% for sleep–scoring inter-rater agreement[80]. It should be acknowledged that the Actigraph software uses algorithms to process data based on one of three sleep-wake threshold settings (Low, Medium, and High) therefore validation should be conducted on specific populations to decipher the most accurate threshold. A recent study utilising elite team sport athletes found, the Medium sleep-wake threshold produced the smallest mean bias compared with PSG for sleep duration, sleep efficiency and wake after sleep onset[77]. Therefore, scientists using actigraph devices to monitor sleep in elite team-sport athletes should consider using thresholds that are moderately sensitive to sleep (Medium threshold) where activity counts are above 40[77]. The greatest recognised disadvantage of actigraphy is its inability to detect specific sleep stages[73]; however despite this, usage of actigraphy within sleep research is increasing with at least 23% of studies employing actigraphy alone[73, 76].

The most cost and time effective method to measure sleep is via the use of self-reported sleep diaries[73, 75]. It has been argued that subjective sleep questionnaires have clinical credibility and may be sufficient as a stand-alone assessment[75]. However, this argument is likely due to insomnia defined clinically by subjective complaints of sleep disruption[75]. Whilst a convenient, affordable and non-invasive measure of sleep, diaries assume that subjective measures of sleep quality accurately reflect objective measures, when in fact discrepancies may be present between measures[20, 81]. The notion of discrepancies between objective and subjective sleep measures is often reported in studies[41, 82, 83]. While subjective sleep questionnaires remain appealing to researchers and are commonly used, it is important to be aware of the limitations.

2.1.4 Neurophysiology of Sleep Wake Cycle

To understand the sleep wake cycle, it is essential to address the proposed interaction with the ascending arousal system. Behaviourally, sleep is defined as a reversible state involving perceptual disengagement from an environment with the inability to respond to stimuli[84]. Distinctively different from a coma, sleep may be instantly terminated through activation of an arousal system in response to a biological signal or physiological stressor[24, 60]. During the 1940s and 1950s Giuseppe Moruzzi and colleagues sought to examine the influence of brainstem control of waking and arousal, discovering two distinct sleep states; 1) the ascending arousal system in the hypothalamus that promotes wakefulness and 2) sleep promoting neurons in the ventrolateral preoptic nucleous (VLPO)[24]. The ascending arousal system comprises a number of monoaminergic cell populations such as noradrenergic, serotoninergic, dopaminergic, histaminergic and cholinergic neurons and orexin/hypocretin nuclei located along two branches (Figure 2.3)[24, 85, 86]. The first branch innervates the thalamus, while the second branch projects into the lateral hypothalamus, basal forebrain and cerebral cortex[24, 85, 86]. Discharging in a coordinated and overlapping manner, the monoaminergic systems promote sustained wakefulness[24]. Every 24-hours however, the arousal system is blocked by inhibitory neurotransmitters y-aminobutyric acid (GABA) and galanin within the VLPO, down-regulating monoaminergic cells leading to sleep (Figure 2.3)[24, 85]. The mutual inhibition that exists between the arousal system and the sleep producing system creates definitive wake and sleep states[87]. Systems such as these are called ‘flip-flop’ switches by electrical engineers as they tend to avoid transitional states, when either side dominates over the other, the switch flips into the alternative state; hence explaining why wake-sleep transitions are often quite abrupt (ability to quickly fall asleep and wake suddenly)[87]. A disadvantage to this type of circulatory system is that unwanted perturbations causing physiological arousal (exercise, stress etc.) may turn off the alternative state abruptly without warning[88].

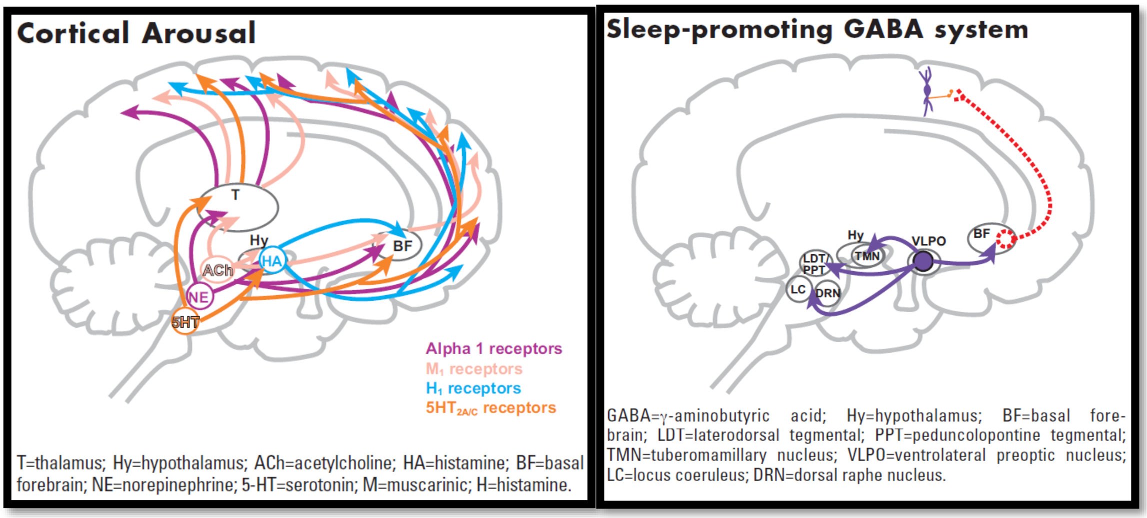

Figure 2.3. Illustration of the ascending arousal system and the sleep promoting GABA system and their neurotransmitters[89].

Whilst primarily active during sleep, the VLPO also receives afferents from each of the monoaminergic systems[87]. Noradrenaline and serotonin can inhibit the VLPO[87] ultimately resulting in a down regulation of the sleep promoting GABA system by the very arousal system it blocks during sleep[24, 87]. Studies in the 1970s and 1980s clarified the nature of this pathway and identified neurotransmitters originating from the ascending arousal system[87]. Indeed, occupational studies have observed increased activation of monaminergic cells of the ascending arousal system following physiological stressors that led to suppression of sleep, ultimately disrupting the sleep-wake cycle[25].

It should be noted that the ascending arousal system is proposed to comprise only one component of the sleep-wake cycle and exactly how much influence it has on the cycle remains unknown. Mathematical models have been developed in an attempt to explain the mechanisms and dynamics associated with the sleep-wake cycle[90]. The most current model by Phillips and Robinson proposes links between homeostatic and circadian processes as well as the mono-aminergic neurons in the ascending arousal system that promote wake and sleep neurons in the VLPO area of the hypothalamus promoting sleep[91, 92]. This model highlights the complexity of the sleep-wake cycle in relation to the homeostatic need to sleep as a function of prolonged wakefulness, the circadian drive of the daily cycles of sleep and wakefulness, as well as the brain circulatory system[8, 13, 88].

The rapid expansion of knowledge in the past decade has increased understanding of the basic circuitry underlying the sleep-wake cycle and the regulation of the two primary endogenous systems mentioned previously; the circadian pacemaker located within the suprachiasmatic nucleus of the hypothalamus and the homeostatic drive for sleep regulation[88]. Although on the surface there is an increased understanding of the sleep-wake cycle, at a deeper level the circuitry remains a challenge to comprehend due to the complexity of the systems adaptation to ever changing environments and variables[88]. It is clear that homeostatic and circadian drives for sleep can be overcome and desynchronised for brief periods when external events demand a sympathetic response. For an elite level athlete, possible sympathetic influencers such as training and competition may present as external perturbations to the sleep system. As it has been previously suggested by Davenne[8] athletes are highly sensitive to any disruptive factors that can desynchronise their circadian rhythms when compared with sedentary individuals. Consequently, it is vital an understanding of the arousal system and its interaction with sleep is attained.

2.2 Sleep and Athletes

With most sleep research focused on clinical populations[93-95], little research exists in other populations such as athletes where the restorative properties of sleep are likely to be of importance[75]. Indeed sleep has been recognised as an important component of both the psychological and physiological state of an athlete[20, 75]. Data regarding the sleep habits of athletes are ambiguous with the majority of research examining sleep and performance from anecdotal or non-athletic populations[6, 75]. Furthermore, while a great amount is understood regarding the duration of sleep obtained by adults in the general population, the ideal quality and quantity of sleep is yet to be elucidated for athletes[1]. Athletes may in fact require more sleep than non-athletes to recover from the stresses of training and competition and to consolidate what was learnt from training[96]. In 2005 the first known review on sleep in sport[97] concluded little is known on the relationship between sleep and performance in athletes[9]. Since then research in the area has increased with recent athlete sleep monitoring studies revealing far from ideal sleep durations and quality (Table 2.1)[9, 98]. However, sleep research in athletes remains a challenge as conjecture exists regarding data collected from laboratory-based sleep observations in athletes, as this data is likely artificial and not reflective of the demands made in real performance settings[52]. Regardless, with team and individual athlete rankings, athlete selections and sponsorship deals dependant on consistent high-level performances, it is important researchers understand the sleep demands of athletes in order to optimise an athlete's recovery and overall exercise performance[10, 12, 75].

2.2.1 Importance of Sleep in Athletes

Sleep has anecdotally been suggested as the single best recovery strategy available to an athlete[1, 10]. Despite the significance of this statement, research into athlete recovery has heavily focused on techniques such as hydrotherapy, compression garments, massage and nutritional interventions with sleep and napping frequently overlooked[1, 15]. Whilst indirectly these recovery techniques may aid sleep by decreasing inflammation[99, 100] and pain[100, 101] as well as modulating body temperature[10], research aimed specifically at sleep as a recovery strategy is needed. Sleep, in particular slow wave sleep (SWS), provides a restorative function to the body to recover from prior wakefulness and fatigue by repairing processes and restoring energy[47, 48]. This repair process ensures the body is refreshed and prepared for full functioning in the subsequent wake period[47, 48]. In addition, the impact and importance of sleep for an athlete's performance may also be demonstrated through studies where athletes who experienced non-restorative sleep exhibited increased tiredness, decreased mood and decreased cognitive functions such as impaired reaction times and decision making abilities (discussed in detail below)[9, 98].

2.2.2 Incidence of Sleep Disruption in Athletes

Sleep studies on athlete populations in the literature is limited with most information from studies using subjective or non-PSG objective measures. Recently, an actigraphy monitoring study of 46 Great Britain Olympic squad members by Leeder et al.[1] found athletes experienced poorer markers of sleep compared to age and sex-matched non-athletic individuals (sleep efficiency: 80.6 ± 6.4% and 88.7 ± 3.6%, respectively) however the athletes remained within a healthy sleep range[1]. Following this, an Australian study utilising actigraphy revealed 124 international and national athletes slept on average 6 hours and 42 minutes per night, well below the recommended 8 hours[102]. Interestingly, this study highlighted differences between team and individual sport athletes, with team sport athletes reported sleeping 30 minutes longer than individual sport athletes[102]. In agreement, a study analysing 70 elite Australian athletes over two weeks during a normal training block observed 88% of the sleep periods fell below the recommended 8 hours of sleep per night and 60% were below 7 hours, in addition to 76% of the sleep periods below 90% sleep efficiency[16]. Further breakdown of the results indicated significant differences in sleep/wake behaviour on training days compared with rest days. On nights prior to training days, time spent in bed was significantly shorter (08:18 ± 01:12hrs) and the amount of sleep obtained was significantly less (06:30 ± 01:18hrs) compared with nights prior to rest days (08:42 ± 01:36; 06:48 ± 01:42 respectively)[16]. Together the above three studies indicate growing evidence suggesting elite athletes do not obtain sufficient sleep during normal training phases[16] (Table 2.1). In contrast to the above studies, examination of 103 Italian Olympic athletes via a questionnaire, showed no greater likelihood of athletes to display sleep disturbances when compared with recreational athletes[103]. One explanation provided was Olympic athletes engage in a variety of healthy habits that promote sleep and limit alcohol and tobacco intake[103]. The variation and extent to which an athlete’s sleep may be disturbed is highly individual and should be taken into consideration as some athletes will be more likely to incur sleep disturbances than others. Despite many proposed explanations to account for possible variances in athlete sleep study findings, all the above monitoring studies (Table 2.1) provide a useful platform for researchers to further explore sleep and the causes of sleep disruption in specific athlete populations.

Table 2.1 Sleep monitoring studies conducted in athletes.

Author	Participants	Type	Design	Sleep Monitoring Measure	Measures	Findings
Abelyn et al. 2014[104]	18 M sub-elite soccer players and 21 sport students as control	8 weeks of brainwave entrainment (auditory stimulation) v Control group (pillow with no sound)		Sleep diary and questionnaires	Self- assessment questionnaire of Sleep and Awakening quality (SSA), Subjective sleep TST, SOL, sleep quality, wake and sleep times. Psychophysical state of participants (Mood).	Auditory stimulation had a positive effect on sleep and awakening quality and sleepiness.
Driver et al. 1994[105]	8 M fit ultra-triathlon athletes	Sleep following: no strenuous exercise, 15 km run day, 42.2 km run day and an ultra-triathlon day	Cross over design	Polysomnography	Sleep stages, TST, TRT, SOL, ROL, first and second sleep cycle.	Ultra-marathon: ↑ wakefulness and delayed and ↓ REM sleep but did not affect SOL compared to other conditions. REM sleep is a sensitive index of exercise induced stress.
Duffield et al. 2014[106]	8 M professional tennis players	Control v mixed recovery methods (cold water immersion, compression, and sleep hygiene)	Cross over design	Wrist watch actigraphy (Rediband)	TST, SE, SOL, TIB, perceived muscle soreness (1-10 Likert scale), Brunel Mood Scale (fatigue measure).	Sleep hygiene recommendations ↑ sleep duration and ↓ fatigue and perceived soreness. No changes in SE or SOL.
Eagles et al. 2014[54]	10 M rugby union players	Comparison of home based training nights v home competition nights	Observational	Bodymedia sensewear units	TST, SE, bedtime, awakening time.	Sleep quantity ↓on game nights compared to non-game night. Time to sleep on game nights was also significantly later than non-game nights. No change in SE.
Fowler et al. 2014[104]	6 M, football players	Comparison of 6 home and away matches	Observational	Wrist watch actigraphy (Rediband)	SE, TST, SOL, bedtime, awakening time, technical and tactical performance measures.	↓ Sleep quantity and perceived sleep quality in elite football players after both home and away matches
Fullagar et al. 2016[51]	16, M football players	Comparison of training days, day match and night match sleep	Descriptive, observational design	Sleep and sporting activity questionnaire (SosciSurveyTM)	SE, SOL, TST, bedtime, awakening time, sleep restfulness measure, subjective wellness, wake episodes.	↓ Sleep duration, ↓ perceived recovery and later bedtime following night match compared to both training day and day match.
Fullagar et al. 2016[107]	15, M football players	Comparison of international air travel, non-match nights and match nights during a 10-day tour.	Descriptive, observational design	Wrist watch actigraphy (Rediband)	SE, SOL, TST, wake episodes, Recovery-Stress Questionnaire for Athletes, sleep restfulness, training load.	↓ Sleep duration on match nights compared with non-match nights. No significant differences in perceptual recovery between baseline and any day of the tour. Sleep duration ↓ during long-haul international travel with a 4h time-zone delay.

Author	Participants	Type	Design	Sleep Monitoring Measure	Measures	Findings
Kolling et al. 2016[108]	55 (30 M, 25 F) junior rowing team	Monitor of a 26-day training camp	Observational	Bodymedia sensewear units (n=14) and sleep log (n=55)	TST, SE, WASO, sleep restfulness, TIB, SOL, Short Recovery and Stress Scale.	↓ TST in the first two weeks, while training volume and intensity were higher. Overall, the findings highlight the impact of sleep on subjective recovery measures in the setting of a training camp.
Lastella et al. 2014[109]	21 M endurance cyclists	Comparison of baseline, pre-competition and during competition sleep	Observational	Wrist watch actigraphy (Actical), sleep diary	Bedtime, get up time, SOL, TIB, TST, SE, mean activity score, subjective sleep quality.	Less sleep on the night prior to competition 6.5 ± 0.9h compared to baseline 7.4 ± 0.6h. Bed and wake time were earlier during competition than at baseline. SE, SOL, and subjective sleep quality did not change during phases.
Lastella et al. 2011[110]	21 M endurance cyclists	Target bedtime (22:00) and wake time (07:30). 3 groups (morning, evening type or neither type)	Observational	Wrist watch actigraphy (Actical), sleep diary	Morningness-Eveningness questionnaire, bed time, wake-up time, TST, SE.	All groups could obtain greater than 7 hours of sleep per night. Target bed and wake times can allow coaches and staff to control recovery and sleep opportunities for athletes.
Lastella et al. 2014[102]	124 (104 M, 20 F) Australian athletes	Monitor out of competition training phase	Observational	Wrist watch actigraphy (Actical)	Bedtime, get up time, SOL, TIB, TST, SE, moving minutes, WASO, nap duration.	Individual sport athletes had earlier bed time and get-up times, poorer SE and shorter sleep durations compared with team sport athletes. Individual athletes had a higher napping frequency.
Leeder at al. 2012[1]	46 Great Britain Olympic squad and 20 age, sex matched control	4 days of sleep monitoring (home environment out of competition training phase)	Observational	Wrist watch actigraphy (Actiwatch)	TIB, SOL, SE, moving minutes, percentage moving time, sleep restlessness, fragmentation index.	Significant poorer markers of sleep within athlete group compared with control in all measures except ‘time asleep’.
Leger et al. 2008[52]	8 Tour de France a` la voile sailors	Competition monitoring. Monitor sleep and alertness of sailors before and during a long-haul yacht race	Observational	Sleep diary, Wrist watch actigraphy (Actiwatch) and a night cap (head Actigraph and electro-oculograph) and ambulatory Polysomnography	TST, SOL, SE, % of SWS, % of REM, total sleep debt, PSQI, Epworth sleepiness scale, Horne and Otsberg questionnaire and Spiegel sleep index.	The greater the sleep debt, the sleepier the participants. During one leg, almost all sailors were sleep deprived. Final race rankings related to the sleep management strategy of participants.

Author	Participants	Type	Design	Sleep Monitoring Measure	Measures	Findings
Netzer et al. 2001[111]	15 M amateur cyclists	Post competition (120km) v non-training and non-racing recovery period	Cross over design	Polysomnography	Urine catecholamine, HR, sleep stages, TST, SE.	Post competition: ↑ in night and day catecholamine levels, ↑ REM onset latency and ↓ REM in the first half of the night and no effect on SE compared to resting condition.
Paxton et al. 1983[112]	8 M athletic ability, 9 M sedentary	Day of no exercise v sleep following afternoon exercise	ABBA design	Polysomnography	TIB, SOL, TST, sleep stage minutes, REM latency.	↑ SWS for athlete group irrespective of their level of fitness. SOL was shorter in athlete group.
Petit et al. 2014[54]	16 M athletes	Monitoring of 5h phase advance in a sleep laboratory	Observational	Polysomnography	TST, SE, SOL, number of awakenings, sleep stage minutes, Wingate test, rectal temperature.	First night of phase advance ↓ TST, SE, SOL, Stage 2, and REM compared with baseline. Second night of phase advance ↓ Stage 2 and ↑ SWS and REM.
Richmond et al. 2007[113]	19 M Australian rules footballers	Baselines sleep period v night before home and away games	Observational	Wrist watch actigraphy (micro mini-motion logger)	TST, SOL, SE, bedtime, awakening time, number of wakings, sleep-rating scale, game performance rating.	Compared to baseline, TST ↑ on the nights before home and away games. Small changes in sleep quality on the night before a game do not appear to have a significant impact on performance.
Sargent et al. 2013[91]	7 (1 F, 6 M) national swimming athletes	Sleep period preceding a training day v sleep preceding a rest day	Observational	Wrist watch actigraphy and sleep diary	SOL, TST, TIB, SE, sleep duration, WASO, daytime nap duration.	Training days: bedtime and get up times were earlier; TIB was shorter and amount of sleep ↓ when compared with rest days. Overall SE was poor.
Sargent et al. 2013[114]	10 M elite youth soccer players	Monitor training camp at altitude v sea level	Within-subject research design	Polysomnography	TIB, TST, SOL, WASO, SE, sleep stages, respiratory arousals, oxygen saturation, total arousals.	Altitude: ↓ REM sleep and caused disordered breathing in 50% of athletes immediately upon ascent.
Sargent et al. 2014[16]	70 (24 F, 46 M) elite athletes from a range of sports	2 weeks of normal training monitoring, rest day v training days.	Observational	Wrist watch actigraphy and sleep diary	SOL, TST, TIB, SE, sleep duration, WASO, 7-point fatigue scale.	Nights prior to training: ↓ time spent in bed, earlier sleep onset and offset times and ↓ sleep duration than on nights prior to rest days.
Sargent et al. 2016[53]	22 M Australian rules footballers	Night before and after a day game v an evening game	Observational	Sleep diary, Wrist watch actigraphy (Actiwatch-64)	TIB, SOL, TST, SE, bedtime, awakening time.	After the evening game, sleep onset was later, time in bed ↓ and total sleep obtained ↓than after the day game.

Author	Participants	Type	Design	Sleep Monitoring Measure	Measures	Findings
Teng et al. 2011[81]	28 M cyclists	Normal training v high training and recovery	Sleep monitor	Wrist watch actigraphy (Actical), sleep diary	TST, SE, mean activity score, subjective sleep quality.	High training: TST and SE ↓ and sleep activity↑. Subjective sleep measures did not differ during high training periods. Suggesting athletes may be inaccurate at perceiving their own sleep.
Trinder et al. 1985[115]	10 M athletes	Group comparisons on 2 consecutive non-exercise nights	Sleep monitor. 4 groups: 1. Aerobic training, distance runners; 2. Power training weightlifters; 3. Mixed, team sports; 4. unfit, non-athletic	Polysomnography. 2 consecutive nights	Sleep stage minutes, TST, TIB, SOL, SPT, REM latency.	No significant differences were found between athletes and non-athletes on any sleep variable. The aerobic group had ↑ SWS and NREM sleep, slept longer, and had shorter SOL compared to the power group.
Robey et al. 2013[116]	12 M elite youth soccer players	High intensity training nights v home nights and a cold-water immersion intervention	Repeated measures	Wrist watch actigraphy (Actiwatch)	Karolinska 9-point sleepiness scale, sleep quality, SOL, SE, WASO, sleep diary, food diary.	Early evening high intensity exercise had no impact on subsequent sleep quality and quantity or following cold water immersion.

Key: F – female, M- male, PSD- partial sleep deprivation, PSQI- Pittsburgh sleep quality index, REM- rapid eye movement, ROL- REM onset latency, SE- sleep efficiency, SOL- sleep onset latency, SWS- slow wave sleep, TIB-time in bed, TRT- total recording time, TST- total sleep time, WASO- wake after sleep onset.

2.2.3 Causes of Sleep Disruption in Athletes

Numerous internal and external factors such as; temperature, late competitions, anxiety, training volume, whole body stiffness, technology, anticipation prior to competition and psychological stressors have anecdotally been suggested to negatively impact sleep in athletes[18, 19]. For travelling athletes additional factors such as time zone changes[54], unfamiliar surroundings (bedroom), altitude[114], stress of travel and noise may make sufficient sleep difficult to obtain[6, 8]. Whilst it is pertinent to list the sporting factors that may affect sleep in athletes there may be addition factors to consider outside of sport such as study, occupations, exams, relationships etc. as athletes often have dual commitments. Furthermore, it is believed that it is not necessary to elicit total sleep deprivation to influence performance, as even fragmented sleep (e.g. where individuals are awoken at regular intervals throughout a sleep period in that it results in disrupted sleep[117]) has been shown to compromise athletic performances[6, 18, 19]. Current research has sought to monitor athletes' sleep following numerous training phases[5, 81], different training schedules[91, 102], at altitude[114], during and following competition[52, 109, 111], following interventions such as cold water immersion[106, 116] and during hot and cold environments[118] in an attempt to comprehend the scenarios athletes are exposed to and the effects these may have on subsequent sleep and performance (Table 2.1).

Due to athletes subjecting their bodies to large physical demands on a regular basis it is believed they may require more sleep than the average person to repair and recuperate[119]. Following a high training block of increased load Teng et al.[81] reported 28 male cyclists decreased total sleep time from 7.3 hours to 6.9 hours and sleep efficiency from 86.3% to 84.3%, whilst sleep activity increased from 15.4 average count/epoch to 18.4 average count/epoch, compared with a baseline week. Similar results were found in seven national swimmers following increased training volumes with increased sleep movements, increased time spent in SWS and decreased mood compared with a taper period[5]. In addition to changes in sleep variables noted during the different training phases, the authors also observed the amount of sleep an athlete obtained may have been dictated by their training schedule[102]. The earlier the swimmers were required to start training, the less sleep they obtained the night before (5h and 24min) compared with the nights prior to no training days (7h and 5min)[91]. In contrast to the sleep disturbances observed during increased training volumes, a study of 16 aerobic based athletes found sleep architecture changes following a day of no exercise (SWS reduced by 15.5 ± 7, REM sleep increase by 17.9 ± 5.7min) compared with a training day indicating a taper phase may also have effect on an athlete's sleep architecture[120]. These studies raise an interesting question as to whether certain training periods/environments illicit reduced sleep variables and should be further explored, as this may be an important consideration for staff when programming training.

To explore sleep habits during competition Erlacher and colleagues[20] questioned 632 German athletes with results indicating 65.8% had been subject to poor sleep in the nights prior to an important competition with 79.7% experiencing problems falling asleep due to nervousness and thoughts about the upcoming competition[20]. Further analysis of this cohort confirmed differences in team and individual sport athletes with greater sleep problems observed in individual athletes when compared with team sport athletes[20]. These differences were suggested to be a direct consequence of the type of sport, with individual athletes likely to experience increased pressure due to the individual nature of their events[20]. These findings of disturbed sleep prior to competition in individual sport athletes is supported with objective data indicating endurance cyclists took 30 minutes longer to fall asleep the night before competition in addition to experiencing reduced sleep duration on competition night (6.5 ± 0.9h) compared with a baseline night (7.4 ± 0.6h)[109]. Together these findings raise an interesting question as to whether athlete sleep patterns change around competition periods to illicit poor sleep or are athletes by nature generally poor sleepers. Insomnia, as defined by The

American Academy of Sleep Medicine, is difficulty initiating or maintaining sleep, or non-restorative sleep accompanied by daytime impairment such as fatigue or difficulties with memory or concentration[118]. While an athlete may not be diagnosed with insomnia, it is important for athletes, coaches, and support staff to recognise that insomnia like symptoms may present during crucial periods within a season and are likely to influence overall performance. These studies have provided a baseline for exploring sleep in athletes and create a platform to raise further research enquiries.

2.2.4 Relationship between Exercise and Sleep

Research investigating the effects of exercise on sleep commenced in the 1960's and focused primarily on sleep related changes in central nervous system (CNS) function using EEG[121]. The first known study exploring the relationship of exercise and sleep demonstrated that a single-bout of exercise could increase the amount of subsequent SWS sleep, while exercise shortly before bed could decrease subsequent SWS via a possible stress effect[122]. Following these first studies, the understanding of the influence of exercise on sleep has evolved into a complex model of interactions (Figure 2.4) between physical activity, the CNS and physiological processes[121]. Indeed, in a recent review Uchida and colleagues stated sleep should be affected by daytime exercise, as exercise alters the endocrine and autonomic nervous systems in addition to somatic physiology[121, 122]. Despite the expansion of knowledge since the 1960's, the effects of exercise on sleep have not been explored thoroughly, particularly within athlete populations[121].

It has been suggested that physiological stress, the type an athlete is exposed to, has the ability to cause widespread alterations to both the physiology of the brain and body[34, 66, 123]. At a neuroendocrine level within seconds of a stressful episode, norepinephrine is released from nerve endings and the adrenal glands release epinephrine and norepinephrine to the bloodstream creating a 'flight or fight response'[26]. Within minutes, a complex interaction occurs between endocrine and nervous systems resulting in stress responses that have the potential to last hours[26].

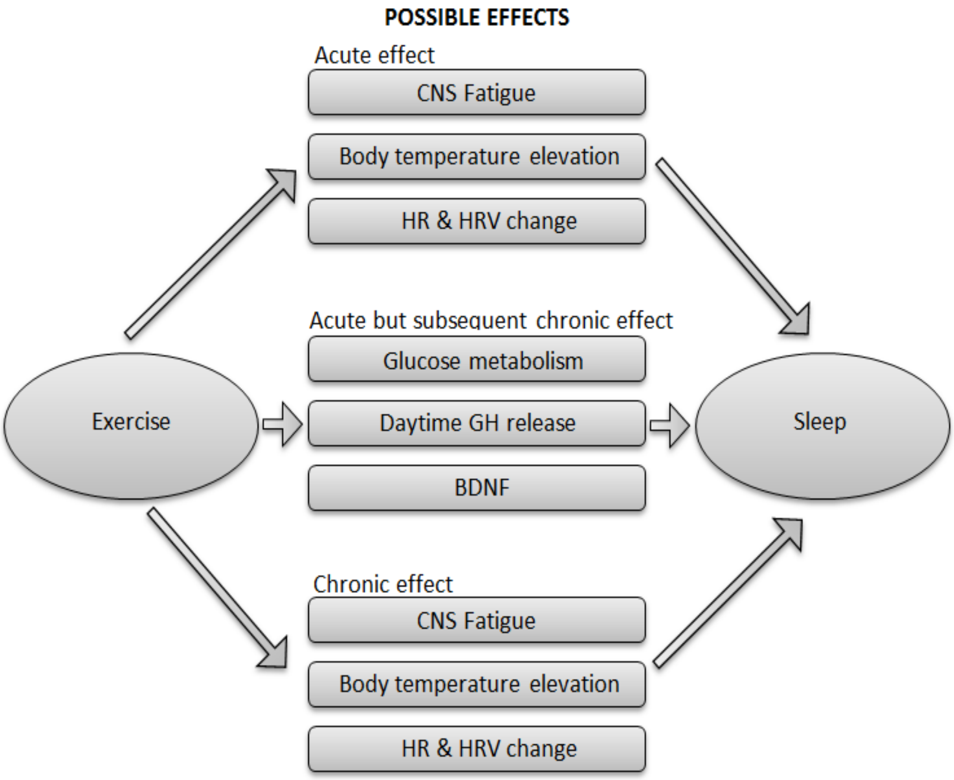

Figure 2.4. Illustration from Uchida et al. on the possible effects of exercise on sleep[122].
CNS- central nervous system, HR- heart rate, HRV- heart rate variability, GH- growth hormone, BDNF- brain derived neurotrophic factor.

Simultaneously within the brain, the hypothalamus releases corticotrophin-releasing factor signalling the pituitary gland to discharge adrenocorticotrophic hormones bringing about the release of cortisol (primary stress and steroid hormone of the body) from the adrenal glands[26]. Increased cortisol and noradrenaline, both of which have been shown to negatively influence sleep in occupational studies[25, 27], have been investigated both prior to (anticipatory response) and during competitions such as tennis, volleyball, wrestling matches, triathlon, judo, endurance cycling and women's football competitions[34]. To date, the time course of the elevated stress response (i.e. cortisol and noradrenaline) post-competition remains unknown and therefore should be a target of future research. This post competition elevation may be due to elevated peripheral hormone concentrations remaining high as a function of stress and intense exercise, which may result in difficulty initiating sleep[26, 98].

Two studies have explored sleep architecture in endurance based athletes following competition using polysomnography sleep recordings[105, 111]. Driver et al.[105] observed a 40% increase in wakefulness of stage one sleep in the first 6 hours of recording compared with a night of no exercise, suggesting stress and muscle pain to be a contributing factor. Furthermore, REM sleep was shorter by 45 minutes (CI 21-70min) and delayed (186 ± 83min) following an ultra-marathon compared with no exercise (90 ± 31min) suggesting REM sleep may be a sensitive index to exercise induced stress. Additionally, in 13 trained cyclists following a 120km cycling race, REM sleep was altered demonstrated by an increased latency (124.0 ± 46min) and a decrease in duration (15.5 ± 3.8% of total sleep time, TST) when compared with a rest day (97.2 ± 41.9min; 17.6 ± 4.9% of TST)[111]. The authors proposed the change in REM was a consequence of the intense exercise associated with the cycling race due to the increased extraction of urinary catecholamines (45.5 ± 25.2 ng/min and 133 ± 87.4 ng/min for epinephrine and norepinephrine respectively on competition day compared with 17.8 ± 5.9 ng/min and 49.2 ± 26.7 ng/min on the rest day)[111]. Together, these findings indicate stress experienced in competition or high intensity training sessions may impact sleep architecture, specifically the configuration of REM sleep in athletes that should be further explored to investigate if this may account for the anecdotal reports of reduced sleep quality post competition[6].

On the contrary physical exercise for the general population is widely considered by physicians and sleep experts to be an important, inexpensive and simple sleep promoting factor[103, 124]. Furthermore, there have been a growing number of studies indicating individuals who exercise regularly experience enhanced sleep compared with those who do not[8]. As suggested by Ushida and colleagues, exercise may be a robust stimulus for the global tendency of the CNS sleep-wake oscillations that affects the entirety of the sleeper's physiological mechanisms[121, 122]. Whilst appropriate amounts of exercise could alter the physiological mechanisms in a desirable direction, excess amounts of exercise combined with stress could alter sleep mechanisms in a less desirable manner, which may hypothetically be the case in athletes.

2.2.5 Impact of Sleep Disruption in Athletes

As previously highlighted, a lack of research exists examining the influence of sleep on performance. As such, this section will review information from existing athlete data (Table 2.2) to provide a theoretical construct for the influence that sleep disruption has shown to have on an athletic population. In an attempt to understand the importance of sleep in athletes, studies have utilised sleep deprivation protocols (Table 2.2). Total sleep deprivation refers to a period of sustained wakefulness greater than 24-hours whereas partial sleep deprivation is where a participants sleep is restricted to less than or equal to six hours[98].

Sleep deprivation in an athletic population has been shown to severely affect both physiological[125, 126] and psychological[7, 19] wellbeing. Most sleep deprivation studies have highlighted an altered mood state affecting motivation as a primary outcome of lack of sleep[6, 13]. Sinnerton and Reilly explored swim performance following 2.5 hours of sleep compared with normal sleep (around 8hrs) in eight swimmers over four consecutive days. The results showed decrements in mood states following reduced sleep with increased fatigue, anger, depression and tension and no change in back or grip strength, lung function or swim times[13]. Reilly and Piercy[7] found comparable results following three hours of sleep per night for three nights in eight male participants. The participants displayed impaired mood states of confusion, vigour and fatigue which, the authors implied may have led to the decreased power performance variables (bench press and leg press)[7]. In addition, lack of sleep, even partial sleep deprivation has been found to negatively influence cognitive function and psychomotor performance through reduced focus[8], determination[3], processing[3], logical thinking[3] and vigilance[8]. For example, 60 dart players demonstrated decreased alertness, increased fatigue and decreased accuracy (frequently missing the target) following 3-4 hours of sleep compared with a normal night of 7-8 hours' sleep[4]. These results led the researchers to conclude acute partial sleep deprivation of one night decreases overall psychomotor performance in dart players[4].

Physiologically, both total[127] and partial sleep deprivation[128] has been shown to compromise the transmission speed of impulses from the brain to the working muscles, affecting reflex and reaction times (Table 2.2)[3]. Four hours of partial sleep deprivation at the end of the night (athletes slept from 22:00 to 03:00) decreased attentional capacities and increased reaction times (593.00 ± 8.27ms) in twelve handball goal keepers compared with a minimum of eight hours sleep (398.28 ± 4.91ms)[128]. Mean choice reaction times were also shown to be compromised following a night of total sleep deprivation (281.65 ± 31ms) compared with a night of habitual sleep (244 ± 39ms) in college athletes[127]. Together these findings suggest that adequate sleep is essential for peak performance as executive function tasks are particularly sensitive to sleep[127]. For many athletes, total sleep deprivation and fragmented sleep is of concern, as athletes are reliant on the ability to make fast, accurate decisions and execute skills effectively for optimal performances[58].

Studies focusing on sleep restriction and their direct effects on athlete performances display equivocal results and thus are not as clear as the effects found on mood states and cognitive function (Table 2.2). Studies enforcing total sleep deprivation in athletes, whilst not entirely ecologically valid, have demonstrated reduced countermovement jumps (CMJ), intermittent sprint times and distance covered in team sport athletes[126, 129, 130]. A night of total sleep deprivation decreased and delayed the recovery of lower-body power; mean and peak CMJ heights ($p = 0.10–0.16$; $d = 0.95–1.05$) up to 16 hours following a competitive rugby league match in eleven athletes compared with a control night of normal sleep (8hrs)[126]. Further, knee extensor maximal voluntary contraction was significantly lower post-game following total sleep deprivation ($p = 0.02$; $d = 0.67–0.76$). Similarly, Skein et al.[129] reported that 30 hours of sleep deprivation in 10 male team sport athletes resulted in reduced intermittent sprint performance with mean sprint times slower following sleep deprivation (2.78 ± 0.17s) compared with a control night (2.74 ± 0.15s). In addition, less mean and total distances were covered by 8 of the 10 team sport athletes following the sleep deprivation night ($p = 0.01$)[129].

Along with total sleep deprivation, partial sleep deprivation studies have displayed reduced maximal anaerobic power variables in football players[131] and judo athletes[130] (Table 2.2). Partial sleep deprivation of four hours towards the end of a night's sleep resulted in decreased muscle strength and power with relative decreases ranging between 2.2 and 9.3% for peak power and between 2.8 and 7.3% for mean power during a Wingate cycle test in the afternoon when compared with a night of normal sleep in 12 judo athletes[130]. A similar study of 12 male soccer players following 4.5 hours sleep found a significant decrease in peak power and mean power ($p < 0.001$) during the Wingate cycle test after partial sleep deprivation compared with a reference night of normal sleep (8hrs)[131]. These studies highlight the importance sleep has on athletic performance.

In contrast, Mougin et al.[12] found following a 30 second Wingate cycle test, performance was able to be maintained following a delayed bed-time until 3am compared to a night of 8 hours sleep suggesting maximal performance may be maintained under partial sleep loss conditions[12]. This finding suggests athletes may be able to overcome sleep loss to produce maximal all out efforts; however, they may not be able to maintain these levels during sustained, repeated effort exercise[7, 10]. Following a series of weight-lifting tasks using traditional weight training exercises (biceps curl, bench press, deadlift and leg press), Reilly and Piercy[13] found deterioration in all four exercises particularly after the second night of restricted sleep. From this study it was apparent that the greatest impairments in performance were seen with sustained exercise later in the session implying a cumulative fatigue effect following sleep restriction[13]. Regardless, considering the adverse effects of the above sleep deprivation studies on mood, cognitive and athletic performance, it is evident that total and partial sleep deprivation has the ability to negatively impact athletes and therefore warrants further exploration[98].

Table 2.2 Sleep deprivation studies conducted in athletes.

Author	Participants	Type	Design	Sleep monitoring measure	Measures	Findings
Abedelmalek et al. 2012[125]	13 M football players	PSD 4.5h at beginning of the night v normal sleep	Cross over	Wrist watch actigraphy (Actiwatch)	Blood- Interleukin-6, growth hormone, cortisol, testosterone.	PSD: ↑ pro-inflammatory cytokine, growth hormone & testosterone after repeated bout of high intensity maximal exercise. No Cortisol change.
Abedelmalek et al. 2012[131]	12 M football players	PSD 4.5h sleep v normal night	Randomised cross-over design	Wrist watch actigraphy (Actiwatch) and sleep diary	30s Wingate test (peak power and mean power) at 8:00 and 18:00. Oral temperature and plasma concentration of IL-6.	PSD: ↓ anaerobic performances (mean power and peak power) and IL-6 concentration remained elevated in the afternoon.
Blumert et al. 2007.[19]	9 M collegiate weightlifters	24h sleep deprivation v 8h normal sleep	Randomised, counterbalance design	Sleep diary	Plasma cortisol and testosterone (pre, post, 1hr), performance (snatch, clean and jerk, front squat), training journal, POMS.	No significant differences in physical performance. Sleep deprivation: ↓ cortisol, caused confusion, fatigue, vigour, and total mood disturbance.
Bougard 2012[132]	8 M motocross riders	24h sleep deprivation v normal sleep	Counterbalanced order	Nil	Balance (Stork stand test, narrow board riding test), flexibility (sit and reach, riding under a rod test), maximal anaerobic alactic power (Abalakov test, long jump test).	Sleep deprivation: significantly affected rider's physical abilities in laboratory tests however to a lesser extent in field tests.
Cook et al. 2011[58]	10 M elite rugby players	3-5h sleep v 7-9h sleep with either (caffeine, creatine, placebo)	Blinded, repeated measure, placebo-controlled crossover	Sleep diary	Saliva (free cortisol and testosterone) and repeated rugby passing skill.	Sleep deprivation: ↓ rugby passing skill performance Supplementation: performance was alleviated.
Edwards et al. 2009[4]	60 (44 M, 16 F), dart players	Normal sleep (7-8h) v PSD (3-4h) at the start of the night	Randomised cross over	Nil	Accuracy of 20 dart throws, core temperature, subjective alertness & fatigue.	PSD: ↓ alertness, ↑ fatigue, less accuracy & more frequent dart target misses. Overall ↓ in psychomotor performance.
Jarraya et al. 2013[128]	12 M handball goal keepers	Normal sleep v 4h PSD at the beginning v 4h at the end of the night	Randomised cross-over protocol	Nil	Reaction time test, Stroop test and barrage test for attention.	PSD: ↑ reaction time (especially PSD at end of night) & ↓ attentional capacities when compared with normal sleep.
Mejri et al. 2016[133]	10 M Taekwondo players	Normal sleep v 4h PSD at the beginning v 4h at the end of the night	Randomised, counterbalance design	Nil	Yo-yo intermittent recovery test (YYIRT) level 1, RPE, plasma lactate concentration, heart rate peak.	PSD: ↓evening intermittent recovery test performance and ↓ lactate concentrations in the evening of the following day, without alteration of HRpeak and RPE in comparison to the reference night.

Author	Participants	Type	Design	Sleep monitoring measure	Measures	Findings
Mougin et al. 1996[12]	8 M highly trained athletes	Delayed bedtime till 3am or normal schedule	Randomised order, cross-over protocol	Sleep diary	30 sec Wingate cycle test (peak velocity, peak power, mean power), lactate and ventilatory parameters.	Sleep deprivation resulted in no impairments to performance variables and ventilatory parameters.
Oliver et al. 2009[134]	11 M recreational participants	30h sleep deprivation v normal sleep (496min)	Randomised cross-over protocol	Nil	30min self-paced treadmill distance test (speed, RPE, core temperature, mean skin temperature, heart rate, and respiratory parameters.	Sleep deprivation: ↓ endurance performance with limited effect on pacing, cardiovascular or thermoregulatory function.
Reilly et al. 1994[7]	8 M participants	3h sleep for 3 nights v normal sleep	Counterbalanced	Nil	Maximum and submaximal bicep curls, bench press, leg press and dead lift. Profile of mood state and sleepiness scale.	Sleep deprivation: ↓ maximal bench press, maximal leg press and all submaximal lifts. Mood state impairment.
Sinnerton et al. 1992 [135]	8 (5 M, 3 f) swimmers	PSD 2.5h v normal night sleep	Randomised cross-over design	Nil	Grip and back strength, lung function, resting hear rate and mood states. 50 and 400m swim	PSD: No performance decrements. Impaired mood states- ↑ depression, tension, confusion, fatigue, and anger.
Skein et al. 2013[126]	11 M amateur rugby league players	Normal night sleep (~8h) v sleep deprived night (0h)	Randomised cross-over protocol	Nil	Countermovement jump, knee extensor MVC, modified Stroop test, venous creatine kinase and C-reactive protein.	Sleep deprivation: impaired countermovement jump, slowed reaction response of Stroop test, ↑ creatine kinase and C-reactive protein release.
Skein et al. 2011[129]	10 M team sport athletes	30 h sleep deprivation v normal night sleep	Counterbalanced cross-over design	Wrist watch actigraphy (Actiwatch) and sleep diary	30-min graded run, 50min intermittent-sprint protocol (15m sprint time, distance covered during submaximal bouts, double leg bounds), MVC knee extensor, modified POMS, RPE.	Sleep Deprivation: slowed pacing strategies, reduced intermittent sprint performance (↑ 15m sprint time and ↓ volume completed), reduced muscle glycogen content and reduced peak voluntary force.
Souissi et al. 2013[130]	12 M judo athletes	Normal sleep v 4h PSD at the beginning v 4h at the end of the night	Randomised cross over design	Nil.	Handgrip, MVC, Wingate test (peak power, mean power), RPE pre-and post a judo match.	PSD at the end of the night: ↓ muscle strength and power in the afternoon when compared with PSD at the start of the night.
Taheri et al. 2011[127]	18 M college athletes	1 night sleep deprivation v normal sleep	Balanced, randomised design	Sleep diary	30s Wingate test and choice reaction time test.	Sleep deprivation: ↑ reaction time. No differences in anaerobic power.
Youngstedt et al. 1999[136]	16 M highly fit cyclists	4h of sleep 1) bright light + exercise or 2) bright light alone before bed	Counterbalanced trial	Wrist watch actigraphy (Actillume Actigraph)	SOL, WASO, TST and subjective ratings of SOL, WASO and insomnia using a VAS and rectal temperature.	Exercise 30 min before sleep did not disrupt sleep. No differences in subjective or objective results between groups.

Key: HR- heart rate, MVC- maximum voluntary contraction, POMS – profile of mood state, PSD- partial sleep deprivation, REM- rapid eye movement, ROL- REM onset latency, RPE- rating of perceived exertion, SE- sleep efficiency, SOL- sleep onset latency, SWS- slow wave sleep, TIB-time in bed, TRT- total recording time, TST- total sleep time, VAS- visual analogue scale, WASO- wake after sleep onset.

On the contrary, the importance of sleep for athlete performance can be demonstrated through the extension of sleep duration (Table 2.3). A group of Stanford University swimmers extended their sleep to 10 hours per night for six to seven weeks from their normal sleep durations varying between 6-8 hours with swim results indicating superior performances[137]. Specifically, athletes swam a 15-meter sprint 0.51 seconds faster, reacted 0.15 seconds quicker off the blocks and improved turn time by 0.10 seconds[137]. The authors from this study stated "the sleep extension results begin to elucidate the importance of sleep on athletic performance and, more specifically, how sleep is a significant factor in achieving peak athletic performance"[3]. Despite the initial positive indications on the use of sleep extension for performance, further work is warranted to fully elucidate its true effect. Future explorations would benefit from larger sample sizes than the limited population of swimmers used n=5 and a greater level of experimental control should be achieved through using a true control group for comparison. Practically, for modern day athletes who have demanding work and training schedules it may not be feasible to simply extend sleep durations. It therefore, remains to be answered whether comparable results may be induced by increasing sleep quality for a given sleep duration through exploring effective sleep interventions[104].

Table 2.3 Sleep extension studies conducted in athletes

Author	Participants	Type	Design	Sleep Monitoring Measure	Measures	Findings
Mah et al. 2011[138]	11 M college basketballers	Sleep extension 10h min per night v normal sleep (6-9h)	Cross over	Wrist watch actigraphy (Actiwatch) and sleep diary	Timed sprint, shooting accuracy (free-throw) reaction time, psychomotor vigilance test, Epworth sleepiness scale, profile of mood state.	Sleep extension: ↑shooting accuracy by 9% for free-throws & faster timed sprint. ↓ reaction time, sleepiness scale and fatigue on the profile of mood state. Overall physical and mental well-being during practice and games.
Mah et al. 2008[137]	5 college swimmers	Sleep extension 10h min per night v normal sleep (6-9h)	Cross over	Wrist watch actigraphy (Actiwatch) and sleep diary	15m sprint, reaction time off the blocks & turn time. Epworth sleepiness scale, profile of mood states.	Sleep extension: faster 15m sprint time, ↓ reaction time, improved turn time & mood improvements.
Schwartz and Simon 2015[139]	12 (7 F, 5 M) college tennis	Sleep extension 9h min per night v normal sleep (7h)	Cross over	Sleep diary	TST, Epworth Sleepiness Scale, Stanford Sleepiness Scale, tennis serve accuracy (25 to both the deuce and add side of the court).	Sleep extension: ↑ accuracy of the tennis serves (35.7% vs. 41.8%). ↓ in both the Epworth Sleepiness Scale and Stanford Sleepiness Scale scores.

Key: F- female, M- male, TST- total sleep time

2.3 Sleep Interventions

It is widely acknowledged that sleep is a necessary component to overall health[10] and recent studies appear to suggest it may assist athletic performance[8]. For this reason, there are a variety of non-pharmacological means that an athlete can utilise to promote sleep including the use of regular sleep/wake routines and sleep hygiene education, skin warming, hydrotherapy, napping, cognitive behaviour therapy, biofeedback and neurofeedback[10, 37, 140]. Sleep hygiene focuses on avoiding behaviours that interfere with sleep patterns, hence encourages the engagement in behaviours that promote sleep. These can include: ensuring quiet, dark and comfortable sleeping environments; eliminating the bedroom clock; avoiding coffee, alcohol and nicotine; and encouraging individuals to abide by regular sleep /wake routines[37]. A current and novel tool shown to be beneficial for sleep enhancement in patients with insomnia[41] and healthy participants[89] is bio and neurofeedback[41]. Biofeedback (BFB) and neurofeedback are a form of training used to teach individuals to self-regulate and gain awareness and control over their bodies.

2.3.1 Biofeedback

Biofeedback is a technique enabling an individual to learn and gain voluntary control over physiological processes that otherwise are out of conscious awareness, for the purpose of improving health and performance[43, 45]. During BFB an individual receives real time information regarding physiological processes on a computer screen and via operant conditioning (i.e. rewarding experience) is able to manipulate and entrain their physiology to achieve a desired outcome[43]. Peripheral (EMG, electro dermal response, heart rate, temperature, blood volume pulse) and central (EEG) biofeedback is increasing in its usage as both a non-pharmacological therapeutic treatment and research tool[43].

The use of BFB in patients with insomnia has been shown to provide a successful treatment modality leading the American Psychological Association to include BFB as an intervention classed as a 'probable efficacious treatment'[81]. Within this literature, the use of BFB is associated with increases in total sleep time and reduced onset latency[41, 42, 141]. Despite these positive results no established protocols exist for BFB in its application to enhance sleep nor has such an intervention been used to increase sleep efficiency in individuals with no sleep pathology (i.e. athletes)[42, 141]. Interestingly, the use of BFB already exists within athletic populations with its application rapidly growing in the field of sport psychology. While not focused on sleep, BFB is currently used to lower competition stress, help athletes gain control over their arousal levels, manage emotions and mood swings, control anxiety and muscle tension with the ultimate goal of enhanced performances[43]. As many of the above-mentioned stressors could influence sleep, it is possible that BFB can be used as an effective sleep aid within an athletic population.

2.3.2 Neurofeedback

Neurofeedback (NFB) is a specific type of biofeedback intervening on the level of the central nervous system using EEG measurements[41]. The goal of NFB is for an individual to gain control over their electro-physiological processes in the brain and learn how to train and alter the frequency and amplitude of their brainwaves[43, 48]. Traditionally there are four types of brainwaves that differ according to frequency, these being delta (0.5-4 Hertz), theta (4-8 Hertz), alpha (8-12 Hertz) and beta (13-30 Hertz)[48]. Electrodes are attached to the scalp at specific identifiable areas to achieve particular outcomes such as alpha rhythm, sensorimotor rhythm or theta/beta ratio depending upon the desired outcome[46]. During NFB training, EEG is recorded and the individual receives real time feedback regarding the cortical activity of the brain through either visual or acoustic displays[41, 46]. This is achieved through the use of software programs that utilise simple shapes or video games to instruct the participant to alter the feedback display by either increasing or decreasing a visual display, resulting in altered brain activity[46]. It must be acknowledged that the electrical activity is simply relayed to the computer through electrodes placed on the scalp, there is no electrical current administered to the brain[41]. The goal of the treatment through rewarding experiences, illustrated by visual changes in EEG recordings, enables an individual to gain awareness and normalise the function of the brain by inhibiting and or reinforcing specific frequency bands[43, 46, 49].

There are many applications of NFB. Such applications include the treatment of learning disabilities, epilepsy, attentional deficit hyperactivity disorder (ADHD), migraines, chronic pain, mild traumatic brain injury, stroke patient rehabilitation, conduct disorder and sleep dysregulation[46, 49]. Different NFB training protocols have not only helped individuals with pathologies but also demonstrated positive effects on creativity, intelligence, memory, reaction time tasks and performance[46, 49]. The use of NFB training is becoming popular as an inexpensive, useful, non-pharmacological intervention that enables an individual to recondition and retrain their brain[46]. The most widely used NFB protocols include either the enhancement of the sensorimotor rhythm (SMR; 12-15Hz) or the modulation of the theta/beta ratio[46].

In addition to the above listed uses, NFB training has recently been used as a modality to enhance sleep[41, 142] . In a study of seventeen insomnia patients, Cortoos et al[41] found that by applying a NFB protocol focusing on increasing SMR and inhibiting theta power and a high beta power participants experienced greater sleep efficiency (71.1 ± 17.3% compared with 54.6 ± 23.2%) and subjective sleep changes as well as a significant increase in TST (340.0 ± 82.1min compared with 255.0 ± 109.9min) using wristwatch actigraphy[41]. These results indicated that by intervening on a level of cognitive processing, cortical arousal and information processing was influenced during sleep, hence increasing total sleep time[41]. As athletes may demonstrate physiological hyperarousal symptoms and stress (measured by increased catecholamines and cortisol concentrations) which is similar to that of patients with insomnia i.e. following heavy training periods or prior to important competitions[41], it is possible NFB training could be used to help enhance and optimise sleep.

2.4 Summary

The above information on sleep highlights its vital role not only for general health and wellbeing but also for the preparation, recovery, and performance in elite level athletes. The majority of research currently available focuses on sleep deprivation and training periods with scarce amount exploring critical competition periods. Based on the presented information there are clear knowledge gaps on the objective sleep of athletes during competition, the reasons and mechanisms behind poor sleep and the lack of interventions established to enhance sleep. The series of four studies found within this thesis aim to advance knowledge in these areas

CHAPTER THREE

Understanding sleep disturbance in athletes prior to important competitions

Juliff LE, Halson SL, Peiffer JJ. Understanding sleep disturbance in athletes prior to important competitions. *Journal of Science and Medicine in Sport*. 2014; 18 (1):13-18.

3.1 Abstract

Objectives: Anecdotally many athletes report worse sleep in the nights prior to important competitions. Despite sleep being acknowledged as an important factor for optimal athletic performance and overall health, little is understood about athlete sleep around competition. The aims of this study were to identify sleep complaints of athletes prior to competitions and determine whether complaints were confined to competition periods. Design: Cross-sectional study. Methods: A sample of 283 elite Australian athletes (129 male, 157 female, age 24 ± 5 yr) completed two questionnaires; Competitive Sport and Sleep questionnaire and the Pittsburgh Sleep Quality Index. Results: 64.0% of athletes indicated worse sleep on at least one occasion in the nights prior to an important competition over the past 12 months. The main sleep problem specified by athletes was problems falling asleep (82.1%) with the main reasons responsible for poor sleep indicated as thoughts about the competition (83.5%) and nervousness (43.8%). Overall 59.1% of team sport athletes reported having no strategy to overcome poor sleep compared with individual athletes (32.7%, p = 0.002) who utilised relaxation and reading as strategies. Individual sport athletes had increased likelihood of poor sleep as they aged. The poor sleep reported by athletes prior to competition was situational rather than a global sleep problem. Conclusion: Poor sleep is common prior to major competitions in Australian athletes, yet most athletes are unaware of strategies to overcome the poor sleep experienced. It is essential coaches and scientists monitor and educate both individual and team sport athletes to facilitate sleep prior to important competitions.

3.2 Introduction

Within elite sport, success is underpinned by optimal preparation[143] and, equally important, adequate recovery between training and during competition[1, 144]. Sleep has been recognised as an essential component for athlete preparation and is suggested to be the single best recovery strategy available to an athlete[10, 145]. Despite the importance of sleep for athletic performance, data on elite athletes is limited[145]. Anecdotal reports suggest athletes often sleep worse around competition periods, particularly the night(s) prior to an important competition[20, 129]. With reduced sleep shown to negatively influence performance this reduction may become problematic[39, 58]. Sleep deprivation studies in athletes has found decreased anaerobic performances through decreased mean and total sprint time in team sport athletes after 30h of sleep deprivation[130] and decreased aerobic performance following 24h of reduced sleep[128]. Whilst it may be seldom that athletes experience total sleep deprivation prior to competition, acute partial sleep deprivation may exist. One night of poor sleep in athletes is associated with reduced reaction times[138], reduced anaerobic performance the following afternoon in football players[4] and declines in cognitive processes such as; visual tracking, focus, determination and mood[3, 19]. As many sports rely on fine motor movements and the ability to make fast accurate decisions, reduced sleep in athletes is a genuine concern[146].

As it is possible that sleep quantity and quality may influence performance[8], there is a growing need to understand sleep patterns in elite athletes. To date, relatively few studies exist that provide this information[1, 9, 105, 111, 129]. In a survey of 632 German athletes prior to competition, 65.8% acknowledged worse sleep than normal at least once before a competition, indicating their main issue to be “problems falling asleep” (79.9%), due to “thoughts about the competition/game” (77%) and because of this “increased daytimes sleepiness” with athletes indicating “no special strategy” to enhance sleep[20]. These findings provide valuable information on sleep habits of the elite athlete and provide a stimulus for further investigation. Furthermore, if elite athletes do present as “poor” sleepers it is important to differentiate poor competition sleep from chronic sleep issues if coaches, athletes, and sports scientists hope to use this knowledge to enhance future performance.

The purpose of this study was to document the occurrence of sleep disturbances in athletes prior to important competitions and/or games. If athletes indicated sleep disturbances, we aimed to examine the particular problems, reasons and perceived consequences associated with the sleep disturbance. In addition, from the information obtained we sought to determine whether a particular group of athletes had an increased likelihood of sleep disturbance. This study additionally aimed to provide a comprehensive analysis of whether individual versus team sport athlete sleep habits differ. Finally, a novel aspect of the study was to establish whether sleep disturbances are a general complaint present on a day-to-day basis in athletes or whether it is merely situational.

3.3 Methods

A sample of 283 elite Australian athletes (mean ± SD: age: 24 ± 5 y, age range: 16-47 y) volunteered to participate in the study from a variety of Australian sports (Table 3.1 and 3.2). Athletes were recruited from the Australian Institute of Sport, Australian Winter Olympic team, Australian Paralympic team, and National Sporting Organisations through personal contact with researchers or through coaching and/or support staff. All athletes were at an international level or were members of professional teams. The athletes sampled had competed in their sport for a mean of 11 ± 6 y, trained on average 16:42 ± 6:42 hours per week, slept on average 7:42 ± 0:54 hours per night and had competed in 14 ± 13 important competitions or games in the past twelve months (Table 3.2). Ethical approval was obtained through Murdoch University and the Australian Institute of Sport ethics committees prior to data collection.

Table 3.1. Distribution of athletes by sport.

Individual	Team
Athletics *n*=21	Basketball *n*=14
Canoe/Kayak *n*=6	Football (soccer) *n*=24
Cycling *n*=17	Hockey *n*=30
Gymnastics *n*=3	Netball *n*=30
Moguls *n*=1	Rugby League *n*=15
Rowing *n*=4	Rugby Sevens *n*=44
Sailing *n*=2	Softball *n*=14
Short Track Speed Skating *n*=1	Volleyball *n*=10
Ski Cross *n*=3	Water polo *n*=4
Surf Life Saving *n*=1	Wheelchair Basketball *n*=19
Swimming *n*=9	Wheelchair Rugby *n*=6
Tennis *n*=3	
Triathlon *n*=1	
Power Lifting *n*=1	

Table 3.2. Characteristics of athletes by gender, sport, and season (mean ± SD).

	Overall	Gender		Sport		Season	
	(*n*=283)	Male (*n*=126)	Female (*n*=157)	Individual (*n*=73)	Team (*n*=210)	In-Season (*n*=187)	Out of Season (*n*=96)
Age	24.1 ± 5.1	24.0 ± 5.5	24.2 ± 4.9	24.4 ± 5.8	23.9 ± 4.9	24.5 ± 5.2*	23.2 ± 4.8
Years in Sport	11 ± 6	11 ± 7	11 ± 6	11 ± 6.0	11 ± 7	11 ± 6	11 ± 6
Practice hours per week (hh: min)	16:42 ± 6:42	16:42 ± 6:00	16:48 ± 7:12	23:00 ± 7:30*	14:36 ± 4:42	16:06 ± 6:06*	18:00 ± 7:30
Sleep duration per night (hh: min)	7:42 ± 0:54	7:48 ± 0:54	7:36 ± 0:54	7:48 ± 1:00	7:36 ± 0:54	7:42 ± 0:54	7:42 ± 1:00

* Difference (p<0.05) between groups within category

In the period prior to (1 month) and following (7 months) the 2012 Olympic games, participants were asked to complete two questionnaires regarding their sleep (Competitive Sports and Sleep Questionnaire[20] and the Pittsburgh Sleep Quality Index[147]) either online (Survey Monkey©) or through hard copy.

The Competitive Sports and Sleep questionnaire[10], previously described by Erlacher and colleagues[20], is a sport specific questionnaire used to assess sleep habits and dreams of athletes prior to important competitions and games. The questionnaire is divided into three main sections. The first section is used to obtained demographic data and information about the athlete's chosen sport. This information was used to categorise athletes into male and female, team sport or individual sport and in season or out of season at the time of answering the questionnaire, for statistical purposes. The subsequent section aimed to obtain information on athlete sleep habits prior to important competitions or games. If an athlete answered "yes" to having poor sleep at least once before an important competition or game in the past year, they were required to complete a further four closed response questions.

The initial closed response question assessed the types of sleep problems the athlete experienced. The response options were; ''problems falling asleep'', ''waking up at night'', ''waking up early in the morning'', and ''unpleasant dreams'' with the first three options referring to typical sleep problems associated with insomnia. The second question addressed reasons for the sleep disturbance; ''not used to surroundings'', ''noises in the room or from outside'', ''nervousness about competition/game'', and ''thoughts about the competition/game''. The third question addressed the perceived consequences of poor sleep with options including; ''no influence'', ''bad mood the following day'', ''increased daytime sleepiness'', and ''poorer performance in competition''. In the fourth question, athletes report on the strategies used to deal with sleeping problems with responses; ''no special strategy'', ''methods to relax'', ''sleeping pills'', ''reading'', and ''watching TV''. In the final section of the questionnaire, an additional series of questions were used to obtain information regarding general sleep habits and training. Within this section athletes answered questions such as; "If you have a late training session or game do you find it hard to sleep after?" and "Do you take sleeping medication?".

The validated Pittsburgh Sleep Quality Index (PSQI) has been used throughout numerous sleep studies as a standardised sleep questionnaire estimating general sleep quality[147], however there has been limited use in athletes[16]. For the current study the questionnaire was used to identify 'good' or 'poor' sleepers. Prior to filling out the PSQI athletes were notified that all answers were to indicate the most accurate reply for the majority of days and nights in the past month only. Seven component scores were generated (using a 0-3 scale): subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction. From the sum of the seven component scores a global score (range: 0-21) was calculated[148, 149]. If an athlete scored between 0-5 they were classed as a 'good sleeper' as specified by the PSQI and a score above 5 classed an athlete as a 'poor sleeper'[147].

Differences for age, years in sport, practice hours per week and sleep per night between the groups for gender, sport, and time of season the questionnaire was answered, were analysed using an independent sample t-test for the continuous variables. The percentage of athletes, who responded yes to reporting poor sleep the night before an important competition or game in the past year, was calculated. For the "yes" respondents, associations between categorical variables for sex (female vs. male), sport groups (individual vs. team sports) and time of season the questionnaire was answered (in season vs. out of season) was calculated for each sleep disturbance question using a 2 x 2 frequency table and Pearson's chi-squared test ($\chi 2$). To determine whether an association existed between athletes who reported "yes" or "no" to sleep disturbance prior to a competition and athletes who were classed as generally 'good' or 'poor' sleepers through the Pittsburgh Sleep Quality Index, a chi-squared test was calculated. A binary logistic generalized linear model was run to ascertain the effects of the dichotomised variables age, gender, sport, and athletes in or out of season on the predicted likelihood of athletes having poor sleep prior to an important competition. All statistics were completed using SPSS© Statistics (version19, IBM©, USA) and R (R Foundation for Statistical Computing, Vienna) statistical software programs with significance set to $p \leq 0.05$.

3.4 Results

From the 283 Australian athletes sampled, 181 (64.0%) indicated they had slept worse than usual in the night(s) prior to an important competition or game over the past 12 months. There were no significant differences between gender (62.4 % male vs. 65.9% female), sport (71.23 % individual vs. 61.4% team) or athletes currently in or out of season (61.3 % in-season vs. 69.1% out of season); (Table 3.3). In addition, of the 283 athletes sampled 35% were classed as having poor sleep in general when scored using the Pittsburgh Sleep Quality Index.

The 181 Australian athletes who reported worse sleep at least once prior to a competition or game answered further questions in relation to their sleep disturbances (Table 3.3). Overall, the majority of athletes indicated they had “problems falling asleep” (82.1%) due to “thoughts about the competition/game” (83.5%) however (46.6%) believed this had “no influence” on their performance.

There was an association between genders for unpleasant dreams, with dreams affecting sleep in females (10%) more frequently than males (0%); ($x^2_{(1)} = 9.16$, $p = 0.002$). In addition, females reported reading more frequently (32.6%) as a strategy to obtain improved sleep on the night prior to a competition than males (18.5%); ($x^2_{(1)} = 4.51$, $p = 0.034$). No further differences were found between genders.

There were no differences observed between individual versus team sport athletes for problems and reasons for sleep disturbance with both indicating internal factors “nervousness about the competition/game" and "thoughts about the competition/game" as the main reasons for their sleep disturbance (Table 3.3). An association ($x^2_{(1)}$ = 8.36, p = 0.005) was found for individual athletes reporting worse sleep to have no influence on performance (63.5%) when compared with team sport athletes (39.7%). Increased daytime sleepiness was stated more frequently in team sport athletes (48.4%) compared with individual athletes (26.9%); ($x^2_{(1)}$ = 6.97, p = 0.012). Additionally, a higher percentage of team sport athletes (59.1%) reported having no special strategy to obtain better sleep on the night before an important competition or game compared with individual athletes (32.7%); ($x^2_{(1)}$ = 9.87, p = 0.002). Individual athletes reported using methods to relax ($x^2_{(1)}$ = 5.53, p = 0.024) and reading ($x^2_{(1)}$ = 12.4, p = 0.001) as strategies to enhance sleep more often than team sport athletes (Table 3.3).

Table 3.3. Absolute and relative number of responses for each person who states, “Yes” they have had disrupted or fragmented sleep prior to an important competition or game in the last 12 month.

	All Participants		Gender				Sport				Season			
	Absolute	Frequency (%)	Male (%)	Female (%)	Chi square	p-value	Individual (%)	Team (%)	Chi square	p-value	Out of Season (%)	In Season (%)	Chi square	p-value
Overall	181	64.0	65.9	62.4	0.55	0.619	71.2	61.4	0.13	0.158	69.1	61.3	0.20	0.240
“What kinds of problems did you experience with your sleep prior to an important competition or game?” *n=179*														
Problems falling asleep	147	82.1	80.7	83.3	0.21	0.698	80.7	82.7	0.09	0.831	86.2	79.8	1.13	0.318
Waking up early in the morning	48	26.8	24.1	29.2	0.58	0.501	32.7	24.4	1.29	0.269	24.6	28.1	0.25	0.726
Waking up at night	68	38.0	32.5	42.7	1.96	0.169	44.2	35.4	1.21	0.310	43.1	35.1	1.12	0.337
Unpleasant dreams	10	5.6	0	10	9.16	0.002*	4	6	0.42	0.726	6	5	0.06	1.000
Not feeling refreshed in morning	65	36.3	34.9	37.5	0.13	0.757	32.7	37.8	0.42	0.608	30.8	39.5	1.36	0.262
“What reasons were responsible for your sleeping problems prior to an important competition or game?” *n=176*														
Thoughts about competition	147	83.5	82.9	84.0	0.16	0.837	76.5	86.4	2.59	0.120	83.1	83.8	0.01	1.000
Nervousness about competition	77	43.8	42.7	44.7	0.07	0.877	49.0	41.6	0.81	0.405	44.6	43.2	0.03	0.876
Not used to surroundings	39	22.2	23.3	22.3	0.02	1.000	21.6	23.3	0.05	1.000	26.2	20.7	0.69	0.458
Noises in room or outside	31	17.6	15.0	19.0	0.75	0.428	26.0	14.0	3.62	0.076	15.0	18.0	0.31	0.666
“In what manner did the sleeping problems influence your performance during the competition or game?” *n=178*														
No influence	83	46.6	48.2	45.3	0.15	0.764	63.5	39.7	8.36	0.005*	56.9	40.7	4.36	0.043*
Increased daytime sleepiness	75	42.1	36.1	47.4	2.29	0.171	26.9	48.4	6.97	0.012*	35.4	46.0	1.91	0.207
Bad mood the following day	24	13.4	13.3	13.7	0.01	1.000	11.5	14.3	0.24	0.810	4.6	18.6	6.90	0.011*
Worse performance in competition	25	14.0	17.0	12.0	1.03	0.388	17.0	13.0	0.65	0.478	11.0	16.0	0.91	0.380
“Which strategies did you use to sleep well in the nights preceding a competition?” *n=176*														
No Strategy	91	51.7	54.3	49.5	0.41	0.548	32.7	59.1	9.87	0.002*	48.4	53.6	0.43	0.534
Methods to relax	37	21.0	22.2	20.0	0.13	0.853	32.3	16.5	5.53	0.024*	20.3	21.6	0.03	1.000
Sleeping pills	23	13.1	12.3	13.7	0.07	0.826	12.2	13.4	0.04	1.000	15.6	11.6	0.58	0.490
Reading	46	26.1	18.5	32.6	4.51	0.034*	44.9	18.9	12.4	0.001*	29.7	24.1	0.66	0.477
Watching TV	34	19.3	22.2	16.8	0.81	0.445	25.5	16.5	2.27	0.141	20.3	18.8	0.06	0.844

*Association (p<0.05) between groups within a category.

There was an association between poor sleep responses prior to competition and the PSQI ($x^2_{(1)} = 5.195$, $p = 0.002$) indicating the two variables are statistically independent of one another. The logistic regression model which predicted the likelihood participants had poor sleep was statistically significant ($x^2_{(3)} = 15.819$, $p = 0.001$). Of the four predictor variables, age, gender, sports, and season, only two were statistically significant; age ($p = 0.019$) and sport ($p = 0.004$). Increasing age was associated with an increased probability of exhibiting poor sleep in individual sport athletes whereas team sport athletes' probability of poor sleep decreased with age (Figure 3.1).

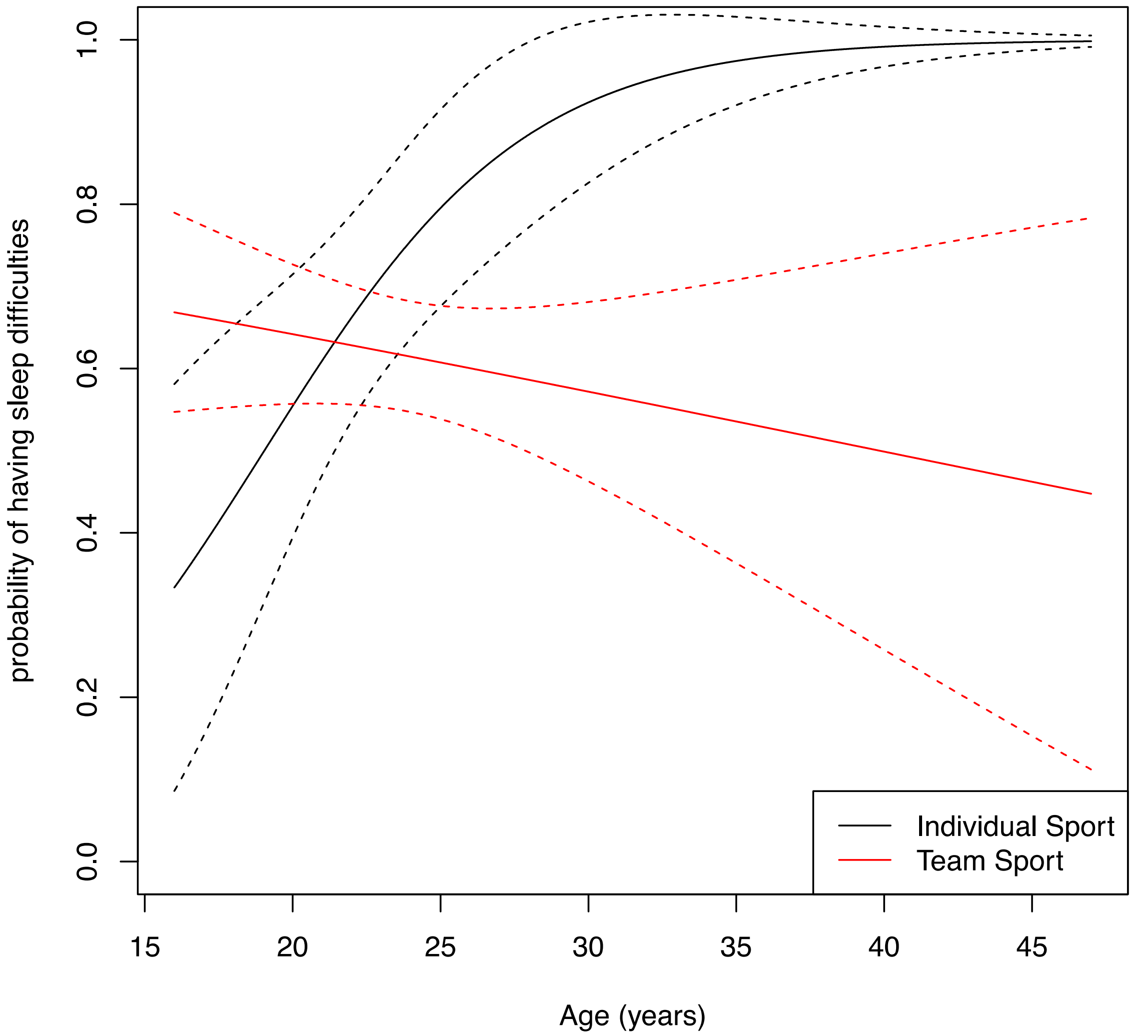

Figure 3.1. The predicted probability of sleep difficulties prior to an important competition for individual and team sport athletes based on age. Predicted probabilities and 95% confidence intervals are displayed.

General sleep disturbance percentages indicate 52.5% of athletes experience poor sleep post late game whilst 47.5% show no sleep disturbance. Following a rest day 28.4% of athletes indicate having sleep disturbance whilst 71.6% did not. Finally, 27.7% of athlete's experience sleep disturbance during heavy training periods.

3.5 Discussion

The purpose of this study was to understand the sleep complaints of elite Australian athletes prior to important competitions and games. The main findings were; 1) 64% of Australian athletes surveyed experienced sleep problems prior to a major competition at least once in the previous 12 months. The key sleep complaint reported was difficulty-initiating sleep due to nervousness and thoughts prior to competition. 2) The perceived influence of poor sleep on performance varied between individual and team sport athletes. 3) When further examining individual and team sport variances, the percentage use of strategies was statistically different. 4) The predicted likelihood of sleep disturbance due to an athlete's age differed with individual and team sport athletes. 5) A novel finding revealed through correlation analysis was the sleep problems reported by athletes in this study were confined to competition periods only.

In the present study, we observed 64% of the athletes surveyed indicated sleep disturbance prior to important competition, which supports previous anecdotal evidence. This finding is comparable to the occurrence of sleep complaints found in German athletes (65.8%) prior to major competitions[20]. The majority of Australian athletes who indicated experiencing worse sleep prior to competition reported internal factors as the main reason responsible (Table 3.3). Specifically, nervousness and thoughts about the competition were the most common reasons for sleep problems regardless of an athlete's gender or sport. This finding is consistent with previous research in both marathon runners[129] and German athletes[20] who reported experiencing anxiety and excessive thoughts prior to competition. Whilst external factors such as noise may impact sleep, our results confirm internal factors strongly influence sleep disturbance in the current athlete population.

Consequences of fragmented sleep on performance are of importance to athletes and coaches, as sleep restriction whether chronic or acute may have detrimental effects on health and performance[121]. In our study, the two most commonly reported consequences of sleep disruption were; 1) no perceived influence on performance (46.6%) and/or 2) increased daytime sleepiness (42.1%). The later finding is consistent with previous studies in athletes[20] and the general population[121] where daytime sleepiness was recognised as the most frequently described consequence of insufficient sleep. Interestingly, only 14% of all surveyed athletes believed reduced sleep directly resulted in worse performance during competition. Performance was not assessed during the study therefore there is little information to determine whether an athlete had an accurate perception of performance impacts.

Results indicate individual sport athletes are similar to team sport athletes in the reported occurrence of sleep complaints prior to major competitions. These findings contrast those by Erlacher et al.[20] who observed greater reporting of poor sleep in individual sport athletes compared with team sport athletes. This difference was explained by the lower pressure and anxiety experienced in team sports as these athletes, unlike individual sport athletes, are not solely responsible and accountable for their own results[20]. Although this explanation is feasible our data does not support this hypothesis as we observed team sport athletes to report nervousness and thoughts prior to competition as reasons responsible for the poor sleep similar to the individual athletes. While additional research is needed to examine differences in sleep habits of individual versus team sport athletes to fully appreciate the diversity, our current data indicates sleep education through methods such as sleep hygiene (behaviours that are believed to promote improved quantity and quality of sleep[125]) and targeted cognitive arousal interventions to address internal factors for sleep disturbance could provide benefits of sleep enhancement in both individual and team sport athletes.

Despite team and individual sport athletes reporting similar sleep problems and reasons responsible for sleep disturbance, team sport athletes reported a greater incidence of daytime sleepiness compared with individual sport athletes (Table 3.3). It is possible the greater daytime sleepiness in team sport athletes is due to a lack of sleep strategies utilised to overcome sleep complaints compared with individual sport athletes (Table 3.3). For instance, individual sport athletes reported more frequently the reliance on reading and/or methods to relax to combat sleep complaints in comparison with team sports athletes who were more likely to have no strategies in place (Table 3.3). Furthermore, as individual athletes indicated having a greater number of strategies to overcome sleep disturbance this possibly explains why these athletes reported sleeping problems to have little influence on their performance more frequently than their team sport counterparts.

Increasing age in individual sport athletes was associated with an increased likelihood of sleep disturbance prior to competition. Intuitively it could be hypothesised that sleep quality before competition would improve as an athlete aged due to being accustomed to the experience of competition however this does not seem to be the case. Defining normal sleep in athletes and differing age categories remains a challenge due to multiple factors contributing to poor sleep[120]. Indeed, age related differences in sleep have been documented; however, these changes are most prominent in individuals beyond 40 years of age thus, limiting the usefulness of this data in our athlete population[132]. The exact reason for the increased likelihood of sleep disturbance in individual sport athletes as they age remains unknown and warrants further investigation.

Interestingly, a lack of association was observed between athletes who reported poor sleep prior to competition, from the Competitive Sports and Sleep Questionnaire and whether the athlete was classed as a “poor” sleeper in general, as determined by the Pittsburgh Sleep Quality Index. This finding implies that although an athlete may not be classed as a problematic sleeper on a day-to-day basis, sleep complaints may arise around competition periods that otherwise are not present. Indeed, in our athletes more than half reported sleep disturbance following a late game or training session. In addition, a smaller number indicated fragmented sleep following heavy training periods and days of rest. These findings highlight the need for caution when using a single subjective sleep quality questionnaire to assess an athletic population, as global sleep quality assessments may not display the same efficacy as with the general population, due to situational stressors and events athletes’ encounter.

3.6 Conclusion

Our findings highlight the majority of Australian athletes surveyed subjectively indicated sub-optimal sleep surrounding important competitions mainly due to nervousness and thoughts prior to competition. With evidence suggesting athletes sleep poorly pre-competition more research is needed to investigate the effects of acute sleep loss on athletic performance. The current sleep strategy results were concerning with few athletes aware of sleep strategies to utilise during these critical competition periods. Whilst no gender differences were exhibited, there were age and team sport versus individual sport differences that should be considered. The poor sleep reported during competition appears to be situational and not associated with poor sleep in general. The current study highlights the need for individual monitoring of athlete sleep habits and the need for increased sleep hygiene education and targeted cognitive arousal interventions within both individual and team sports.

CHAPTER FOUR

Longer sleep durations are positively associated with finishing place during a national multi-day netball competition

Juliff LE, Halson SL, Herbert J, Forsyth PL, Peiffer JJ. Longer sleep durations are positively associated with finishing place during a national multi-day netball competition. *Journal of Strength and Conditioning Research*. 2017. doi: 10.1519/JSC.0000000000001793.

Link: Findings from Study one indicate a large majority of athletes subjectively report poor sleep around important competition periods. Whilst subjective reports are important in sleep medicine it is imperative objective assessments are conducted to consolidate athlete reports of disturbed sleep around critical competition periods. Study two therefore sought to monitor athlete sleep around a national multi-day competition to objectively quantify whether these reports are validated through sleep activity monitors.

4.1 Abstract

Sleep is often regarded as the single best recovery strategy available to an athlete, yet little is known about the quality and quantity of sleep in athletes during multi-day competitions. The present study objectively evaluated sleep characteristics of athletes during a national netball tournament. Using wrist actigraphy monitors and sleep diaries 42 netballers from four state teams were monitored for the duration of a tournament (6 days) and 12 days prior in home environments. Significant differences were found between teams based on final competition standings, suggesting enhanced sleep characteristics in athlete's whose team finished higher in the tournament standings. The top two placed teams when compared with the lower two placed teams slept longer (8:02 ± 36:43; 7:01 ± 27:33), had greater time in bed (9:03 ± 0:52; 7:59 ± 0:54) and reported enhanced subjective sleep ratings (2.6 ± 0.5; 2.3 ± 0.6). Sleep efficiency was no different between teams. A strong correlation (r = -.683) was found indicating longer sleep durations during competition were associated with higher final tournament positions. Encouraging athletes to aim for longer sleep durations in competition, where possible, may influence the outcome in tournament style competitions.

4.2 Introduction

During national and international sporting tournaments, it is common for teams to compete on consecutive days providing a challenge for coaches and support staff to manage player fatigue[150]. It is vital to limit the impact of physiological and psychological fatigue in order for the athlete to recover adequately for both the subsequent game, and the duration of the tournament[150]. Decrements in performance (e.g. reduced speed, agility and vertical jump) have been observed throughout a 3-day basketball tournament[150] with similar results in soccer[90] and rugby league[121]. Sleep is often regarded as the single best recovery strategy available to an athlete[119], thus adequate sleep for athletes during multi-day tournaments could prove fundamental to the overall outcome[98, 121].

Physiologically, total and partial sleep deprivation have shown to compromise reaction time[3, 4] and psychomotor performance via reduced focus[8], determination[3], processing[3], logical thinking[3] and vigilance[8]. Total sleep deprivation in athletes is associated with reduced running endurance[134], decreased countermovement jump performance[126], reduced distance covered and slower intermittent sprint times[129]. Whilst it is unlikely that athletes will experience total sleep deprivation during periods of competition, even partial sleep deprivation may result in reduced performances[130, 131]. Furthermore, athletes may be able to overcome the detrimental effects of one night of sleep loss to produce a single maximal all-out effort, however may not be able to sustain this level during repeated effort exercise, both during a single game and during multiple day competitions[10].

With many sporting teams participating in multi-day tournament style competitions (e.g. netball, basketball, football, rugby league/union), there is a demand for understanding the sleep patterns experienced by athletes throughout these competition conditions. Currently, a lack of scientific evidence exists to confirm whether sleep complaints are present during tournaments[151, 152]. Therefore, the purpose of this study was to objectively monitor the sleep patterns of state netballers during a multi-day national competition using actigraphy, with the specific aim of exploring whether any differences in sleep variables exist between high and low performing teams. It was hypothesised that lower performing teams would demonstrate reduced sleep durations and efficiency than higher performing teams. In addition, a secondary hypothesis was late night games would result in poor sleep when compared with an afternoon game. The sport of netball was selected for this study as it places high physical demands on players via repeated rapid accelerations and decelerations, explosive jumps, contact trauma and muscle damage from eccentric loading[153]. This study was conducted during a national competition; thus, the outcomes should provide ecologically valid information as to the current sleep habits of athletes during athletic tournaments.

4.3 Methods

4.3.1 Experimental Approach to the Problem

To examine the hypotheses and observe any differences between teams over the course of the national netball tournament, an observational study design was employed to continuously monitor the sleep/wake behaviour of athletes in four of the seven state netball teams. Sleep variables were measured over the six-day tournament using Actical® actigraphy monitors (Philips Respironics, Bend, Oregon, USA) worn on the non-dominant hand. Netball games were 60 minutes in duration (4 x 15 minute quarters; with two games played on days 1, 2 and 3, one game on day 4, a semi-final on day 5 and grand final as well as minor placing playoffs on day 6, totalling 7 games over a 6-day period; Table 4.1). One state team withdrew from the competition part way through the tournament resulting in an additional bye for selected teams, thus seven games were played instead of the programmed eight. To gain a baseline of each participants sleep in their home environment, actigraphy monitors were also worn twelve days prior to the tournament

Table 4.1 Team schedule and game times for the four monitored teams in the netball tournament.

	Day 1		Day 2		Day 3		Day 4	Day 5	Day 6
	Am	Pm	Am	Pm	Am	Pm			
Team 1	9:00	17:00*	12:00	20:00*		17:00	10:00	13:00	13:00
Team 2		17:00*	10:30	17:00	12:00	20:00*		11:30	13:00
Team 3	10:30	20:00*	10:30	17:00*	9:00		10:00		10:00
Team 4	9:00		9:00	18:30	12:00	18:30	13:00		10:00

* Indicates a night or afternoon game used for analysis of late games

4.3.2 Participants

A sample of 42 Australian athletes competing in an aged 21 and under national championship tournament (mean ± SD; age: 19.2 y ± 1.0, age range = 18 to 21, height: 179.8

cm ± 5.7, weight: 71.9 kg ± 7.7) volunteered to participate in the study. Participants were from four of the seven state teams participating in the tournament and all were in a peak/competition phase of training. Participants were thoroughly familiarised and instructed regarding the use of actigraphy monitors and subjective ratings by the principle supervisor and the respective team head coaches. Sleep diaries were completed prior to the tournament, which identified on average, athletes required 8 ± 1 hours a night to feel rested and rated their current sleep satisfaction as 7 ± 1 out of 10 on a visual analogue scale. The University and Institution Review Board approved this study and each participant was informed of the benefits and risks of the investigation prior to signing an informed consent document before participation.

4.3.3 Procedures

Throughout the two analysis periods (home and competition), participants were instructed to wear the wrist actigraphy monitor at all times unless showering or competing (due to rules constituted by the game). Each actigraphy monitor contained a piezo-electric accelerometer, sampling activity counts in one-minute epochs[91, 102]. Epoch-for-epoch concordance rates of 81 - 90% with polysomnography (gold standard sleep measure) have been found for sleep/wake activity using Actical® wrist actigraphy monitors in athletes[79]. In addition, participants were required to record bedtime, wake-time, and sleep quality ratings for each sleep period in a sleep diary. Detailed instructions were included on the bottom of each page of the sleep diary to ensure accurate ratings. Sleep quality ratings were obtained by participants circling the most appropriate answer from a 5-point scale of “very good”, “good”, “average”, “poor” and “very poor”. Diary information along with actigraphy monitor data was used to determine sleep/wake periods according to the methods of Sargent, Lastella [16]. Effectively, all times were recorded as wake unless activity counts from the monitor were low indicating immobility or the event marker on the watch and the sleep diary indicated the participant was attempting to sleep[102]. Individual nights of sleep were analysed in Actiware®

sleep software (Respironics Actiware, Version 5.61, Respironics Inc.) using the actigraphy monitor and sleep diary data for the following sleep variables: time to bed (bedtime), time upon waking (wake-time), time in bed (period between going to bed and awakening; ICC = 0.99-1.00[80]), sleep duration (amount of time spent asleep; ICC = 0.90 – 0.97[80]), sleep onset latency (amount of time between bedtime and sleep onset; ICC = 0.77 – 0.94[80]) and sleep efficiency (sleep duration expressed as a percentage of bed time; ICC = 0.71 – 0.92[80]). During the data collection period, there was no experimental manipulation of the participants; therefore, the data reflects a true competition setting as participants could partake in normal recovery strategies administered by coaching staff such as cold-water immersion, compression garments and consumption of training supplements.

4.3.4 Statistical Analysis

Descriptive analyses of the athletes' sleep/wake behaviors were conducted. These analyses were based on all sleep periods obtained during the data collection period, including data in the home environment and competition. To assess sleep variables on final team placing using competition data an analysis of variance (ANOVA) was conducted comparing differences between sleep duration and efficiency between all four state teams. If no differences were observed for the variables of interest when comparing teams ranked 1st and 2nd and when comparing teams ranked 5th and 6th place data was selectively grouped to provide data for top and bottom finishing teams. This methodology was followed to increase the sample size of top and bottom finishing teams to provide the best chance of observing differences between top and lower standing teams in the competition for all sleep variables. Following the regrouping of data, differences between top and bottom finishing teams were analysed using a T-test. To determine the relationship between sleep variables, Pearson's product-moment correlations were run. Finally, a paired-sample t-test was used to determine whether a mean difference existed between sleep variables from a subset of data when athletes competed in both an afternoon game (17:00) compared to a night game (20:00) during the tournament (Table 4.1). All analyses were completed using SPSS© Statistics (version 19, IBM©, USA) with significance set to $p \leq 0.05$. All data are reported as means ± standard error unless otherwise noted.

4.4 Results

Of the 486 athlete sleep periods collected for analysis in the study including home and competition periods, 65.64% fell below the recommended eight hours of sleep per night for healthy adults[17]. Further, there was a mean difference of 64.0 ± 5.5 minutes between time spent in bed and time spent asleep (sleep duration). In the exploration of differences between teams during competition sleep duration and time in bed were greater in teams who finished higher in the tournament (Figure 4.1). No differences were observed for sleep efficiency or sleep onset latency between the high and low finishing teams.

Following the regrouping of data to represent top (team 1 and 2) and bottom (team 5 and 6) finishing teams, time in bed during competition was significantly greater for the top finishing compared with the bottom finishing teams; 9:03 ± 0:52 hours versus 7:59 ± 0:54 hours (Table 4.2). Similarly, the top finishers had significantly longer sleep durations during competition in comparison with lower ranking teams; 8:02 ± 36:43 versus 7:01 ± 27:33 (Table 4.2). There were no differences in home environment sleep duration, time in bed, sleep latency or efficiency (Table 4.2).

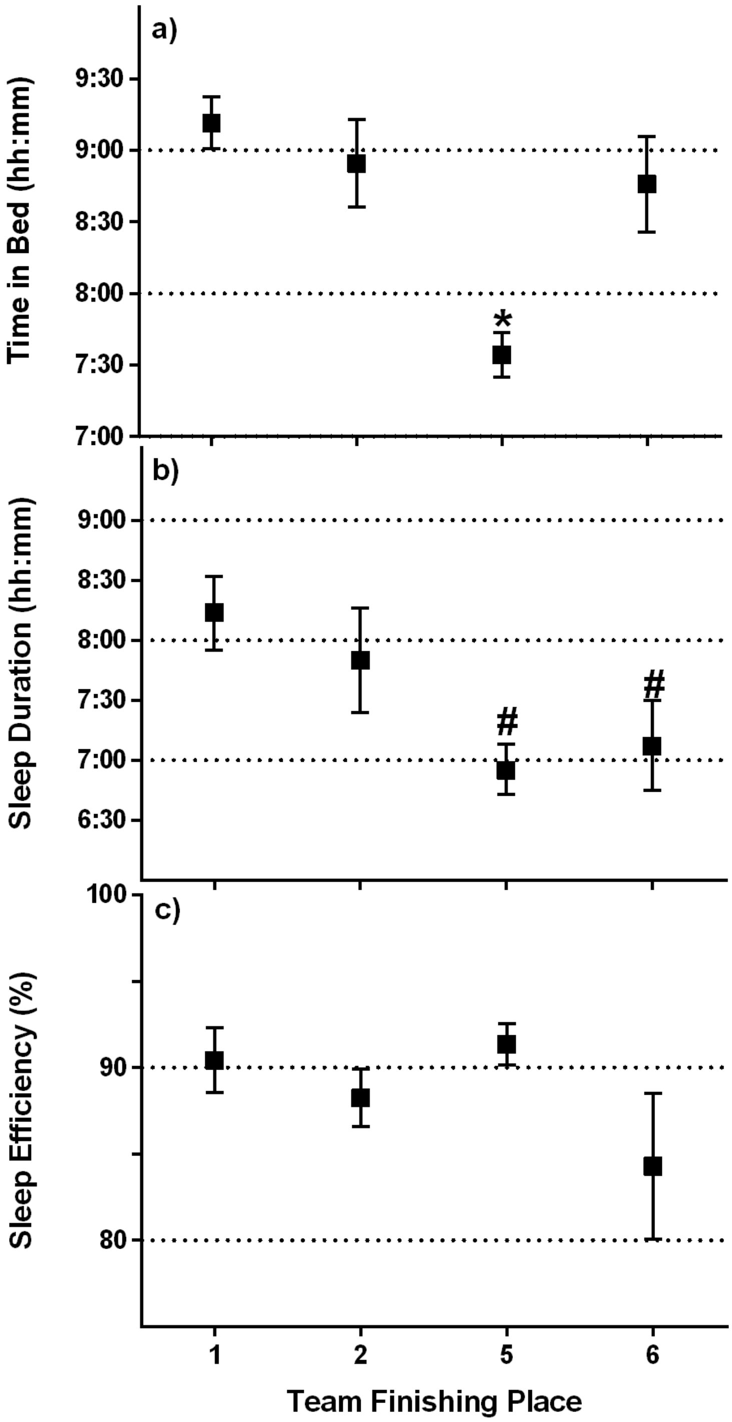

Figure 4.1. Mean sleep characteristics during competition in teams based on final finishing position, with 95% confidence intervals for a) time in bed, b) sleep duration and c) sleep efficiency * indicates significant (p<0.05) difference between team 3 and all other teams. # indicates significant (p<0.05) difference between both team 1 and 2.

Table 4. 2. Comparison of sleep characteristics for home and competition monitoring based on final team standings

	Finishing place		Test statistic
	Top two teams	Lower two teams	*p*
Time in Bed (hh:mm)			
Home	8:37 ± 1:21	8:27 ± 1:13	0.5201
Competition	9:03 ± 0:52	7:59 ± 0:54	<0.001*
Sleep Duration (hh:mm)			
Home	7:27 ± 1:02	7:20 ± 00:51	0.731
Competition	8:02 ± 36:43	7:01 ± 27:33	<0.001*
Sleep Efficiency (%)			
Home	88.3 ± 3.5	87.3 ± 4.3	0.432
Competition	89.3 ± 2.9	88.0 ± 5.7	0.330
Sleep Latency (mm: ss)			
Home	7:36 ± 3:48	5:55 ± 5:32	0.352
Competition	12.08 ± 6:13	9.20 ± 9.00	0.224
Subjective Sleep Rating			
Home	3.0 ± 0.5	2.8 ± 0.5	0.025*
Competition	2.6 ± 0.5	2.3 ± 0.6	0.008*

Values are mean ± (SD). * Significant difference between teams.

Correlation analysis indicated a strong negative correlation between sleep duration during competition and final competition position ($r = -0.68$, $p < 0.01$), with increased sleep durations during competition associated with a better final tournament position. There was a moderate positive correlation between subjective sleep rating during competition and sleep duration during competition ($r = 0.36$, $p < 0.05$). A positive correlation was found between teams that finished higher in the competition and higher subjective sleep ratings (Table 4.2). For the subset of data exploring late games it was found that athletes had increased sleep durations following an afternoon game (7:37 ± 1:06 h) when compared with night games (7:08 ± 00:45 h), a statistically significant difference of 28:20 ± 43:51 minutes ($p < 0.05$).

4.5 Discussion

The present study monitored sleep in elite female netballers during a multi-day (7 games in 6 days) national competition period and explored whether differences existed between teams during the tournament. The findings from this study were; 1) actigraphy data indicated 65.6% of all sleep nights recorded in the study were less than the recommended eight hours per night, 2) a strong association was observed between the teams who had longer sleep durations and higher final tournament placing's, 3) longer sleep durations were observed in athletes following afternoon games when compared with evening games, 4) time in bed was on average 64 minutes longer than time spent asleep, and 5) higher positive subjective sleep ratings were associated with longer sleep durations.

Sleep is essential for athletes preparing for and recovering from training and competition, yet the study's findings revealed 65.6% (n= 316) of the sleep nights recorded (total n= 486) were below the recommended eight hours of sleep per night for a healthy individual[17]. When asked prior to the commencement of the tournament our participants indicated on average eight hours of sleep was needed to feel rested; therefore, perceived sleep needs were not met throughout the competition. Based on current knowledge in the area of sleep and its known importance for performance and recovery, the reduced sleep durations in the current group of athletes may have disadvantaged these athletes during the tournament. Lack of sleep can expose athletes to potential disturbances in immune function, physical performance, neurobehavioral deficits, cognitive capacity and glucose metabolism[3, 16, 91]. These findings add to the current literature, which have examined out of competition sleep patterns in athletes. Sargent, Lastella [16] observed 83% of sleep nights (n=926) in 70 elite Australian athletes from several different sports (swimming, road cycling, triathlon, race-walking, basketball, mountain biking, Australian rules football) fell below the recommended targeted eight hours of sleep per night. The lower percentage of nights below eight hours of sleep in our study may indicate athletes may be more receptive to sleep hygiene during competition periods however regardless; athletes in competition should be encouraged and have the time made available in the schedule to allow for longer sleep periods.

Findings from the present study indicate that teams whose average sleep duration was longer were found to have finished higher in the final tournament placing's supporting our hypothesis. These findings are consistent with research examining sleep extension in sport. Mah and colleagues[138] observed faster sprint times and increased free-throw accuracy in eleven basketball players when, following two weeks of normal habitual sleep, they were instructed to obtain as much extra sleep as possible per night. Similarly, five college swimmers increased sleep time to 10 hours per night and found significant improvements in 15-meter sprint time, reaction time and turn time. Whilst the association found between sleep duration and performance in the current study demonstrates a relationship between the two variables it is acknowledged the finding does not necessarily mean causation. Whilst speculative, the relationship may be explained utilising sleep literature studies where changes in central nervous system and cognitive function under periods of reduced sleep were found in athletes[3, 128]. Reduced sleep can decrease the transmission speed of impulses from the brain to the working muscles, and therefore affect reaction times[3, 128]. Additionally, reduced sleep durations have been found to affect cognitive function and psychomotor performance[3, 8]. Together these findings suggest that adequate sleep is essential for peak performance as executive function tasks are particularly sensitive to sleep deprivation[127]. In team sports such as netball, the ability to make fast accurate decisions is an important skill essential for performance and any reductions due to reduced sleep could compromise results such as final competition standings[13]. Therefore, in the preparation for the tournament the team support staff should reiterate a sleep focus to athletes and when programming ensure every endeavour is made in the schedule for the athletes to obtain adequate sleep durations.

Analysing a subset of data (n=29), our hypothesis was confirmed with decreased sleep durations (28 minutes) recorded in athletes following late games (7:08hrs) compared with afternoon games (7:36hrs) (Table 4.1). It has been suggested that vigorous exercise close to bedtime may impair sleep due to physiological arousal; however, we did not observe any differences in sleep onset latency between playing times thus suggesting a similar level of arousal at both time points[136]. Nevertheless, as we did not measure physiological and hormonal data prior to bedtime we cannot confirm or deny this hypothesis. Alternatively, it is possible the later sleeping times associated with late games were due to; athlete perceptions that they would be unable to sleep immediately post-game (and thus stayed up later) or due to team logistics where athletes were not in a situation to sleep until later. The poor sleep results following late competition objectively compliment recent reported reductions of sleep quantity in male footballers (-181 min)[51] and Australian rules footballers (-171 min and -126 min) following night games[53, 113], in addition to a recent subjective questionnaire finding 52.5% (n=283) of athletes surveyed indicated experiencing poor sleep following late competitions[154]. Given the documented deficiency in sleep duration within team sport athletes following late competitions[51, 54, 104], future studies should seek to explore physiological and hormonal variables following late competitions to explore the mechanisms responsible for the reduced sleep findings.

Quantitative findings from this study indicate the use of questionnaires to acutely assess sleep within athletes should be done with caution. A mean difference of 64 ± 5.5 minutes was observed between time spent in bed and actual sleep duration (Table 4.2). It is possible athletes may be unaware the discrepancy exists, expecting their total time asleep to correspond to the number of hours from going to bed to waking up. A clear understanding of the differences between the two variables should be explained to athletes prior to using questionnaires to assess sleep and to ensure athletes plan accordingly to obtain optimal sleep durations. Specifically, it should be highlighted that sleep duration does not take into account any movements experienced, time awake and sleep onset latency. Additionally, in the current study we observed athletes who reported better subjective sleep ratings were positively correlated to experience greater sleep durations during competition. With no differences in sleep efficiency it may be suggested that subjective reports recorded were based on the duration of sleep and not sleep quality (efficiency). Our findings are consistent with previous research indicating athletes subjectively rate sleep based on quantity more than quality of sleep[41, 82, 83]. While subjective sleep questionnaires remain appealing to researchers and are commonly used, the current results are relevant to teams and athletes who currently partake in athlete daily monitoring systems. It is important for staff to be aware of the limitations of subjective sleep questions when interpreting results entered by athletes. Athletes should also be carefully instructed through such questionnaires in a bid to collect reliable data.

In conclusion, our results provide a novel insight into the sleep habits of athletes during a real-life tournament setting with minimal manipulation. The present study findings suggest appropriate sleep durations during multi-day tournaments for team sport athletes may contribute to final tournament standings. Athletes experienced shorter sleep durations following evening games in comparison to afternoon games. Further, the differences found between time in bed and actual sleep time coupled with the suggestion that athlete subjective sleep reports were based mostly on sleep duration rather than sleep quality emphasise the value of sleep education for athletes. Overall, the present study objectively highlights the habitual sleep of athletes during competition and provides evidence supporting a likely interactive effect between sleep and performance.

4.6 Practical Applications

Ensuring athletes are performing optimally throughout a competition is an important focus for support staff and coaches. Due to the physiological and restorative effects of sleep there is a need for support staff to ensure athletes have every opportunity available to obtain optimal sleep during tournament style competitions. The current study demonstrated athletes experienced reduced sleep durations during the tournament. The importance of sleep for athletic performance was demonstrated by the association between teams who placed higher in the final tournament standings obtaining longer sleep durations. In practice, this result highlights the need to ensure athletes have sufficient time made available to maximise sleep durations during competition. The impetus is therefore on the support staff in conjunction with the team coach to schedule training and other team activities at appropriate times and consider logistics where possible to ensure adequate sleep durations are obtained. Further, in addition to careful scheduling, educating athletes on both the importance of sleep and the common misconceptions such as highlighting the difference between time in bed and actual sleep time will allow accurate planning to potentially initiate behaviour change and promote optimal sleep habits.

CHAPTER FIVE

Night games: physiological, neuroendocrine, and psychometric mechanisms to explain poor sleep in team sport athletes

Juliff LE, Peiffer JJ, Halson SL. Night games: physiological, neuroendocrine, and psychometric mechanisms to explain poor sleep in team sport athletes. *International Journal of Sports Physiology and Performance*. 2017; In-press.

Link: Study two demonstrated the importance of sleep around multi-day competition periods with results suggesting teams who slept longer finished higher on the competition final standings. A finding such as this conveys the importance of ensuring athletes have a sufficient amount of time allocated around competition periods to ensure sleep durations are maximised. A subset of data analysed in the study found poorer sleep variables following night games compared with afternoon games. Study one also supports the idea that sleep around night games may be disturbed with athletes subjectively indicating, through the sleep questionnaire, that they perceived worse sleep following night competitions. Given the regularity of night games within sport the third study sought to explore and explain the potential mechanisms and nuances of a night game that result in sleep complaints and poor sleep parameters.

5.1 Abstract

Purpose: Night games are a regular occurrence for team sport athletes, yet sleep complaints following night competitions are common. The mechanisms responsible for reported sleep difficulty in athletes is not understood. Methods: An observational cross-over design investigating a night netball game and a time matched rest-day in twelve netball athletes was conducted to ascertain differences in physiological (core temperature), psychometric (state and trait) and neuroendocrine (adrenaline, noradrenaline, cortisol) responses. Results: Following the night-game, athletes experienced reduced sleep durations, lower sleep efficiency, early awakenings and poorer subjective sleep ratings compared with the rest-day. No differences were found between core temperature, state psychometric measures and cortisol at bedtime. Adrenaline and noradrenaline concentrations were elevated compared with the time matched rest-day prior to (26.92 ± 15.88 versus 12.90 ± 5.71 and 232.6 ± 148.1 versus 97.83 ± 26.43nmol/L, respectively) and following the night-game (18.67 ± 13.26; 11.92 ± 5.71 and 234.1 ± 137.2; 88.58 ± 54.08nmol/L, respectively) however did not correlate to the sleep variables (duration, efficiency, and sleep onset latency). A correlation (r_s = -0.611) between sleep efficiency and hyperarousal (trait psychometric measure) was found. Conclusions: Athletes' experienced poor sleep following a night-game. Further, results suggest athletes who have a tendency towards a high trait arousal may be more susceptible to sleep complaints following a night-game. This data expands knowledge and refutes frequently hypothesised explanations for poor sleep following night competition. It may also assist support staff and coaches to target strategies for individual athletes at a higher risk of sleep complaints.

5.2 Introduction

Despite the acknowledged importance of sleep for performance and recovery[119], athletes commonly experience sleep loss following late competitions[51, 54, 104]. Specifically, team sport athletes such as male footballers[51] and Australian rules footballers[53, 113] have reported reduced sleep quantities of 181, 126 and 171 minutes respectively, following night games. Given the regularity of night games for athletes, it is essential the mechanisms responsible for disturbed sleep are understood in order for targeted interventions to be implemented.

Sleep is a complex phenomenon, regulated by several regions of the brain through modulations of neurotransmitters and neuropeptides that control daily cycles of wakefulness and sleep[21]. The ascending arousal system in the hypothalamus and sleep active neurons in the ventrolateral preoptic nucleus (VLPO) interact much like a “flip flop switch” turning on and off periods of sleep and wakefulness[24]. Athletic competitions have the ability to stimulate neurotransmitters (adrenaline, noradrenaline) of the ascending arousal system triggering the release of cortisol, potentially causing a disruption of the sleep-wake cycle[26]. Indeed, within insomniac patients high levels of cortisol prior to bedtime are consistent with disrupted sleep (increased nocturnal awakenings), confirming an interaction between sleep and the hypothalamic-pituitary-adrenal (HPA) axis[35].

Within sport, large increases in cortisol concentrations have been reported during competitions[34]. However, to date, no studies have explored neurochemical measures of the HPA axis (cortisol, adrenaline, and noradrenaline) post exercise on subsequent sleep. Within civil servants[27] and insomniacs[35], increased urinary catecholamines and increased psychological arousal are associated with poor sleep quality. It is therefore plausible that the demands of athletic competition could stimulate alertness and vigilance into an athlete’s sleep period providing rational for the reported decrease in sleep following late competitions[155].

Given the documented deficiency in sleep (duration and quality) within team sport athletes following late competitions[51, 54, 104], the lack of literature available to provide a mechanistic explanation indicates a need for research. Therefore, the current study examined commonly hypothesised mechanisms thought to impact on sleep (cortisol, adrenaline, noradrenaline, core temperature and psychometric measures) following a night-game and a time matched control day in elite netballers.

5.3 Methods

5.3.1 Participants

Twelve Australian netball athletes (mean ± SD; age: 19.2 y ± 0.9, height: 184.1 cm ± 6.9, body mass: 72.8 kg ± 5.2) volunteered to participate in the study. All athletes were members of their relevant age group national representative team. Over a two-week period, prior to the study, sleep diaries were completed which identified on average participants required 8.5 ± 0.7 h per night to feel rested, scored 8 ± 4 for the Epworth Sleepiness Scale, and rated their current sleep satisfaction as 8 ± 1 out of 10 on a visual analogue scale. All participants were provided, in writing, with the risks and benefits of their participation and informed consent was obtained from all individual participants included in the study. The Australian Institute of Sport Ethics Committee and Murdoch University Human Research Ethics Committee approved this study.

5.3.2 Study Design

An observational cross-over design was employed to ascertain differences in physiological and hormonal responses to an international night netball game (game starting at 6pm)[51] and its consequent effect on sleep, compared with a time matched rest-day. The time-matched rest-day was conducted ten days following the night-game. Participants were asked not to engage in any physical activity during the rest day. Additionally, participants were familiarised with the study procedures and collection times before the collection period (Figure 5.1) and were encouraged to partake in normal nutritional protocols during the study. The sport of netball was selected for this study, as it is common for games to occur late in a day and to be played over consecutive days within a tournament setting. A game of netball is played over a 60-minute duration and places high physical demands on players via repeated rapid accelerations and decelerations, explosive jumps, contact trauma and muscle damage from eccentric loading. Sleep was monitored for two weeks throughout the study using Actical® actigraphy monitors (Philips Respironics, Bend, Oregon, USA). No sleep education was provided prior to or during the sleep-monitoring period. Each testing session (night-game and rest-day) consisted of a waking salivary cortisol measure followed 30 minutes later by an additional measure to calculate CAR (cortisol awakening response; the difference between the second and first morning sample). Salivary cortisol measures were later sampled 10 minutes prior to the game, 10 minutes post-game, one hour post-game, at bedtime and upon awakening the next morning (Figure 5.1). Additionally, commencing from waking, 24-h urinary catecholamines (adrenaline and noradrenaline) were measured. Core temperature was recorded continuously in one-minute intervals via a radio telemetric core temperature pill (HQ Inc., Florida, USA) from the cessation of the netball game (time matched on the control day) until awakening the following morning (ad libitum). All pills were calibrated and checked at three different temperatures against a certified mercury thermometer in a water bath prior to use. Four hours prior to the game the core temperature pill was ingested to ensure it was not sensitive to ingested fluid. No hydrotherapy was conducted following the netball game to avoid temperature interferences from immersion. A Pre-Sleep Arousal Scale was administered prior to bed to assess measures of state arousal whilst the Karolinska Sleep Questionnaire was completed upon awakening to determine subjective sleep perceptions from the previous night's sleep.

During the rest-day, data collection was time-matched to the competition day, with the exclusion of the waking and pre-bedtime measures (self-selected to the body's natural rhythm) to account for any diurnal variations.

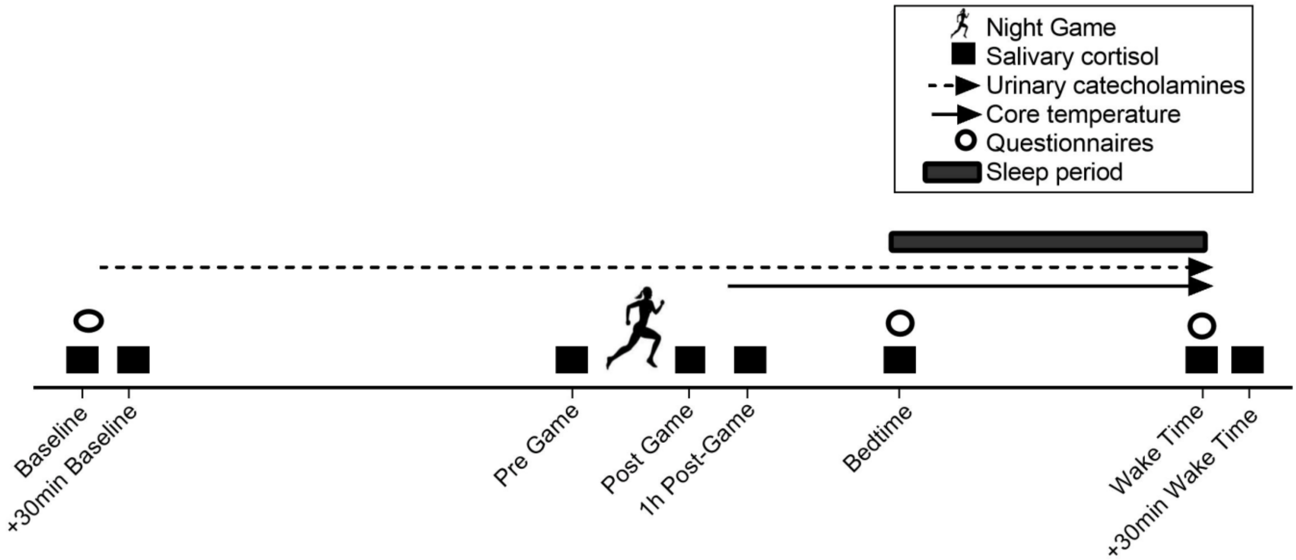

Figure 5.1. An illustration of the collection time points for each variable measured. Game measures were time matched on the rest day.

5.3.3 Sleep Analysis

Participants completed two weeks of sleep assessment via sleep diaries and wrist actigraphy monitors. Each actigraphy monitor contained a piezo-electric accelerometer, which sampled activity counts in 1-minute epochs. Epoch-for-epoch concordance rates of 81 - 90% with polysomnography (gold standard sleep measure) have been found for sleep/wake activity using Actical® wrist actigraphy monitors[79]. Participants wore the monitor at all times unless showering or competing. Participants recorded bedtime, wake-time, and sleep quality ratings for each sleep period in a sleep diary the morning after the sleep period and selected sleep quality ratings from a 5-point scale of "very good", "good", "average", "poor" and "very poor". Diary information along with actigraphy data (event markers) were used to determine sleep/wake periods Lastella, Roach [110]. Individual nights of sleep were analysed in Actiware® sleep software (Respironics Actiware, Version 5.61, Respironics Inc.) with the threshold sensitivity set to 'medium'[16]. Bedtime, wake-time, sleep duration (amount of time spent asleep), sleep onset latency (amount of time between bedtime and sleep onset), number of wake bouts and sleep efficiency (sleep duration expressed as a percentage of time in bed) were calculated following the rest and night-game.

5.3.4 Neuroendocrine Assessment

Salivary Cortisol Assessment

Salivary cortisol samples were measured using Salimetric oral swabs, placed under the tongue for one minute, at eight designated time points (Figure 5.1). Oral swabs were selected due to ease of data collection in the athletic field and due to the non-invasiveness when compared with venepuncture[34]. In the researcher's absence participants collected the overnight samples at each designated time point and documented the collection time to ensure adherence to time in the subsequent trial. Once received, saliva samples were stored at -20°C as instructed by the manufacturer (Stratech PTY, NSW) and analysed within two months of collection. Salivary cortisol was measured using a commercially available ELISA assay (Salimetrics, USA). The intra-assay variance was 3.1%, and the sensitivity of the assay was 0.003 ug/dL.

24-Hour Urinary Catecholamine

Catecholamine excretion was measured from urine samples collected during two time periods over 24-hours adapted from Netzer and colleagues[111]. The first-time period was from awakening after emptying bladder to the start of the netball game. The second was immediately post-netball game until awakening the next day. The time points recorded from the night-game were time matched on the rest-day. A commercial lab analysed the urine collection for adrenaline and noradrenaline using high performance liquid chromatography with electrochemical detection. Catecholamines were measured as an excretion rate and reported in nmol. L^{-1}. Urinary noradrenaline levels are considered a reliable indicator of overall sympathetic activity whilst adrenaline levels reflect the adrenal response[111].

5.3.5 Psychometric Assessment

A modified version of the Karolinska Sleep Questionnaire was used to subjectively assess sleep quality from the previous night's sleep as described by Garde et al[27] and Åkerstedt et al[156]. In total, seven items (1) difficulties falling asleep, (2) disturbed/restless sleep, (3) repeated awakenings, (4) premature awakenings, (5) difficulties waking up, (6) non-refreshing sleep, and (7) exhausted at awakening were scored between 1 (zero awakenings) and 5 (four or more awakenings). A disturbed sleep index (DSI; Q1-4) and an awakening index (AWI; Q5-7) was calculated with high scores representing a more disturbed sleep and less sleep satisfaction upon awakening[27]. Responses were calculated for the morning of the collection day and the morning following.

The Pre-Sleep Arousal Scale (PSAS) was used to measure subjective pre-sleep arousal at bedtime in participants the night prior to testing and the night following testing[157]. The PSAS is a 16-item self-reported scale that assesses somatic ("a jittery, nervous feeling in your body") and cognitive ("worry about falling asleep") manifestations of arousal[157]. Participants rated how intensely they experienced each item as they tried to fall asleep from the previous night on a scale from 1 "not at all" to 5 "extremely". All answers were calculated and divided into a somatic and cognitive domain, with a minimum score of 8 and maximum possible score of 40.

To assess trait arousal, participants completed the Hyperarousal Scale one week prior to the night-game (when the actigraph was distributed). The scale is commonly utilised in insomnia patients due to their increased cortical responsiveness that is less modulated by inhibitory processing[142]. The Hyperarousal Scale contained 26 items of which participants selected one of four responses (0= not at all, 1= a little, 2= quite a bit, 3= extremely). Completed item scores were aggregated to yield an overall hyperarousal score. Sub-measures included an extreme score (number of items checked "extreme"), an introspectiveness score (summed score for items ‘‘My mind is always going,’’ ‘‘I think a lot about feelings,’’ ‘‘I tend to anticipate problems,'' ''I take things personally,'' ''Some thoughts return too often,'' and ''I take a long time to make decisions'') and a react score (sum score for items ''Bright lights, crowds, noises of traffic bother me,'' ''I get rattled when a lot happens at once,'' and ''A sudden loud noise would cause me a prolonged reaction'')[142].

5.3.6 Statistical Analysis

Data are expressed descriptively as means (SD) of the individual data and as single individual data. Statistical evaluation was completed using paired sample t-tests for significance of differences between the night-game and rest-day sleep data. Differences in cortisol, core temperature and catecholamines between condition (night-game and rest-day) and time of day were analysed using a two-way analysis of variance (ANOVA) with repeated measures. Significant main effects or interactions were further analyses using Fisher's LSD post-hoc analyses. Standardised effect sizes (Cohen's d) were calculated to interpret the magnitude of the mean differences between data with $d<0.20$ (trivial), $d = 0.20$ (small), $d = 0.50$ (medium), $d > 0.80$ (large). A Wilcoxon signed rank test analysed arousal and subjective sleep measures to test for differences between night-game and rest-day. To satisfy the assumption of correlation analysis a Spearman's correlation coefficient (rx) was utilised with rx < 0.4 (weak), rx 0.4 – 0.59 (moderate) and rx > 0.8 (strong) to explore associations between physiological, neuroendocrine and psychometric variables and sleep data for the night and rest-day data[111]. All statistics were completed using SPSS© Statistics (version 19, IBM©, USA) statistical software program with significance set to $p \leq 0.05$.

5.4 Results

5.4.1 Objective Sleep Variables

Mean and individual data for sleep efficiency and sleep duration following the night-game and rest-day are illustrated in Figure 5.2. Sleep duration for the night-game condition was less compared with the rest-day ($p = 0.02$, $d = 1.13$). Participants experienced reduced sleep efficiencies following the night-game when compared with a rest-day ($p < 0.001$, $d = 0.73$). No differences were evident between conditions for bedtime; sleep latency and number of wake bouts in the sleep period measured ($p > 0.05$) (Table 5.1). Participants woke earlier following the night-game when compared with a rest-day (p = < 0.01, $d = 0.959$).

5.4.2 Psychometric Variables

From the sleep diary, eight participants (67%) experienced worse subjective sleep (average) following the night-game compared with a rest-day (good), whereas four participants (33%) experienced no change. There was an increase in the median subjective sleep rating from the sleep diary to reflect poor sleep (p = < 0.01, $d = 1.03$). No differences ($p > 0.05$) were found for calculated variables in the Karolinska Sleep Questionnaire and the PSAS between conditions (Table 5.1).

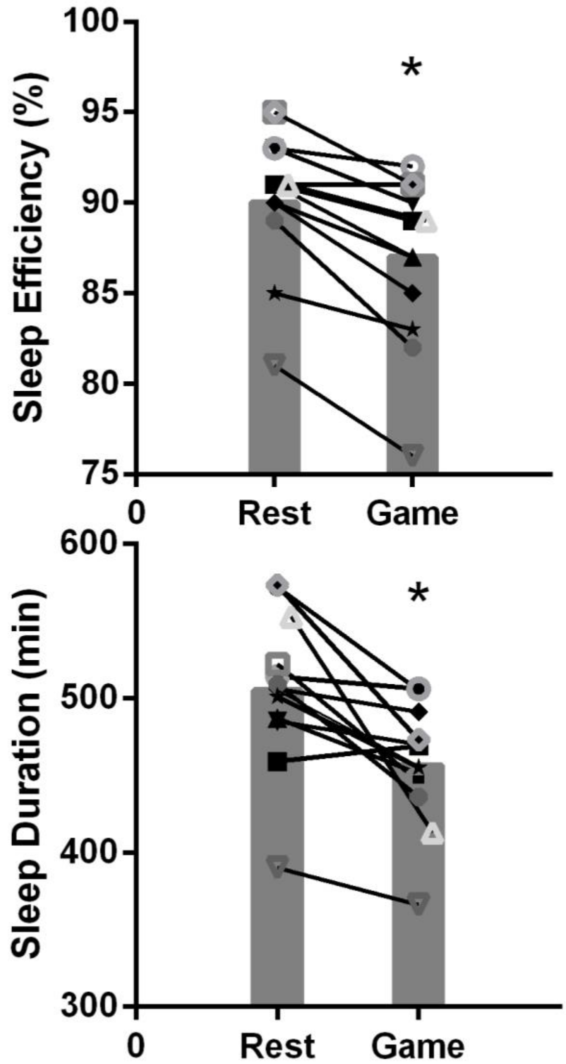

Figure 5.2. Mean (shaded bars) and individual participant (n=12) sleep efficiency and sleep duration for the night following a rest day and a night game. * Significant differences between night game and rest day (P < 0.05).

Table 5.1. Mean (± SD) and effect sizes (Cohens *d*) for sleep, physiological and psychological measures comparing a time matched rest-day to a night-game in netballers.

	Condition		
	Rest Day	**Night Game**	**Cohens *d***
Sleep Variables			
Bedtime (hh:mm)	22:32 ± 00:55	22:27 ± 00:52	*d* = 0.09
Wake time morning after testing (hh:mm)	7:55 ± 00:34	7:08 ± 00:34*	*d* = 1.38
Sleep latency (min)	14.5 ± 15.1	24.4 ± 27.4	*d* = 0.45
Number of wake bouts	19 ± 7	19 ± 7	*d* = 0.00
Core Temperature (°C)			
Post-exercise	37.42 ± 0.18	38.81 ± 0.51*	*d* = 3.63
Bedtime	37.24 ± 0.31	37.18 ± 0.37	*d* = 0.18
Waking	37.10 ± 0.27	37.00 ± 0.31	*d* = 0.34
Noradrenaline (nmol. L^{-1}) #			
Pre-game	97.83 ± 36.43	232.6 ± 148.1	*d* = 1.25
Post-game	88.58 ± 54.08	234.1 ± 137.2	*d* = 1.40
Adrenaline (nmol. L^{-1}) #			
Pre-game	12.91 ± 5.71	26.92 ± 15.88	*d* = 1.17
Post-game	11.92 ± 4.56	18.67 ± 13.26	*d* = 0.68
Psychometric Variables			
Pre-Sleep Arousal - Somatic			
Night before game	10.0 ± 1.8	10.8 ± 3.8	*d* = 0.27
Night after game	9.4 ± 1.4	10.3 ± 4.3	*d* = 0.28
Pre-Sleep Arousal - Cognitive			
Night before game	14.3 ± 3.1	16.8 ± 7.0	*d = 0.46*
Night after game	13.4 ± 3.9	14.6 ± 6.2	*d = 0.23*
Disturbed Sleep Index			
Morning of the game	8.1 ± 2.8	8.7 ± 2.8	*d = 0.21*
Morning post-game	6.3 ± 2.6	7.4 ± 3.4	*d = 0.36*
Awakening Index			
Morning of the game	5.6 ± 2.2	7.1 ± 2.7	*d = 0.61*
Morning post-game	4.4 ± 2.0	5.3 ± 2.9	*d = 0.36*

Data are means ± SD. * Significant difference between night-game and rest-day conditions ($p < 0.05$). # Significant main effect for condition; the night-game greater than rest-day ($p < 0.05$). All night before game and after game time points were time matched on the rest-day. d <0.20 trivial, d=0.2 (small), d=0.5 (medium), d>0.8 (large).

5.4.3 Physiological and Neuroendocrine Variables

A main effect for condition ($p < 0.01$) was found for noradrenaline levels with participants experiencing elevated levels of noradrenaline in the night-game condition when compared with the rest-day (Table 5.1). Adrenaline levels also demonstrated a main effect for condition ($p = 0.02$) with levels for the night-game condition elevated compared with the time matched rest-day. An interaction was observed for measures of cortisol with greater baseline levels measured in the morning of the night-game when compared to a time matched rest-day

($p = 0.027$, $d = 0.60$; Figure 5.3). Additionally, greater cortisol measures were observed immediately post-game and one hour post-game when compared to the time matched rest-day ($p = 0.006$, $d = 1.49$ and $p = 0.031$, $d = 0.245$ respectively) (Figure 5.3). No differences were observed for the cortisol awakening response the morning of the game and the morning following the game compared to a rest-day. An interaction was observed for core temperature with greater temperatures measured immediately post-game in the night-game condition compared with the rest-day ($p < 0.01$, $d = 3.63$). No differences were found for bedtime and awakening core temperatures before and after the night-game compared to a rest-day (Table 5.1).

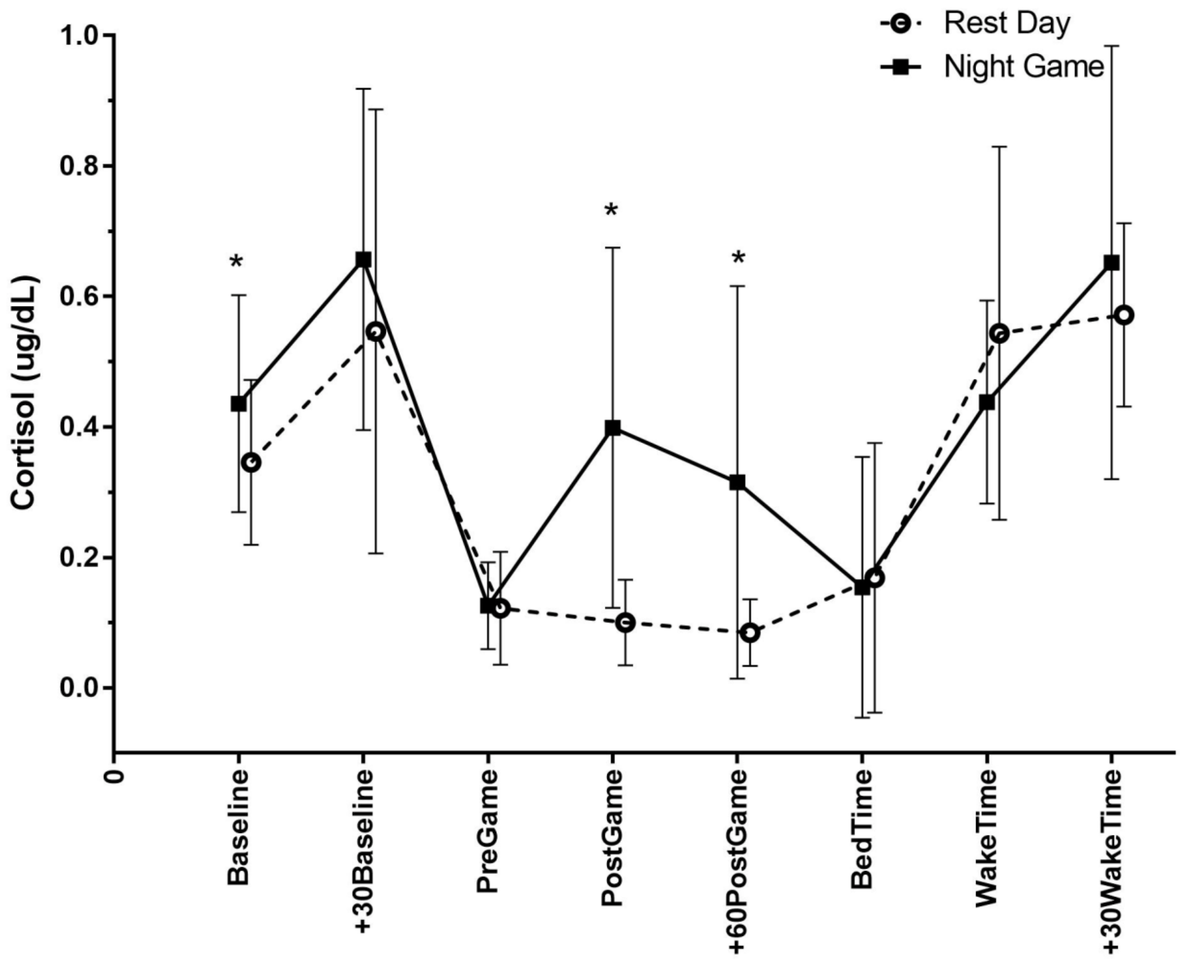

Figure 5.3. Mean salivary cortisol values collected at eight designated time points a day of (pre- and post) a night game and a time matched rest day in netballers. * Significant difference found at the time point between conditions (rest day and night game) ($p < 0.05$).

5.4.4 Correlation between Sleep and Physiological, Neuroendocrine and Psychometric Variables

Significant correlations were found for trait psychometric measures between the hyperarousal scale and sleep efficiency. A decrease in sleep efficiency was strongly associated with an increase in hyperarousal scores (trait) in netballers (r_s (23) = -0.611, p = < 0.01). A moderate negative correlation was identified between sleep efficiency and both the extreme score and introspectiveness score calculated from the hyperarousal scale (r_s (23) = -0.541, p = < 0.01 and r_s (23) = -0.476, p > 0.05, respectively). No correlations were found between any physiological and neuroendocrine variables and sleep (efficiency, duration, and sleep onset latency).

5.5 Discussion

The present study examined the impact of night-time competition on sleep in elite netballers. The main study findings were; 1) participants experienced reduced sleep durations, lower sleep efficiency, early awakenings and poorer subjective sleep ratings following the night-game compared to the rest-day; 2) neuroendocrine urinary catecholamines (adrenaline and noradrenaline) were elevated before and after the night-game in comparison with a time matched rest-day; 3) salivary cortisol concentrations were elevated the morning of the game, immediately post-game and one-hour post-game in comparison to a rest-day; and 4) correlation analysis revealed a strong negative correlation between sleep efficiency and the hyperarousal trait score.

Following night-time competition, a decrease in both objective and subjective measures of sleep occurred (Table 5.1, Figure 5.2), which is consistent with recent findings in team sport athletes[51, 54, 104]. When compared with a rest-day, 92 percent (11 out of 12) of participants experienced reduced sleep following the night-game with objectively measured (e.g. actigraphy) sleep durations decreasing in the range of 15 to 140 min (Figure 5.2). These findings are comparable to reported reductions of sleep quantity in male footballers (-181 min)[51] and Australian rules footballers (-171 min and -126 min) following night games[53, 113]. The observed decrease in sleep duration following the night-game was not a consequence of delayed bedtime, but instead due to earlier wake-times, which were ad libitum. Our findings are not completely consistent with Fullager et al[51] who, in addition to earlier wake times observed later bed-times in male football players following a night match compared with a normal training day. We suspect the differences between these studies were likely due to logistical considerations enabling our athletes to avoid delaying bedtime. For instance, participants in the current study did not have media or recovery commitments after the game and were in close proximity to their residential facilities from the sport complex (approximately 800m).

Regardless, the current results suggest that, under normal circumstances (rest day), the netballers obtained adequate sleep durations (Figure 5.2) which are consistent with recommendations for healthy adults[17] and irrespective of condition, sleep efficiency was greater than the clinically relevant 85%, indicative of poor sleep efficiency[158]. Despite this, following late competition sleep needs were not met despite participants specifying their need to obtain nine hours of sleep a night to feel fully rested. This finding is particularly important for netballers as it is common in major tournaments for athletes to play eight games within 10 days, therefore the ability to maximise sleep as a form of recovery is vital.

Compared to the rest-day noradrenaline and adrenaline levels were significantly elevated for the night-game condition, as was cortisol concentration the morning of the game (baseline), immediately following the game and one-hour post-game when time matched to the rest day (Figure 5.3). Similar findings have been observed for cortisol levels in 16 tennis players where a competition day induced a higher level of stress when compared with a rest day[29]. Furthermore, Pierce et alPierce, Kupprat [159] reported elevated epinephrine levels in track and field athletes vying for international selection compared with team members who were not, highlighting the anticipatory stress effect competition can impose on an athlete. The current study was a selection and an international game for participants, therefore elevated levels of stress hormones prior to the game may indicate an anticipatory affect while continued elevation after the game may likely be due to sustained psychological stress in addition to stress from physical activity[159]. The notion that the netball competition caused a degree of physiological stress is therefore supported through the elevation of peripheral stress hormones[29, 160]; however, a lack of correlation between sleep measures and any stress hormone indicate the absence of association.

Despite increased cortisol following the night-game, levels measured immediately before bedtime (~3h 15min post-game) were similar between conditions. Our findings are consistent with Elloumi et al[160] who observed a 2.5 fold increase in cortisol levels in 20 rugby players' immediately following a match (4pm); yet, reported cortisol levels had returned to basal values within four hours (8pm). Decreased cortisol levels from post-game to bedtime although speculative may perhaps represent the flexibility of an athlete's autonomic nervous system to return to basal levels within hours post a competition. Furthermore, in contrast to insomnia patients where elevated cortisol levels are consistent with poor sleep[161], our findings indicate cortisol is not likely to influence the sleep of athletes following night games when the timeframe between the end of competition and sleep onset is greater than three hours. A similar finding was observed for core temperature, a mechanism hypothesised to influence sleep following night competition[53]. Core temperature was elevated immediately post-game compared with the time-matched day (Table 5.1), yet, no differences were evident between conditions immediately prior to bed. Therefore, similar to cortisol, our findings provide evidence against this proposed assumption linking elevated core temperature and sleep following night competition[53].

Psychometric state measures indicated no differences between conditions. This finding is in contrast to a similar study in healthy working populations that found psychological arousal at bedtime to be positively associated with reports of poor sleep in healthy workers[27]. Whilst the current study results indicate athletes may not have impaired sleep due to psychometric state arousal (PSAS; Table 5.1), correlation analysis indicates a high trait arousal (hyperarousal scale) is strongly associated with a decrease in sleep efficiency. Thus, netballers who rate higher in the hyperarousal scale may potentially be predisposed to disturbed sleep around critical competition times or under certain stressful situations. Previous experimental studies in patients with sleep disorders and civil servants have suggested the underlying mechanisms behind sleep problems may be due to hyperarousal[25]. Indeed, the hyperarousal scale has previously been shown to correlate highly to several electroencephological variables signifying a tendency of individuals to exhibit cortical electrical responses that are less modulated by stimulus properties. This reduced ability to modulate consequently results in an inability to cortically de-arouse therefore serving as a vulnerability to poor sleep[142, 162]. Whilst the suggestions are based on inferences from other populations the similarity of the results to the current athlete group could give insight into an area that has not previously been explored.

The limitations of this study should be considered when interpreting results. Firstly, the sample size employed in the current study was a sample of convenience due to the applied setting which may have limited the significance of the results; however, this is not uncommon in studies with elite level athletes. Secondly, numerous factors are known to influence the sleep characteristics of athletes. Whilst a large number of factors were measured in the current study it may be beneficial for future research to explore the match day load interaction with sleep characteristics.

5.6 Conclusion

The present findings confirm athletes have a reduced duration and quality of sleep following a night-game. To the authors knowledge this is the first study to seek to explore the hypothesised mechanisms proposed for poor sleep in athletes following late competitions. Results suggest neuroendocrine and physiological variables are not related to poor sleep following a night-game when sleep is more than three hours post-competition. However, correlation analysis suggested athletes who had a tendency toward a high trait arousal (hyperarousal scale) may be susceptible to sleep complaints following a night-game. Given that the occurrence of night games is common in sport, our findings provide information that is useful for athletes, coaches and support staff when devising individualised recovery plans.

5.7 Practical Applications

Our results demonstrate athletes experience worse sleep following night competitions however obtain adequate sleep under normal conditions (rest-day). A novel contribution is that trait psychometric measures appear to predispose athletes to poor sleep following a night competition and refute commonly hypothesised explanations (neuroendocrine variables and core temperature). Practitioners should be aware of this occurrence and look to alleviate poor sleep through targeted interventions addressing hyperarousal in susceptible athletes.

CHAPTER SIX

Non-pharmacological intervention for improving sleep in athletes: the effectiveness of neurofeedback

Juliff LE, Peiffer JJ, Hegg J, Fuller K, Chan V, Welvaert M, Halson SL. Non-pharmacological intervention for improving sleep in athletes: the effectiveness of neurofeedback. 2016.

Link: Findings from studies one to three indicate athletes' report and experience poor sleep around critical competition periods however effective interventions to promote sleep during such periods are limited. A successful nonpharmacological sleep intervention emerging in disordered and healthy patients is neurofeedback. Due to the emergence of this novel intervention, this study sought to explore whether neurofeedback could be effective in enhancing sleep in an athlete population.

6.1 Abstract

With the importance of sleep recognised, athletes are often unaware of strategies to overcome sleep complaints and practitioners are under increasing pressure to prescribe sleep medication. The aim of the study was to explore the effectiveness of neurofeedback, a novel non-pharmacological sleep intervention intervening on the level of the central nervous system, in optimising sleep in athletes. Utilising a parallel group, single blind design twenty-six elite male athletes were allocated to either an individualised neurofeedback (n=13) or sham (n=13) neurofeedback group to assess changes in sleep parameters measured through polysomnography and actigraphy monitors. Sleep latency was reduced in the neurofeedback group at home following the intervention compared with the sham group. Furthermore, only the neurofeedback group improved overall reported subjective sleep problems measured through the Pittsburgh Sleep Quality Index. Despite the overall improvement found in sleep variables, between group results suggest a lack of effect between neurofeedback and sham group for sleep variables selected. After 15 neurofeedback sessions athletes demonstrated evidence of neurofeedback learning and operant control through changes in targeted brain amplitudes. Neurofeedback successfully reduced the main sleep complaint in athletes, trouble falling asleep, through reduced sleep onset latency when compared with a sham group. This finding coupled with improved subjective sleep reports and evidence of cortical network regulation illustrates the non-pharmacological sleep intervention neurofeedback could be considered an alternative intervention to sleep medication in athletes. However, before neurofeedback is recommended and considered a treatment option for an elite athlete presenting with sleep issues, practitioners should consider the time and expertise required for neurofeedback and ensure the more commonly utilised sleep hygiene/behavioural intervention is trialled before neurofeedback is employed.

6.2 Introduction

Sleep disturbances in athletes are common due to the often-unique challenges faced by athletes during training and competition[163, 164]. Recent studies indicate athletes habitually obtain less than ideal sleep durations[1, 102] with poor sleep shown to worsen as an athlete transitions from pre-season training to competition[154, 164]. Despite the importance of sleep to optimise athlete recovery, reduce injury and illness rates and improve subsequent athletic performance, athletes are often unaware of appropriate methods to overcome sleep complaints[106, 154, 163, 164]. Furthermore, medical practitioners are under increasing pressure to encourage sufficient sleep in athletes and consequently these practitioners may feel increased pressure from team managers, coaches and the athletes to prescribe sleep medications[163]. A recent study of 107 professional ice hockey players found thirty-six per cent of athletes reported taking sleep medication on at least one night per week during the competitive season[164]. Whilst sleep medication may be beneficial to promote sleep initiation, it is also known to increase daytime drowsiness and reduce the amount of deep sleep. Deep sleep (Stages 3 of non-rapid eye movement sleep) is particularly important for an athlete as the increased growth hormone secretion, which occurs during this phase of sleep, aids neural and peripheral cellular restoration[8, 68]. Given the potential disruption sleep medication has on sleep architecture, non-pharmacological strategies that facilitate sleep, both in and out of competition, should be sought in order to provide effective alternatives to the use of medication[165].

An emerging, non-pharmacological intervention that has demonstrated favourable results for enhancing sleep in non-athlete populations is neurofeedback. Also known as EEG (electroencephalogram)-biofeedback[41], neurofeedback involves training and learning self-regulation of brain activity based on an operant conditioning paradigm, which intervenes on the level of the central nervous system[41, 47]. During training, the EEG is recorded and the participant receives live feedback (auditory and/or visual) on the electrical activity of their brain[41, 166]. The goal of neurofeedback is to normalise the functioning of the brain by learning to train the brain to inhibit and/or reinforce specific frequency bands to improve function[167]. The underlying assumption of neurofeedback posits that through this type of feedback one can entrain, regulate and change the way the brain works once the skill is learned, and unlike medication the results appear to be enduring[47, 167]. By training a frequency band of 12-15Hz, known as the sensory motor rhythm (SMR), several studies of insomnia patients, attention deficit hyperactivity disorder (ADHD) patients and healthy participants have reported decreased sleep latency[41, 168, 169], increased total sleep time[41] and increased sleep spindle density during sleep[169, 170]. A specific study by Cortoos and colleagues[41] utilising patients with insomnia found improved sleep changes during sleep and concluded that by intervening on a level of cognitive processing (neurofeedback), cortical arousal and information processing may be influenced during sleep. Considering a recent study suggesting trait hyperarousal in athletes' correlates to poor sleep following night competition (Study 3) and insomnia patients known to exhibit increased cortical arousal (hyperarousal), an intervention such as neurofeedback that intervenes on the cortical networks might prove to be a promising and effective intervention to optimise sleep in athletes.

It is widely accepted that sleep is one of the fundamental aspects of athlete recovery and developing an effective non-pharmacological treatment for enhancing sleep in athletes has great potential to optimise recovery and improve performances[119, 165]. With a growing body of evidence demonstrating the effectiveness of neurofeedback on improving sleep quality in non-athletic populations, the aim of the present study was to test the effectiveness of neurofeedback in optimising sleep in athletes. It was hypothesised that the individuals who received neurofeedback would demonstrate greater improvements on parameters such as sleep onset latency, sleep duration, sleep efficiency and overall reported sleep problems (Pittsburgh Sleep Quantity Index; PSQI) after 15 conditioning sessions when compared to a sham group.

6.3 Methods

6.3.1 Participants

Athletes experiencing poor sleep were recruited for the present study. Ninety-eight male athletes were screened (Australian rules football, rugby league, football, and swimming), of which, 36 were deemed eligible and of those, 28 agreed to participate. Inclusion criteria for the study were athletes with either sleep onset problems (latency >30min), sleep maintenance problems (wake after sleep onset >30min), sleep efficiency less than 85% measured through actigraphy, sleep complaints of more than three per week and/or poor sleep as indicated through the Pittsburgh Sleep Quality Index (PSQI)[41, 147]. Exclusion criteria included: shift workers, participants on current medication which could impact study results, parents with newborns and consumption of more than five caffeine beverages per day[41]. Of the 28 athletes with sleep disturbance one withdrew part way through, whilst another was omitted due to illness. Twenty-six male athletes (Australian rules football n=14, rugby league n=11, swimming n=1) were assigned (parallel group design) to either a neurofeedback (experimental; n=13) or to a sham group (control; n=13). Participants were informed of the existence of the two training groups however were blinded to which one they were assigned. All participants were provided written information on the risks and benefits of their participation and informed consent was obtained prior to the commencement of the study. The study was approved by the Australian Institute of Sport Ethics Committee and Murdoch University Human Research Ethics Committee and was registered with the Australian New Zealand Clinical Trials Registry.

6.3.2 Study Design

Utilising a parallel group, single blind experimental design, multiple objective and subjective sleep variables and EEG correlates of cognitive processing were assessed before and after 15 neurofeedback training sessions of 20 minutes in duration (Figure 6.1). Prior to the implementation of the training program, participants completed a self-report scale for quality of sleep (Pittsburgh Sleep Quality Index; PSQI)[147]. Furthermore, participants completed two weeks of baseline sleep assessment using Actical® actigraphy monitors (Philips Respironics, Bend, Oregon, USA). Study eligibility was determined from the baseline sleep actigraphy results and PSQI. Following eligibility and participation acceptance, polysomnography (PSG) was conducted over two consecutive nights to assess sleep architecture and quality. The PSG data was used in the study for sleep staging whereas actigraphy was utilised for sleep variables. Participants were allocated to either an intervention (neurofeedback) or control (sham) group utilising treatment allocation by minimisation (treatment allocated to the next participant depends on the characteristics of those participants already enrolled)[171]. This allocation method was selected to ensure balance between intervention groups for age, sleep efficiency and sleep onset latency from actigraphy data. Therefore, participants were assigned to groups based on data acquired from actigraphy not PSG. This was because PSG was scored post study due to the time necessary to score. All neurofeedback sessions took place at the athletes training facilities to ensure convenience and compliance. Following the completion of the intervention training program, participants completed two weeks of follow-up assessment, identical to the baseline assessment (actigraphy monitoring, polysomnography and PSQI) (Figure 6.1).

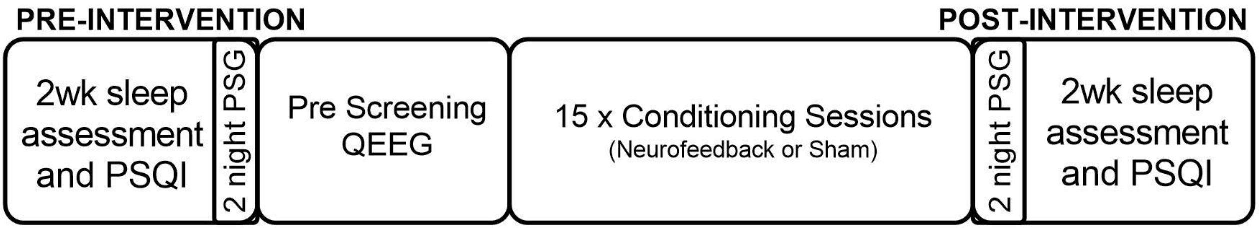

Figure 6.1. An illustration of the study design and collection points.

6.3.3 Sleep Diary and Actigraph

Two weeks prior to the intervention sessions participants wore a wrist actigraphy monitor on the non-dominant hand to measure sleep quality and quantity. Participants wore the monitor at all times unless showering or competing Each Actical® actigraphy monitor contained an omnidirectional piezoelectric accelerometer that generated voltage based on movement, and similarly generated activity counts for each epoch (1-minute epochs) using Actiware 5.61 activity and sleep analysis software (Respironics Actiware, Philips Respironics, Bend, Oregon, USA)[91, 102, 172]. Data from the actigraphy monitor was assessed as sleep or wake based on whether the activity scores exceeded a set wake sensitivity threshold. A wake sensitivity threshold of medium (40 counts per epoch) was used[79]. Time to bed (bedtime), time upon waking (wake-time), time in bed, total sleep time, sleep onset latency and sleep efficiency were measured using the actigraphy monitor. In addition, participants were required to record bedtime and wake-time for each sleep period in a sleep diary for the monitoring period.

6.3.4 Polysomnography

Participants had their sleep assessed using overnight polysomnography (PSG) on four occasions. Two consecutive nights were collected at the beginning of the study and two consecutive nights at the end. Polysomnography (Compumedics Siesta 802 system; Compumedics, Texas, USA) was recorded following the technical specifications of the American Academy of Sleep Medicine (AASM) Manual for the Scoring of Sleep and Associated Events: Rules, Terminology and Technical Specifications[173]. The polysomnography montage included; Four EEG electrodes according to the international 10-20 electrode placement system (F4-A1, C4-A1, C3- A2, O2-A1); electrooculogram electrodes (LOC, ROC); chin electromyogram (EMG1, EMG2) placed on the mentalis and submentalis; a right and left anterior tibialis piezo EMG; thoracic and abdominal respiratory bands; pulse oximeter on the index finger of the non-dominant hand; oronasal airflow sensor; and a single modified lead 11 placement for electrocardiogram[173]. The signals from each polysomnography system were stored in a data card within the portable system as well as transmitted to a laptop in an adjacent room where a researcher monitored the signals throughout the night. All data were scored in 30 second epochs according to the AASM scoring criteria by a trained specialist, unaware of the participants' intervention condition once all data was obtained[173]. To account for a first night effect, data obtained on the first night was excluded in the analyses. To assess any changes in sleep staging the outcome variables calculated were total sleep time, sleep onset latency, wake after sleep onset, sleep efficiency, % slow wave sleep of the sleep period time (SPT), % rapid eye movement (REM) sleep of the SPT, % stage 1 sleep of the SPT and % stage 2 sleep of the SPT. All participants slept in their own individual room within an apartment at either the Australian Institute of Sport Residences or an apartment in their home state. Bedtimes and awakening times for the participants were ad libitum; however, the time when bedroom lights were turned off (bedtime) and on (awakening time) was recorded.

6.3.5 Quantitative EEG (QEEG)

A QEEG (technique of taking EEG data and producing a visual map of the type and location of rhythms in the brain) was obtained prior to neurofeedback training. The goal of the QEEG was to identify any dysfunction of brainwaves at a specific location and derive an individualised neurofeedback protocol to train the characteristics in a desirable direction as described previously by Hammer, Colbert [158]. It should be acknowledged that electrical activity was simply relayed to the computer and no electrical current was administered to the brain during QEEG and neurofeedback.

A 19-channel EEG cap (Electro-Cap International Inc., USA) placed according to the standard 10–20 system was fitted to the participant during a five-minute eye open and five minute eyes closed period. The EEG PC-controlled system Mitsar–EEG (Mitsar Co. Ltd, St Petersburg, Russia) and WinEEG software (Mitsar Co. Ltd, St Petersburg, Russia) were used to acquire, store, process and display the EEG signal. Electrodes were referenced off-line to linked earlobes. Impedances were kept below 5 kOhms(Ω). EEG data was digitised at a sampling rate of 500 Hz and passed through a 0–100 Hz band pass filter. The EEG signals were imported into Neuro Guide software (Applied Neuroscience Inc., Florida, USA) with all artefacts removed prior to processing. The Neuro Guide database compares each participant's scalp electro-physiological activity to a normative database of 625 participants aged 2-82 years. This software yields a Z-score for age and sex distributions for amplitude and three connectivity measures (asymmetry, coherence, and phase lag) at 19 of the 20 standard sites for frequencies 0.5-30 Hz. A trained specialist conducted interpretation of data. The neurofeedback group participants were then prescribed an individualised training program determined from their QEEG results by a trained specialist to ensure training was individualised[158, 168]. The goal of each participant's training program was to normalise any abnormal amplitudes of delta, theta, alpha and beta brainwaves[158]. The neurofeedback group received live feedback of their cortical activity on a secondary screen with participants instructed to either inhibit or reinforce the specific brain frequencies selected (Figure 6.2). On average, the neurofeedback group was trained to increase their sensorimotor rhythm amplitude (SMR; 12-15Hz) whilst inhibiting theta (4-8 Hz) and high beta power (20-30Hz).

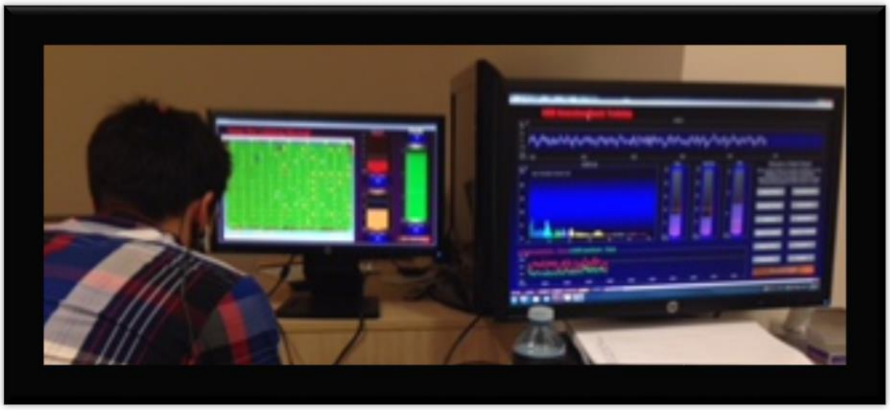

Figure 6.2. An illustration of the neurofeedback set-up.

Unlike the neurofeedback group, who received live feedback of their own cortical activity for the video game, participants in the control (sham) group were shown 'dummy' brainwave activity. Similar to Kober and colleagues[174] the control group (sham) were shown a playback of the training session performed by another participant. The session selection was randomly chosen out of the pool of all available sessions from the neurofeedback group[174]. Using this sham, treatment controlled for possible practice and motivational factors that comes from experimenter-contact and having to undergo and engage in a training regime of equal duration to the experimental group[166, 175].

6.3.6 Neurofeedback Training

Fifteen neurofeedback training sessions of twenty minutes in duration were carried out over the length of the study, with each session conducted on a separate day. On average, participants received training three to five times a week. Similar to Vernon and Colleagues[166] it was not possible to ensure the consistency of time of day for training across each session as sessions were required to fit around the athlete's team and individual training schedules[166]. Training was performed using a NeXus-10 amplifier (Mind Media, Herten, Netherlands) to measure and amplify the EEG signals, and Bio Trace + software (Mind Media, Herten, Netherlands) was utilised for signal processing and to provide feedback to the participants. For the neurofeedback training sessions, participants were fitted with Ag/AgCl disposable electrodes. The designated feedback electrode was Cz-A1 (commonly used active site), whilst the ground was placed on A2 (right earlobe)[166]. During training sessions, participants received different types of feedback; dependent on which group they were in, the neurofeedback or the control (sham) group (as previously described). During training, EEG was recorded and the relevant frequency components were extracted and fed back to the participant using an audio–visual online feedback loop in the form of a video game[166]. The game format represented each frequency component as a bar, with the amplitude of the frequency represented by the size of the bar (Figure 6.2). The participants' task was to increase the size of the SMR training frequency bar whilst simultaneously decreasing the size of the theta and high beta bars[166]. When this operant conditioning goal was achieved, the participant was rewarded through a point system, game activation and game sound. This type of operant conditioning uses

Thorndike's law of effect where responses that produce a satisfying or rewarding effect are more likely to occur again in that situation. The participants were instructed to let the feedback guide them into learning how to activate the game and maximise their 'points' (reflecting enhancement of the given frequency component). This type of learning where the participants are left to explore and develop strategies on their own compared to those who receive explicit instruction are known to have greater success at neural self-regulation[167].

6.3.7 Statistical analyses

All data were analysed using a General Linear Mixed Model in R package lme4[176, 177]. This approach was warranted because of the unbalanced design for certain measures and missing data[178]. The different measurements of sleep were included as dependent variables in subsequent analyses. Independent variables were included as fixed effects for the treatment (2 groups: neurofeedback versus sham) and time (baseline and post), including the two-way interaction. The analyses of the brain frequency training changes only included a fixed effect for time as this was only administered in the treatment group. In the random effects structure of the model, we included a random intercept for participants to resolve the dependence between the repeated measurements. Assumptions of normality and homogeneity of variance were visually assessed using the model residuals and no obvious deviations from these assumptions were detected. Statistical significance of the fixed effects was assessed using Type II Wald F tests with Kenward-Roger degrees of freedom. For those effects that reached statistical significance ($p < 0.05$), we interpret the results based on the estimated effect and the 95% confidence interval calculated using parametric bootstrapping.

6.4 Results

6.4.1 Subjective Measure

The self-report scale for quality of sleep (PSQI) showed no change in the sham (control) group pre-to post treatment (-0.23, 95%CI = [-1.03; 0.54]). A significant decrease in PSQI score was recorded pre-to post treatment in the neurofeedback (experimental) group (-1.34, 95%CI = [-2.50; -0.19], $F (1, 25) = 5.4343$, $p = 0.028$) (Figure 6.3). A PSQI score of 5 out of 21 is a well-validated cut-off for normal sleep quality and has been shown to have high sensitivity and specificity for discriminating normal sleepers from insomnia disorder sufferers[158]. Eleven of the thirteen participants in the neurofeedback group obtained decreased post-treatment PSQI scores below or at the cut-off point whilst two remained stable at the cut of point. Whereas, six of the thirteen control group (sham) participants recorded post-treatment scores at or below the cut-off point. Of the seven sham participants who did not decrease their PSQI scores, two remained the same whilst five scored higher.

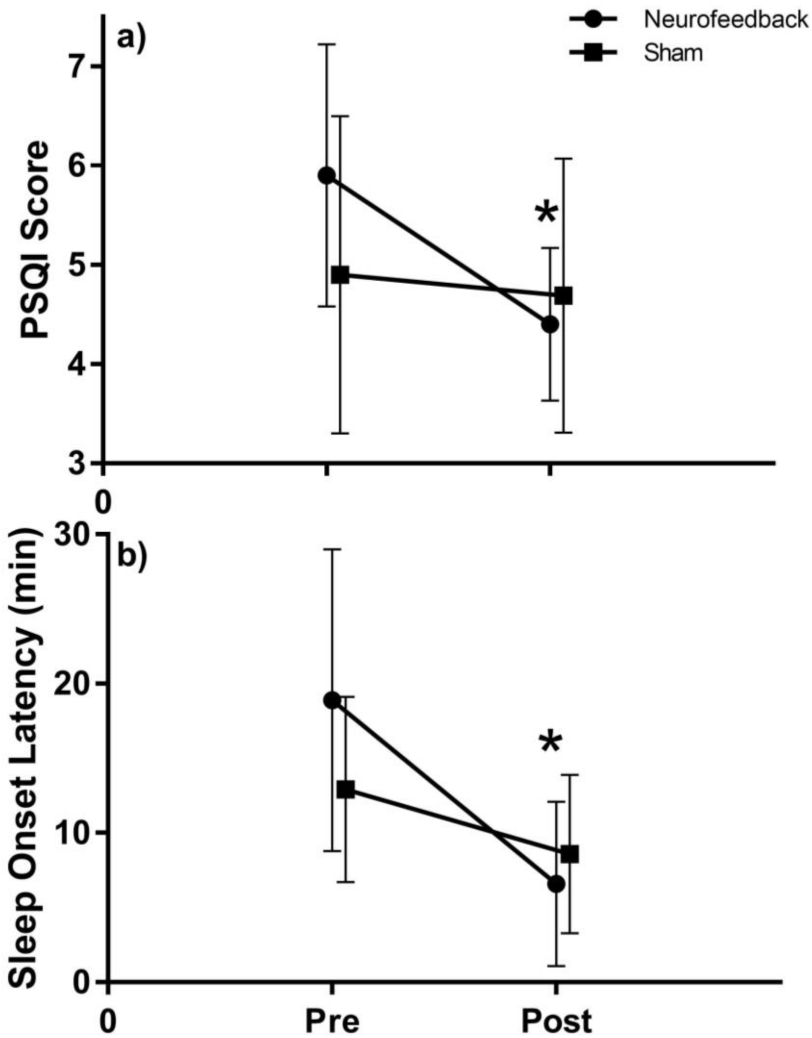

Figure 6.3. Sleep quality changes pre-to post treatment in the neurofeedback and sham group for (a) self-reported Pittsburgh Sleep Quality Index Score (PSQI) and (b) sleep onset latency in the home environment measured by an activity monitor. * Indicates significant difference pre-to post treatment for neurofeedback group.

6.4.2 Sleep Parameters

Sleep parameters for the neurofeedback and sham group using actigraphy and polysomnography are depicted in Table 6.1. A total of 67 successful polysomnography observations (n = 12 neurofeedback, n = 9 sham) were recorded, after 37 recordings were excluded due to technical issues or participant illness. For the polysomnography sleep variables, an overall decrease in wake after sleep onset was recorded for both the neurofeedback and sham groups (-20.14 min, 95%CI = [-20.67; -6.54], F (1, 20.505) = 10.48,

$p = 0.004$) following training, however no differences post intervention were found between groups. An overall decrease was found for stage 1 sleep percentage (-1.67%, 95%CI = [-3.14; -0.10], $F(1, 21.128) = 5.73$, $p = 0.026$) and number of wake bouts (-4.65, 95%CI = [-10.69, 1.76], $F(1, 20.489) = 5.88$, $p = 0.025$) for both groups however no differences were evident between groups ($p > 0.05$). A trend ($F(1, 20.857) = 3.69$, $p = 0.069$) towards an overall increase in sleep efficiency was indicated following the intervention sessions (2.14%, 95%CI = [-1.30; 5.58]). No differences were found between treatment groups (neurofeedback v sham) for any of the polysomnography sleep variables (Table 6.1).

A significant increase over time (pre-to post treatment) was found for sleep efficiency measured by actigraphy (2.54%, 95%CI = [0.32; 4.73]. $F(1, 24) = 15.54$, $p < 0.001$), with no differences found between groups ($p > 0.05$). An overall decrease in sleep latency using actigraphy was found for both the sham and neurofeedback group, with results indicating a more pronounced decrease in sleep onset latency pre-to post treatment in the neurofeedback group, (-4.31 min, 95%CI = [-8.76; -0.23], $F(1,24) = 27.69$, $p < 0.001$) and (-8.00 min, 95%CI = [-13.70; -1.66], $F(1,24) = 6.42$, $p = 0.018$) respectively (Figure 6.3).

Table 6.1. Descriptive sleep parameters (values are means ± SD) in the testing apartment (polysomnography) and home environment (activity monitors) for the sham and neurofeedback groups measured pre-and post-treatment.

	Sham (Control)				Neurofeedback (Experimental)			
	Pre		Post		Pre		Post	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Polysomnography								
Sleep efficiency (%)	86.4	3.8	88.6	5.5	89.4	4.2	91.8	3.4
Total sleep time (min)	420.7	71.7	448.5	45.5	465.2	38.5	454.5	44.3
Time in bed (min)	486.1	75.1	507.2	50.3	520.3	37.4	496	52
Sleep onset latency (min)	9.5	5.9	22.1	25.2	17	11.9	14.3	12.9
Bedtime (hh:mm)	22:51	0:37	23:05	0:47	22:38	0:29	22:50	0:34
Wake-time (hh:mm)	6:58	0:54	7:32	0:34	7:18	0:48	7:05	0:56
Wake after sleep onset (min) #	55.9	20.7	36.6	20.7	38	18.9	27.2	15.1
% Stage 1 sleep#	4.8	1.8	3.2	1.7	3.6	1.6	2.8	1.7
% Stage 2 sleep	47.0	4.6	47.7	5.8	48.1	5.4	49.4	4.7
% slow wave sleep	24.2	4.6	22.8	4.8	22.5	5.1	22.9	5.9
% REM sleep	24.0	4.0	26.4	4.5	25.8	4.6	25.0	4.4
REM latency (min)	94.0	31.8	89.6	34.7	94.6	45.9	94.4	48.6
Number of wake bouts#	34	7	29	7	33	8	28	11
Actigraphy								
Sleep efficiency (%)#	82.8	2.4	88.4	3.8	82.9	3.0	92.3	2.9
Total sleep time (hh:mm)	7:05	0:44	7:17	0:31	7:06	0:37	7:40	0:43
Bedtime (hh:mm)	23:04	0:41	23:05	0:39	22:46	0:36	23:09	0:39
Wake-time (hh:mm)	7:37	0:22	7:37	0:39	7:18	0:27	7:23	0:51
Number wake bouts	29	4	26	7	27	6	26	6

Significant overall interaction effect pre-to post treatment ($p < 0.05$).

6.4.3 Neurofeedback Learning

The brain frequency amplitudes of SMR, Beta and Fast Fourier Transform (FFT) of SMR from early conditioning (session 2-3) to late conditioning (session 14-15) in the neurofeedback group only is depicted in Figure 6.4. Results indicate a significant increase of SMR amplitude between early and late conditioning (0.74, 95%CI = [0.16; 1.45], $F(1, 13)$ =

4.72, p = 0.049). The neurofeedback group showed an increase in the FFT of SMR from early to late conditioning (1.50, 95%CI = [0.35; 2.76], F (1, 13) = 6.07, p = 0.028). No differences were found for the frequency band beta over the duration of neurofeedback training. As the sham group was a replay of the neurofeedback group it was not possible to obtain amplitude data for the sham group.

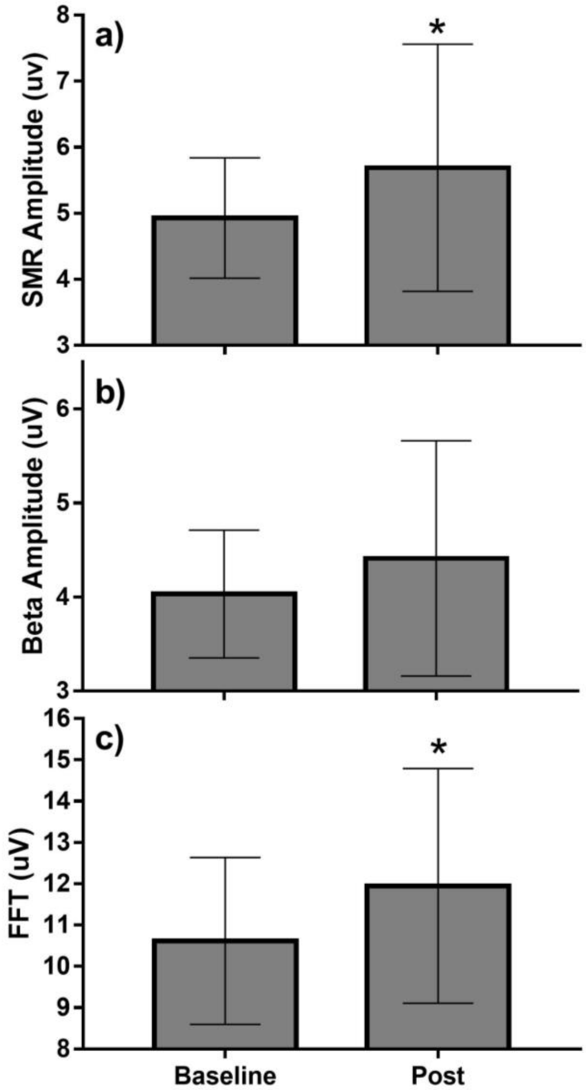

Figure 6.4. Mean amplitude changes in (a) SMR, (b) Beta and (c) FFT of SMR from baseline (session 2-3) to post (session 14-15) conditioning in the neurofeedback (experimental) group only. * Indicates a significant change over time.

6.5 Discussion

The present study examined the effectiveness of an individualised neurofeedback training protocol (experimental) compared to a sham treatment (control) on sleep parameters in athletes. Based on PSG, overall improvements were observed, irrespective of group, in sleep efficiency, wake after sleep onset and number of wake bouts. Supporting our hypothesis, only the neurofeedback group improved their overall reported sleep problems (PSQI) and reduced sleep onset latency in the home environment using actigraphy compared with the control group. In addition, results revealed athletes selectively learned to modify specific components of their EEG following 15 neurofeedback sessions. This finding was demonstrated through changes in amplitude of brain frequency bands from early conditioning (session 2 and 3) to late conditioning (session 14 and 15). No sleep stage changes were evident between conditions measured by PSG.

Within the present study, both PSG and actigraphy were used to provide objective data on sleep within our target population. The use of PSG is acknowledged as the gold standard for measuring sleep however the recording took place over a short period of time (2 days) and in an unfamiliar environment. For this reason, we believe the use of actigraphy, collected over a two-week period, provides a more representative understanding of the athletes' sleeping patterns; thus, providing a more ecological valid representation of sleep changes following the applied intervention. It is acknowledged that actigraphy cannot provide data on the stages of sleep; thus, throughout this discussion we have referenced actigraphy data in relation to sleep variables (i.e. sleep onset latency and sleep efficiency) and PSG data to provide insight into any sleep stage changes.

Within the athletes' home environments, a more pronounced magnitude of change was observed pre-to post intervention in the neurofeedback group for sleep onset latency when compared with the sham treatment. This finding is especially important as previous data in Australian athletes (n=283) indicate initiating sleep as the main sleep problem (82.1%) experienced the night before a major competition[154]. The faster sleep onset observed in the neurofeedback group is in agreement with studies targeting the sensorimotor rhythm (SMR) in healthy participants following a 90 min nap[169], insomnia patients[41] and ADHD patients[168]. The proposed working mechanism for decreased sleep onset latency following SMR neurofeedback is an increased sleep spindle density[168-170]. Whilst the present study did not measure sleep spindle density, training the SMR frequency band is postulated to directly train the sleep spindle circuit given the overlap in location and frequency (12-15Hz spindle oscillations). Evidence of SMR learning was shown in the study through an increase in amplitude pre to post training (discussed below)[168]. Interestingly, research has also found the sleep medication melatonin to result in increased sleep spindle density and decreased sleep latency indicating a possible overlap in working mechanism with neurofeedback[168]. With sleep initiation complaints known in athletes, neurofeedback could be considered a promising and alternate non-pharmacological treatment for initiating sleep.

In line with studies utilising neurofeedback in healthy populations, no change in sleep architecture was found between groups in the current study. Following 10 SMR neurofeedback sessions, Hoedlmoser et al.[169] showed no changes in duration of any sleep stages in 27 healthy participants. Likewise Berner et al.[179] observed no differences in total sleep time and sleep efficiency following SMR neurofeedback in 11 male high school students[179]. Conversely, neurofeedback studies on disordered patients (ADHD and insomnia) have demonstrated changes in sleep variables (total sleep time and sleep efficiency) possibly due to the large room for improvements possible[41, 158, 168]. Whilst it is common practice to demonstrate mean changes in treatment groups, Hammer et al.[158] proposed there is also merit in documenting individual changes in variables for clinical importance of sleep measures. The most commonly used variable for clinical importance is sleep efficiency, with a cut off of less than 85% indicating clinically significant poor sleep efficiency[158]. Using this proposed method 23% of participants in both the neurofeedback and sham group had a sleep efficiency value over 85% in their home environments prior to study commencement. Following training 77% of participants in the neurofeedback group and 62% from the sham group experienced numbers above the clinically significant mark for poor sleep efficiency. An improvement in sleep quality for athletes may be advantageous due to the beneficial effects documented in literature on athletic cognitive and physical performance, mood and immune defence following sleep[119, 128, 137].

The neurofeedback group demonstrated a reduction in the Pittsburgh Sleep Quality Index (PSQI) score pre-to post treatment compared with control (Figure 6.3). The PSQI is a standardised sleep questionnaire estimating general sleep quality therefore all athletes in the neurofeedback group achieved normal or near normal subjective sleep following 15 sessions[147]. Hammer et al.[158] demonstrated comparable results in a population of insomnia patients, with all eight SMR neurofeedback participants decreasing the PSQI score pre to post treatment, indicating all participants finished in a "good" sleep range post treatment[158]. The significance of favourable subjective sleep changes found in insomnia patients was further reinforced when the authors followed up 6-9 months later and found the treatment response was sustained in more than half the insomnia patients[158]. With subjective measures having clinical credibility as an appropriate means of sleep assessment within sleep literature, the implications of the current study suggests an individualised neurofeedback training program in athletes resulted in favourable subjective sleep satisfaction[75, 147].

The current study provides evidence that after 15 neurofeedback training sessions athletes were able to gain control and learn to increase specific components of their EEG activity. The neurofeedback group showed clear evidence of neurofeedback learning and operant control through increased SMR amplitude changes from early (session 2-3) to late (session 14 -15) conditioning sessions as well as increased Fast Fourier Transform (FFT) from pre-to post training sessions (Figure 6.4). The notion that healthy participants are able to learn to selectively enhance their SMR activity is consistent with previous research[166, 168, 179]. Collectively, the ability to demonstrate a learned EEG effect and decreased sleep onset latency in the current study infers athletes were able to regulate their cortical network. This regulation may have enabled the brain to stabilise, allowing the flexibility of the central nervous system to down regulate from a faster frequency (arousal and stress) to a slower frequency where sleep spindles are present and thus result in decreased sleep onset latency[41]. In addition, the neuroplasticity associated with neurofeedback has previously been demonstrated; therefore future studies should explore whether the learned EEG neural circuits from neurofeedback may assist athletes under specific situations when the risk of compromised sleep is high, such as following night competitions[51, 154, 180].

Overall improvements were observed, irrespective of group for PSG variables. Despite the design of an intervention and sham group to negate any influences intrinsic to feedback training such as length (many sessions), medical-like instrumentation and the appeal of brain science other factors may have occurred such as belief of effect[180]. As mentioned previously the sham group experienced feedback not derived from the participant's brain activity but obtained from a previous trial with a different participant. A belief of effect cannot be negated from the sham group in this study as when a participant has the feeling of causing the action or being able to control the feedback in some appropriate way, the outcome is generally better, even if the outcome results in a placebo effect[180]. Finally, it has been reported participants may potentially experience the same level of relaxation as the experimental group despite non-contingency of reward and without the significant enhancement or reduction of specific ratios trained as a result what may have occurred was a placebo phenomenon even though the participant did not receive real feedback[181].

6.6 Conclusion

In conclusion, our findings demonstrate that after 15 neurofeedback sessions improvements were seen in sleep onset latency in the athlete's home environment and general subjective sleep quality was improved compared with a sham group. Overall improvements regardless of intervention (neurofeedback and sham) were seen in sleep efficiency, wake after sleep onset duration and number of wake bouts when measured by PSG. To the authors' knowledge this is the first study to utilise neurofeedback as a sleep intervention in athletes with the aim of optimising sleep. Although results are promising, before neurofeedback is recommended as a practical non-pharmacological intervention for athletes with sleep complaints, practitioners should take into account the time and expertise required for neurofeedback delivery. In addition, the specific sleep complaint contributing to the disturbed sleep should be identified such as sleep onset latency to ensure that the commonly utilised sleep hygiene education strategy is trialled before neurofeedback is employed.

CHAPTER SEVEN

Thesis Discussion, Directions for Future Research, and Conclusions

7.1 Thesis Summary

The results within this thesis advance the knowledge of sleep in elite level athletes. Four studies (subjective, objective, observational and intervention) were completed focusing on the sleep habits and mechanisms responsible for poor sleep in athletes. The perception of sleep and sleep complaints in proximity to competition were examined during Study one. From this study, an athletes' perspective of the challenges experienced around sleep for individual and team sport athletes were reported. Study two involved objective sleep monitoring of a multi-day national tournament to quantify the amount and quality of sleep attained during competition. Building from data obtained in Studies one and two, Study three examined commonly hypothesised mechanisms reported for poor sleep following night games within a sample of elite level netballers. Finally, using the knowledge gained in the initial studies of this thesis, Study four assessed the efficacy of a novel and innovative neurofeedback technique, as an alternate modality to sleep medication, to facilitate effective sleep in athletes (Study four).

Sleep loss can have a profoundly negative impact on athletic performance[125, 126]. The four studies that comprise this thesis were conducted to increase the understanding of challenges to sleep faced by elite level athletes and provide a possible intervention to aid practitioners in providing support to athletes experiencing poor sleep. The contribution of knowledge and major findings of this thesis expand over five key sleep areas; (1) prevalence of sleep disturbance in athletes; (2) sleep related issues faced by athletes; (3) the perceived and objective impact of poor sleep on performance; (4) a novel sleep strategy for athletes and (5) identification of practical application and sleep education topic areas.

7.2 Prevalence of sleep disturbance in athletes

Within both team and individual sport, sleep disturbance in proximity to periods of competition is common. Indeed, of the 283 Australian athletes questioned about their perceived sleep prior to competitions (Study one), 64.0% indicated having slept poorly at least once in the past 12 months before a major competition. This finding was supported from objective sleep data acquired during Study two. Monitoring a national netball tournament (5 nights), 64.4% (n=313) of the sleep nights recorded in the lead in and throughout the tournament (total n=486) were below (6:56 ± 0:47h) the 8 hours of sleep per night recommended for a healthy individual[17]. Collectively these findings are comparable to Erlacher et al.[20] who surveyed 632 German athletes of which 65.8% reported incidence of sleep complaints prior to competition[20]. In high performance sport great focus is placed on the preparation of athletes for competition and this thesis provides both subjective and objective evidence to performance staff and coaches that many athletes experience inadequate sleep in the nights prior to competition. With the impact of reduced sleep known to physiologically compromise reaction time[127, 128], psychomotor performance[4] and immune function[13, 181] etc., it is clear that sleep reduction prior to competition is not conducive to optimal performance preparation.

A specifically novel finding from Study one and three was the situational nature of competition for eliciting poor sleep in athletes. In Study one, a lack of association was observed between athletes who reported poor sleep prior to competition through the Competitive Sports and Sleep Questionnaire and their classification as a "poor" sleeper in general, as determined by the Pittsburgh Sleep Quality Index. This finding indicates that although an athlete may not be classed, on a day-to-day basis, as a problematic sleeper, sleep complaints may manifest around periods of competition. Furthermore, results from Study three indicate netballers appeared to obtain adequate sleep durations (8:25 ± 0:50h) under normal circumstances (rest day) however, sleep durations were significantly decreased (7:36 ± 0:40h) following late competitions. This finding is consistent with a recent sleep study in professional footballers which concluded that players with "normal" sleep patterns can under specific circumstances, such as competition and following a late game, experience reduced sleep durations[51]. Whilst conjecture exists regarding normal out of competition sleep habits of athletes, these findings highlight a pattern of situational based issues with sleep that should be a concern for athletes and support staff around times of competition [1, 16, 51].

7.3 Sleep related issues facing athletes

In order to provide appropriate sleep strategies and sleep hygiene education to athletes during periods of competition, understanding issues associated with poor sleep is essential. Within Study one, athletes, regardless of gender and sport (individual versus team), identified problems falling asleep (82%) as the primary complaint responsible for poor sleep prior to competition, whereas, waking throughout the night (38%) and waking early the following morning (26.8%) were less common. When exploring the factors associated with problems falling asleep 83.5% reported "thoughts about the competition" and 43.8% reported "nervousness about the competition". These findings were consistent across both gender and sport. Whilst external factors such as noise were indicated to impact sleep in certain situations (22.2%), internal factors appear to have a stronger influence on sleep disturbance. These findings are supported by recent research in German athletes and European footballers[20, 51]. Erlacher et al.[20] found 632 German athletes denoted internal factors more commonly as the main reasons for sleep problems. Whilst, 16 elite male European football players reported "nervousness" as the most common problem for an average to poor sleep rating during a 21-day monitoring period in-season[51]. Findings from this thesis add to the understanding of specific sleep complaints experienced by athletes prior to competition and are likely to assist in devising targeted sleep strategies and education to facilitate more optimal sleep during periods of competition.

The theory that situational factors influence athlete sleep was further strengthened by findings in Study one during which 148 of the athletes surveyed (n=282) indicated sleep disturbances after a late training session or game (52.5%). Of this sample, 72% were identified as team sport athletes compared with 28% from individual sports. Indeed, analysis of sleep patterns in elite netballers during a national tournament (Study two) highlighted decreased sleep durations following late games compared with afternoon games (Study two); and reduced sleep durations, lower sleep efficiency and poorer subjective sleep ratings following an international netball game when compared with a rest day (Study three). Together, this data indicates that competition may be a driver for poor sleep and that athletes commonly experience worse sleep following night competitions. However, the mechanisms responsible for this association are unclear with speculation evident throughout the literature[51, 54, 104]. Elevated core temperature at bedtime[53], increased state psychometric measures[51] and increased sympathetic activation from exercise resulting in arousal i.e. from elevated cortisol[53, 54], and adrenaline and noradrenaline carrying over into the sleep periods[51, 54] have all been hypothesised as mechanisms associated with competition and poor sleep within athletes. Following a night netball game (Study three) core temperature and cortisol, although elevated post game, were no different to a time matched rest day at bedtime (3h post-game). This result provides evidence against traditionally held hypotheses and questioning sleep interventions focused on these mechanisms.

Elevated trait hyperarousal was identified as a key factor predisposing netballers to disturbed sleep following night games (Study three). Whilst not theorised by sport scientists as a main influencer to poor sleep following a late game, trait hyperarousal has been suggested as a mechanistic rationale for patients with sleep disorders and sleep deprived civil servants[25, 142, 162]. Sleep loss following competition is likely to compromise the recovery process[119], thus, the identification of hyperarousal within athletes could prove to be invaluable to support and coaching staff. For instance, an intervention that modulates cortical electrical responses to de-arouse the individual, may prevent poor sleep in a predisposed hyperaroused athlete[51, 126].

7.4 The perceived and objective impact of poor sleep on performance

With little known regarding the relationship between sleep and performance in athletes, Study one and two expands knowledge both subjectively and objectively on this topic[97]. Monitoring a national netball tournament through actigraphy it was found that netball teams with the highest sleep duration correlated (r=-0.68) to higher competition standings. This finding suggests appropriate sleep durations during competition for team sport athletes may have significant influence on performance (Study two). With many sporting teams participating in multi-day tournament style competitions, this result highlights that performance staff should endeavor to ensure athletes have sufficient time made available to maximise sleep durations during the competition period. This result is consistent with, and expands on recent knowledge identifying the direct positive effect sleep extension has on athlete performances[137, 138]. The emergence of sleep extension studies and studies objectively monitoring athletes during competition (Study two) has enabled the identification of the impact sleep duration has on athletic performance, as previously research had inferred the importance of sleep on performance from sleep deprivation protocols[129, 130].

Subjectively, increased daytime sleepiness was perceived as the most common consequence of poor sleep in 283 Australian athletes (Study one). Our finding supports previous results in athletes and the general population with daytime sleepiness commonly reported as the most frequently described influence on insufficient sleep[59]. On further exploration our study identified a variance between team and individual sport athletes. Individual sport athletes reported less occurrence of daytime sleepiness (26.9%) and consequently indicated poor sleep to have no influence on performance 63% of the time. Conversely, team sport athletes had a higher incidence of daytime sleepiness (48.4%) indicating poor sleep to have greater influence on performance with only 39.7% indicating "no-influence" when questioned (Study one). The reasoning for the differences observed was potentially due to individual sport athletes indicating a higher usage of strategies to overcome sleep disturbance.

With the need for athletes to perform on a consistent basis and for teams to consistently deliver winning performances it is desirable for staff to understand and acquire knowledge on the consequences of poor sleep on performance. The studies included in this thesis provide further knowledge in this area and highlight the advantage of sleep duration to competition (Study two), as well as providing insight into an athletes perception of poor sleep consequences and impact to performance (Study one).

7.5 Novel sleep strategy for athletes

Sleep loss is undesirable for an athlete and as evidenced with athletes in Study one being largely unaware of sleep strategies to overcome poor sleep (51.7%). The modalities athletes currently utilise are either not recommended (sleeping medication 13%) or conducive to promoting sleep (watching TV 19.3%). Moreover, 59.1% of team sport athletes report not being aware of strategies to combat sleep disturbances (Study one). Until now, investigations into sleep strategies have been derived from research in other population groups largely removed from athletes[9]. With poor knowledge of sleep strategies reported in athletes and the need for specific interventions to overcome poor sleep (Study three), a novel sleep strategy for use in team sport athletes was desired.

Neurofeedback (Study four) aimed to address the main sleep complaint reported in athletes, problems falling asleep (Study one). This was evidenced through actigraphy data yielding a significant and larger decrease in sleep onset latency in the athlete's home environment post treatment (2 week period) when compared with the sham group. Additionally, neurofeedback shifted athletes from clinically bad sleepers to good sleepers as assessed by the Pittsburgh Sleep Quality Index and produced overall improvements in sleep efficiency; wake after sleep onset and number of wake bouts regardless of the intervention applied. Whilst neurofeedback demonstrated a desirable outcome for sleep onset latency in the home environment, no sleep staging differences were found between the intervention and sham group utilising polysomnography, the gold standard measure of sleep. Despite the overall improvement found in sleep variables between groups, results suggest a lack of effect between the neurofeedback and sham group for the sleep variables selected. Due to this finding before neurofeedback is recommended and considered a treatment option for an elite athlete presenting with sleep issues, practitioners should consider the time, the labour intensiveness and expertise required to use neurofeedback as an intervention. In addition, from an applied perspective the identification of the specific complaint contributing to the disturbed sleep in the athlete should be understood to ensure that the more commonly utilised best practice sleep hygiene/behavioural education is trialled before neurofeedback is employed.

Strategies that reduce the reliance on sleep medication in elite athletes is desirable and addressing the sleep related issues identified in the thesis and mitigating the consequences of poor sleep is needed. To the authors knowledge, Study four was the first study to explore the effect of neurofeedback in athletes. Although findings from this study indicate improvements in sleep onset latency in the home environment; subjective sleep quality improvements and evidence of an athletes ability to gain control and learn to modify specific components of their EEG activity, further exploration is warranted before neurofeedback is considered a treatment modality for elite level athletes despite its documented effectiveness with sleep pathology patients[41].

7.6 Practical application and sleep education topics

Understanding the current complaints of athletes and the challenges they experience enables specific, relevant and effective sleep education to be provided. Throughout the thesis chapters, topics and issues were unveiled where education for athletes would be warranted.

Results revealed subjective sleep quality reported by athletes were gauged from sleep duration and not efficiency (Study two). In subjective sleep questionnaires there is often an acknowledged limitation that discrepancies may exist that may not reflect objective measures[20, 81, 82]. Study two results illustrate this limitation, through a positive correlation between sleep duration and subjective sleep quality with no difference in sleep efficiency. While subjective reports from athletes remain appealing in sport monitoring systems due to the ease of collection, caution should be given when interpreting results entered by athletes unless adequate education has been provided. An additional education topic that emerged in Study two was a difference of 64.0 ± 5.5 minutes between reported time in bed and actual sleep duration. An athlete may expect their total time asleep to be the time they went to bed to the time they woke up, consequently adequate sleep durations may not be obtained as sleep duration does not consider movements experienced, time awake and sleep onset latency. Information such as this may allow athletes to accurately plan to obtain optimal sleep, in addition to reporting sleep duration as precisely as possible.

Despite the importance of sleep acknowledged and the incidence of sleep complaints unveiled (Study one, two and three), more than 59.1% of team sport athletes were unaware of sleep strategies to overcome poor sleep. It is essential education and strategies are communicated to equip athletes during times of disturbed sleep. This includes reiterating the novel finding that sleep may not be problematic on a day-to-day basis however complaints may arise around competition periods that are not otherwise present (Study one). Communicating this result may contribute to an athlete being attentive when the sleep advice is offered whereas they may otherwise have not taken note. Finally, with sleep duration shown to have the ability to contribute to competition success, the importance of sleep duration to performance should highlight the necessity to ensure adequate availability of time is programmed by staff and athletes to maximise sleep during competition periods.

7.7 Limitations and delimitations

While the findings presented throughout the thesis have direct and applied outcomes for improving and understanding sleep in athletes around competition periods, some limitations and delimitations should be declared.

Limitations

Across all studies completed within this thesis there were elements where the availability of players and team numbers (sample of convenience) impacted on the sample size. Similarly, given illness and injuries sustained during the testing period, the sample size of Study four was affected. While every effort was taken to ensure controlled environments during competition (Study two and three) and collect all data that may have impacted on an athletes sleep following competition (Study three) inevitably some variables may have been out of the researcher's control (i.e. impact of a phone call on emotions etc.) As such, the results obtained in these studies are typical of real-world situations. Due to schedule restrictions of elite athletes, the accessibility to athletes over a long period of time was not possible therefore informed decisions were made such as conducting 15 neurofeedback sessions instead of the desired 20-25 (Study four). Additionally, due to the intrusiveness, complexity and cost of polysomnography testing it was not possible to utilise this collection method for all thesis studies.

Delimitations

The thesis results can be generalised to Australian athletes, over the age of 18, who are elite and team sport athletes. All studies completed as part of this thesis were obtained on players over the age of 18 due to adolescents exhibiting different circadian rhythms to adults[182]. All athletes monitored were Australian representative level or members of professional teams therefore results are representative of elite level athletes. Due to the results of Study one indicating team sport athletes to have differences compared with individual sport athletes consequently Studies two, three and four focused on team sport athletes. Due to the large number of participants sampled in Study one a sleep questionnaire was chosen that had previously been utilised with Likert scales rather than open-ended questions for compliance and maximisation of participant numbers. Due to practicality and lack of intrusiveness, activity monitoring was selected as the preferred measure of sleep during Study two and three measured during competitions.

7.8 Future directions

From the outcomes presented in the thesis several key areas for future research are provided. A gap in the literature still exists in relation to sleep around competition periods and the impact certain situations or physiological responses may have on recovery sleep. Researchers should further investigate findings in Study three through pragmatically exploring current athlete practices that may interfere with sleep such as pre-game caffeine intake, post-game media commitments and functions, recovery protocols, travel and game feedback sessions. Studies should also consider monitoring longitudinal data throughout a season in different sports to decipher if sleep complaints arise in the majority of competitions or just on occasions.

In future sleep studies, researchers should utilise pre-and post-sleep measures before and after competition instead of conducting research during pre-season or normal training periods to show changes during “known” situations of sleep disturbance and stress. Following this idea future studies should seek to explore and demonstrate whether neurofeedback allows the flexibility of the central nervous system to down regulate from a faster frequency commonly seen from arousal and stress to a slower frequency where sleep spindles are present following a night competition. To test this future neurofeedback studies should look to see if this intervention is not only effective for poor sleepers however good sleepers that may experience stress prior to competition. Finally, with the emergence of a lack of sleep strategy knowledge in athletes, researchers should explore specific athlete sleep strategies to assist with the poor sleep experienced.

Final Summary of Findings

Finding	Study
• It is common for athletes to experience poor sleep the night before a competition	Study one
• Thoughts and nervousness about the competition is attributed to poor sleep the night prior to a competition	Study one
• Difficulty falling asleep is the main sleep complaint in athletes around competitions	Study one
• Team sport athletes attribute poor sleep to influence performance more so than individual sport athletes	Study one
• A lack of sleep strategies is evident for team sport athletes	Study one
• Sleep durations may contribute to the success of a team when a tournament style competition is applied	Study two
• Poor sleep (efficiency and duration) is common following a night game/competition	Study one, two and three
• Core temperature and cortisol did not influence poor sleep in athletes following night time competition	Study three
• Athletes that are classed as “hyper aroused” individuals may be susceptible to poor sleep following a night time competition	Study three
• Practitioners should employ targeted strategies for individual athletes at higher risk of sleep complaints. For instance, an intervention that modulates cortical electrical responses to de-arouse may assist a predisposed hyper aroused athlete	Study three and four
• Neurofeedback shifted athletes from clinically bad sleepers to good sleepers, produced overall improvements in sleep efficiency, wake after sleep onset and number of wake bouts regardless of intervention.	Study four
• Despite some favourable results following neurofeedback, a lack of effect between the neurofeedback and sham group suggests future research is warranted and the more commonly utilised sleep hygiene should be trialled before neurofeedback is employed	Study four

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APPENDICES

Appendix A – Ethics Approval Documents from Murdoch University and the Australian Institute of Sport

Australian Institute of Sport

MINUTE

TO:	Ms Laura Juliff	**CC:**	
FROM:	Ms Helene Rushby		
SUBJECT:	Approval from AIS Ethics Committee	**DATE:**	27th April 2012

On the 17th of April 2012, the AIS Ethics Committee gave consideration to your submission titled ***"A look into the sleep habits of Australian athletes' and coaches prior to important competition of games".*** The Committee saw no ethical reason why your project should not proceed.

The approval number for this project: 20120401

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all researchers involved in the study of Ethics Committee approval and any conditions of that approval. You are also required to advise the Ethics Committee immediately (via the Secretary) of:

any proposed changes to the research design,
any adverse events that may occur,

Researchers are required to submit **annual status reports** and **final reports** to the secretary of the AIS Ethics Committee. Details of status report requirements are contained in the "Guidelines" for ethics submissions.

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214 1577.

Sincerely
Helene Rushby
Secretary, AIS EC

Research Ethics Office
Division of Research and Development
www.murdoch.edu.au

Chancellery Building
South Street
MURDOCH WA 6150
Telephone: 9360 6677
Facsimile: 9360 6686
human.ethics@murdoch.edu.au
www.research.murdoch.edu.au/ethics

Wednesday, 10 July 2013

Dr Jeremiah Peiffer
School of Chiropractic and Sports Science
Murdoch University

Dear Jeremiah,

Project No.	2012/094
Project Title	A look into the sleep habits of Australian athletes and coaches prior to important competitions or games
Chief Investigator	Dr Jeremiah Peiffer
Co-Investigator	Dr Shona Halson
Student Investigator	Laura Juliff

Please be advised that this project was closed on 10 July 2013.

Kind Regards,

E. von Dietze

Dr. Erich von Dietze
Manager of Research Ethics

cc: Dr Shona Halson; Laura Juliff

HREC Closure Receipt 140113

CRICOS Provider Code: 00125J
ABN 61 616 369 313

Murdoch UNIVERSITY

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Tuesday, 05 March 2013

Dr Jeremiah Peiffer
School of Psychology
Murdoch University

Dear Jeremiah,

Project No.	2013/012
Project Title	Sleep, cortisol and catecholamine levels in team sport athletes: The effects of the arousal system on sleep
AMENDMENT:	**Inclusion of wrist sleep activity monitors for extended period of time**

Your application for an amendment to the above project, received on 28 February 2013 was reviewed by the Murdoch University Research Ethics Office and was;

APPROVED

Approval is granted on the understanding that research will be conducted according the standards of the *National Statement on Ethical Conduct in Human Research* (2007), the *Australian Code for the Responsible Conduct of Research* (2007) and Murdoch University policies at all times. You must also abide by the Human Research Ethics Committee's standard conditions of approval (see attached). **All reporting forms are available on the Research Ethics web-site.**

I wish you every success for your research.

Please quote your ethics permit number in all correspondence.

Kind Regards,

E. von Dietze

Dr. Erich von Dietze
Manager of Research Ethics

cc: Dr Shona Halson and Laura Juliff

HREC Outright Approval Letter 140113

CRICOS Provider Code: 00125J
ABN 61 616 369 313

Australian Institute of Sport

MINUTE

TO:	Ms Laura Juliff	CC:	
FROM:	Ms Helene Rushby		
SUBJECT:	Approval from AIS Ethics Committee	DATE:	17th December 2012

On the 11th of December 2012, the AIS Ethics Committee gave consideration to your submission titled "**Sleep, cortisol and catecholamine levels in team sport athletes: the effects of the arousal system on sleep**". The Committee saw no ethical reason why your project should not proceed.

The approval number for this project: 20121203

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all researchers involved in the study of Ethics Committee approval and any conditions of that approval. You are also required to advise the Ethics Committee immediately (via the Secretary) of:

Any proposed changes to the research design,
Any adverse events that may occur,

Researchers are required to submit **annual status reports** and **final reports** to the secretary of the AIS Ethics Committee. Details of status report requirements are contained in the "Guidelines" for ethics submissions.

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214 1577

Sincerely
Helene Rushby
Secretary, AIS EC

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Wednesday, 30 October 2013

Dr Jeremiah Peiffer
School of Psychology and Exercise Science
Murdoch University

Dear Jeremiah,

Project No. 2013/175
Project Title Optimising sleep in elite athletes using Neurofeedback

Thank you for addressing the conditions placed on the above application to the Murdoch University Human Research Ethics Sub-Committee. On behalf of the Sub-Committee, I am pleased to advise the application now has:

OUTRIGHT APPROVAL

Approval is granted on the understanding that research will be conducted according the standards of the *National Statement on Ethical Conduct in Human Research* (2007), the *Australian Code for the Responsible Conduct of Research* (2007) and Murdoch University policies at all times. You must also abide by the Human Research Ethics Committee's standard conditions of approval (see attached). All reporting forms are available on the Research Ethics web-site.

I wish you every success for your research.

Please quote your ethics project number in all correspondence.

Kind Regards,

E. von Dietze

Dr. Erich von Dietze
Manager of Research Ethics

cc: Dr Shona Halson and Laura Juliff

Australian Institute of Sport

MINUTE

TO:	Laura Juliff	CC: Dr Shona Halson
FROM:	Ms Joanne Allen	
SUBJECT:	Approval from AIS Ethics Committee	DATE: 14th August 2013

On the 13th of August 2013, the AIS Ethics Committee gave consideration to your submission titled ***'Optimising sleep in elite athletes using neurofeedback'.*** The Committee saw no ethical reason why your project should not proceed.

The approval number for this project: 20130803

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all researchers involved in the study of Ethics Committee approval and any conditions of that approval. You are also required to advise the Ethics Committee immediately (via the Secretary) of:

Any proposed changes to the research design;
Any adverse events that may occur.

Researchers are required to submit **annual status reports** and **final reports** to the secretary of the AIS Ethics Committee. Details of status report requirements are contained in the "Guidelines" for ethics submissions.

Please note the approval for this submission expires on the 31 January 2015 after which time an extension will need to be sought.

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214 1577.

Sincerely
Joanne Allen
A/g Secretary, AIS EC (Acting)

Appendix B – Statement of Contribution by Others

Declaration by candidate

In the case of Chapters three to six, the nature and extend of my contribution to the work was the following:

Nature of Contribution	Extent of contribution (%)
Development of study design, data collection, analysis, manuscript preparation and submission to journals	80%

The following co-authors also contributed to the work:

Name	Chapter	Contribution (%)
Jeremiah Peiffer	3-6	5%
Shona Halson	3-6	5%
Jeffrey Hebert	4	1%
Peta Forsyth	4	2%
Jon Hegg	6	3%
Kate Fuller	6	3%
Marijke Welvaert	6	1%

Appendix C – Software thresholds alter the bias of actigraphy for monitoring sleep in team-sport

Fuller K.L, **Juliff L.E**., Gore, C.J., Peiffer, J.J, & Halson, S.L. Software thresholds alter the bias of actigraphy for monitoring sleep in team-sport athletes. Journal of Science and Medicine in Sport. 2017. http://dx.doi.org/10.1016/j.jsams.2016.11.021

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Original research

Software thresholds alter the bias of actigraphy for monitoring sleep in team-sport athletes

Kate L. Fuller[a,*], Laura Juliff[b], Christopher J. Gore[a], Jeremiah J. Peiffer[b], Shona L. Halson[a]

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[b] School of Psychology and Exercise Science, Murdoch University, Australia

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ABSTRACT

Objectives: Actical® actigraphy is commonly used to monitor athlete sleep. The proprietary software, called Actiware®, processes data with three different sleep-wake thresholds (Low, Medium or High), but there is no standardisation regarding their use. The purpose of this study was to examine validity and bias of the sleep-wake thresholds for processing Actical® sleep data in team sport athletes.
Design: Validation study comparing actigraph against accepted gold standard polysomnography (PSG).
Methods: Sixty seven nights of sleep were recorded simultaneously with polysomnography and Actical® devices. Individual night data was compared across five sleep measures for each sleep-wake threshold using Actiware® software. Accuracy of each sleep-wake threshold compared with PSG was evaluated from mean bias with 95% confidence limits, Pearson moment-product correlation and associated standard error of estimate.
Results: The Medium threshold generated the smallest mean bias compared with polysomnography for total sleep time (8.5 min), sleep efficiency (1.8%) and wake after sleep onset (−4.1 min); whereas the Low threshold had the smallest bias (7.5 min) for wake bouts. Bias in sleep onset latency was the same across thresholds (−9.5 min). The standard error of the estimate was similar across all thresholds; total sleep time ∼25 min, sleep efficiency ∼4.5%, wake after sleep onset ∼21 min, and wake bouts ∼8 counts.
Conclusions: Sleep parameters measured by the Actical® device are greatly influenced by the sleep-wake threshold applied. In the present study the Medium threshold produced the smallest bias for most parameters compared with PSG. Given the magnitude of measurement variability, confidence limits should be employed when interpreting changes in sleep parameters.

1. Introduction

Sleep is widely accepted as a critical component of the recovery process for an elite athlete.[1,2] As such, monitoring an athlete's sleep has become commonplace as sport scientists look for ways to improve sleep, recovery, and optimise performance. Monitoring sleep using the accepted gold standard method of polysomnography (PSG) is impractical for most athletes since it requires specialist equipment and staff to collect and analyse the data. Also, because PSG monitoring often requires the subject to sleep in a laboratory or setting outside their home environment, long term monitoring of an individual's sleep, or monitoring multiple athletes simultaneously is problematic. For these reasons, actigraphy has become a popular low-cost, non-invasive alternative for collecting sleep data of athletes. Worn on the wrist, actigraph monitors contain a multidirectional accelerometer that detects movements and employs software algorithms to distinguish sleep from wakefulness based on the level of movement.[3] These small devices can store several days and nights of data before downloading to a computer, allowing users to monitor multiple athletes over consecutive nights in any environment; home or away at competition.

The Actical® (Philips Respironics) is an actigraph commonly employed by sport scientists to monitor sleep behaviour in elite athletes.[2,4] Data from the Actical® device can be converted into a format which allows for processing with the Actiware® analysis software (Philips Respironics). This software uses algorithms to process data based on one of three Actiware® sleep-wake threshold settings (Low, Medium and High). Although the sleep-wake threshold algorithms were originally developed and validated with sleep disordered patients, the algorithms and Actical® devices have been validated on a range of populations including sleep disordered

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1440-2440/

and healthy adults.[5–8] There is however, currently no standardised protocol regarding the use of different threshold settings.

Previous research studies investigating the sleep behaviour of elite athletes have used the Medium sleep-wake threshold, based on the work of other industry researchers using this threshold setting.[2,4] Recently, researchers compared the validity of wrist actigraphy across all three Actiware® threshold settings in elite endurance cyclists.[1] Whilst good agreement was observed between activity monitors and PSG for each of the three sleep-wake thresholds (81–90%), the devices underestimated sleep duration and overestimated wake duration depending on which threshold was applied. In contrast to studies using the Medium threshold, Sargent et al.[1] recommended the High sleep-wake threshold be employed when using Actical® actigraphy with elite cyclists.

Considering the widespread use of actigraphy with elite athletes, we sought to expand to work of Sargent et al.[1] to include elite team-sport athletes. Due to the lack of standardisation of the sleep-wake threshold settings used to analyse Actical® data, the aim of this study was to examine the validity and potential bias of the three software thresholds compared with polysomnography. Also, given the way the actigraphy and PSG data is used in a practical setting, only time matched, overall night data values were used for comparison rather than an epoch to epoch analysis which has been used by previous researchers.[3,7]

2. Methods

Participants were 21 male elite team-sport athletes (age: 22.5 ± 2.7 year) from the premier Australian Rules Football League (n = 10) and Australian Rugby League (n = 11). Participants completed a Pittsburgh Scale for Evaluation of Sleep Quality questionnaire to establish inclusion in the study.[9] Exclusion criteria included; shift workers, participants on medication which could impact study results, parents with newborns, presence of primary sleep disorders, and consumption of more than five caffeine beverages per day. Informed consent was obtained from each participant and the study was approved by the Ethics Committees of Murdoch University and the Australian Institute of Sport.

Participants' sleep was assessed using PSG and concurrent actigraphy on four occasions. All athletes were in pre-season training at the time of the study. Data was collected as part of an intervention sleep study which was a randomised, parallel group, single blind experimental design comparing neurofeedback to a sham group. Sixty-seven successful observations were recorded, after some recordings were excluded due to technical issues (n = 16) or participant illness (n = 1). All participants slept in their own bedroom within an apartment. Bedtimes and awakening times were ad libitum; however, the time when bedroom lights were turned off (bedtime) and on (awakening time) was noted. Clocks on the PSG and Actical® devices were synchronised to align the two recording devices. For both devices, the following time-matched, summary measures were collected and calculated for each night: sleep onset latency (SOL), total sleep time (TST), sleep efficiency (SE), wake after sleep onset (WASO) and number of wake bouts. SOL was calculated as time from lights out until the onset of sleep. TST calculated as the total duration of epochs scored as sleep between lights off and on; SE was defined as the percentage of time asleep between lights off and on; WASO was calculated as the number of minutes spent awake between sleep onset and final awakening; wake bouts was defined as the number of discreet wake periods experienced after sleep onset and before final awakening.

Polysomnography (Compumedics Siesta 802 system; Compumedics, Texas, USA) was recorded following the technical specifications of the American Academy of Sleep Medicine manual for the scoring of sleep and associated events.[10] Polysomnograph montage included; four electroencephalogram (EEG) electrodes according to the international 10–20 electrode placement system (F4-A1, C4-A1, C3-A2, O2-A1); two electrooculogram electrodes (Left and Right eye); chin electromyogram (EMG1, EMG2) placed on the mentalis and submentalis; right and left anterior tibialis piezo EMG; thoracic and abdominal respiratory bands; pulse oximeter on the index finger of the non-dominant hand; oronasal airflow sensor; and a single modified lead 11 placement for electrocardiogram (ECG). Signals from each PSG system were stored in a data card within the system as well as transmitted to a laptop in an adjacent room where a researcher monitored the signals throughout the night. All data was scored in 30 s epochs according to the American Academy of Sleep Medicine scoring criteria by a trained specialist, unaware of the participants' intervention condition.[10] The studies were reviewed according to the same criteria by a second sleep specialist blinded to the study design.

Actigraphy data were collected using Actical® Z series activity monitors (Actical® Z series part number 198-0200-03; Philips Respironics, Oregon, USA) worn on the non-dominant wrist. Each activity monitor contains a 3-axis piezoelectric accelerometer sampled at 32 Hz, which generates a voltage when it undergoes a change in acceleration. Sensitive to movements in the 0.5–3 Hz range, the Actical® device records the mean of activity, or movement, sampled each second with the means summed to create activity counts for each 1 min epoch. Actiware® 5.61 activity and sleep analysis software (Mini Mitter Philips/Respironics, Oregon, USA) was used to set up, download and process the data. An activity score was generated for each epoch as a weighted average of the activity count for the current epoch and that of the surrounding epochs (±2 min).[11] Data from the Actical® was assessed as sleep or wake based on whether or not the activity scores exceeded a set wake sensitivity threshold. For the purpose of this study, data from the actigraph devices was processed for all three wake sensitivity thresholds; Low (>20 activity counts scored as wake), Medium (>40 activity counts scored as wake), High (>80 activity counts scored as wake). Time in bed was calculated using the 'lights off' and 'lights on' times recorded on the PSG system. SOL was calculated as the time from lights out until sleep onset and as such, the results for this sleep parameter do not change across the three sleep-wake thresholds.

In previous studies, agreement rates of epoch-by-epoch data have been used to compare PSG and actigraphy, however this technique is not considered fully appropriate as a measure of concordance.[3,12] For this reason, and due to the way PSG and actigraphy data are reported in a practical setting, time matched overall night data values (TST, SE, SOL, WASO and wake bouts) for PSG and Actical® threshold sensitivities (Low, Medium and High) were used for comparison.

Accuracy of each sleep-wake threshold compared with PSG was evaluated by determining mean bias and corresponding ninety-five percent confidence limits (95% CL), as well as the Pearson moment-product correlation and associated standard error of estimate (SEE). Magnitudes of the Pearson correlations were interpreted using the descriptors of Hopkins, low (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9).[13] Bland–Altman plots of absolute error in Actical® from the mean of the PSG and Actical® data across all sleep parameters were conducted.[14] The bias, correlation and Bland–Altman analyses were conducted with GraphPad Prism version 6.01 (GraphPad Software, La Jolla, California, USA), with magnitudes from specialised Excel spreadsheets.[15]

3. Results

Data comparing the three sleep-wake threshold settings on the Actical® devices to PSG are presented in Table 1. Bland–Altman

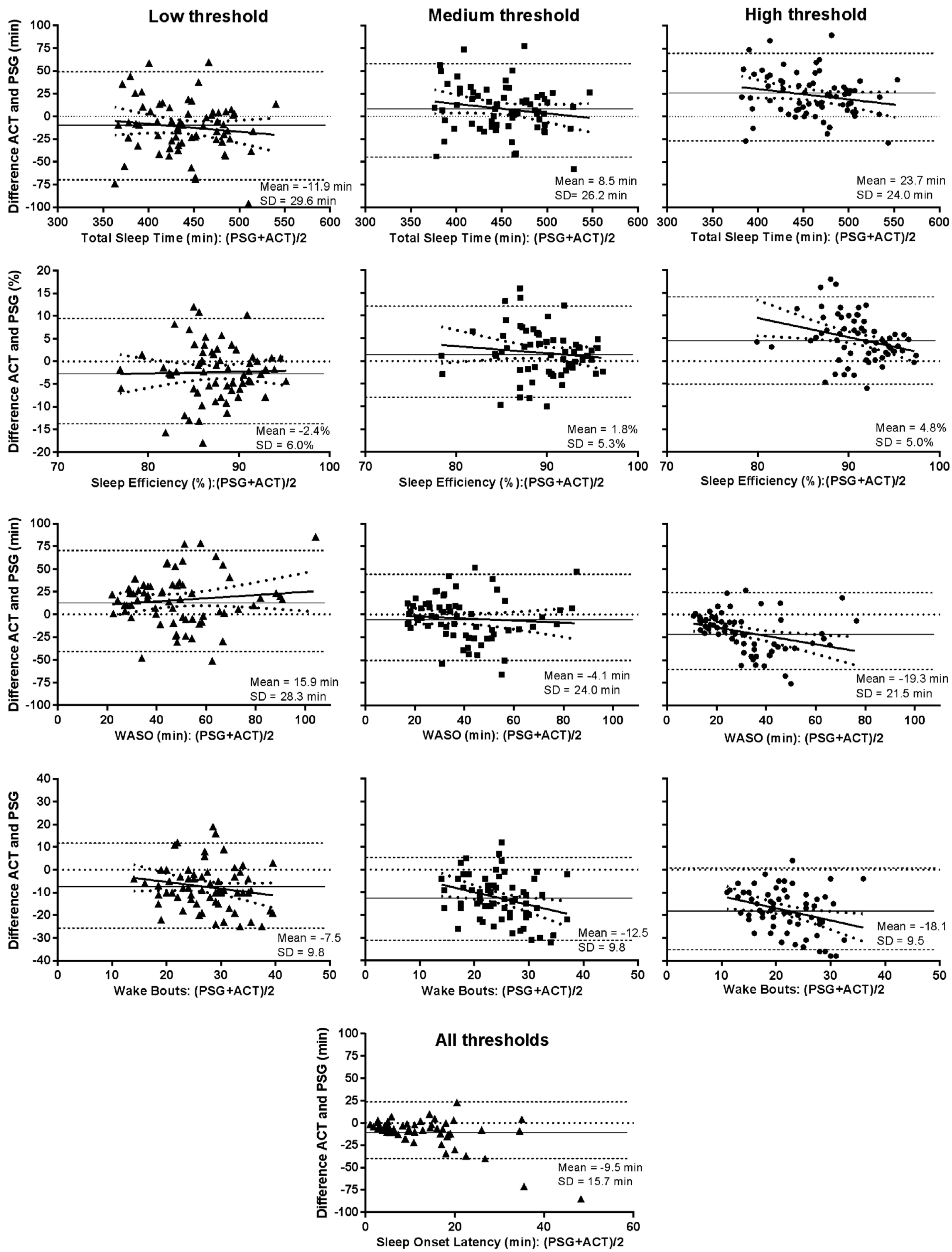

Fig. 1. Bland–Altman plots comparing PSG with the Actical® devices at different sleep-wake thresholds (Low, Medium and High) for total sleep time, sleep efficiency, wake after sleep onset, wake bouts and sleep onset latency. The solid lines indicate the mean bias from PSG and the broken lines indicate 95% limits of agreement (±1.96 SDs). ACT—Actical®, PSG—polysomnography.

Table 1
Comparison of sleep parameters measured by polysomnography (PSG) and Actical® activity monitors.

Measure	n	Mean ± SD	Mean bias (95% CL)	SEE	*r*	p
Total sleep time (min)	67					
PSG		447.1 ± 46.1				
Actical Low (20)		435.2 ± 42.6	−11.9 (−19.1 to 4.6)	29.0	0.78	<0.0001[a]
Actical Medium (40)		455.6 ± 41.8	8.5 (2.1–14.9)	26.1	0.83	<0.0001[a]
Actical High (80)		470.8 ± 41.4	23.7 (17.8–29.6)	24.1	0.85	<0.0001[a]
Sleep efficiency (%)	67					
PSG		88.7 ± 4.9				
Actical Low (20)		86.3 ± 5.0	−2.4 (−3.8 to 0.9)	4.7	0.27	0.0251[a]
Actical Medium (40)		90.5 ± 4.4	1.8 (0.5–3.7)	4.6	0.35	0.0036[a]
Actical High (80)		93.5 ± 3.7	4.8 (3.6–6.0)	4.6	0.34	0.0047[a]
Wake after sleep onset (min)	67					
PSG		41.0 ± 21.6				
Actical Low (20)		56.9 ± 24.0	15.9 (9.0–22.9)	21.1	0.24	0.0571
Actical Medium (40)		36.9 ± 19.9	−4.1 (−10.0 to 1.8)	20.5	0.33	0.0060[a]
Actical High (80)		21.7 ± 15.6	−19.3 (−24.6 to 14.0)	21.3	0.37	0.0024[a]
Wake bouts	67					
PSG		31.0 ± 8.4				
Actical Low (20)		23.5 ± 7.0	−7.5 (−9.9 to 5.1)	8.3	0.20	0.1075
Actical Medium (40)		18.5 ± 6.1	−12.5 (−15.0 to 10.1)	8.4	0.12	0.3505
Actical High (80)		13.0 ± 6.1	−18.1 (−20.4 to 15.7)	8.3	0.16	0.1986
Sleep onset latency (min)	67					
PSG		16.0 ± 15.5	−9.5 (−13.4 to 5.7)	15.2	0.24	0.0496[a]
Actical (Low, Medium and High thresholds)		6.3 ± 8.3				

Positive values indicate an overestimation by activity monitors relative to PSG, and negative values indicate an underestimation by activity monitors relative to PSG.
[a] Significant difference from PSG $p < 0.05$.

plots comparing PSG to Actical® for each sleep-wake threshold are depicted in Fig. 1. Compared to PSG, the Actical® devices underestimated total sleep time and sleep efficiency when the Low threshold was applied, but overestimated these measures on the Medium and High thresholds. For total sleep time, the SEE for all thresholds were similar and very large positive correlations to PSG were observed (r = 0.78–0.85). Similarly, for sleep efficiency measures, the SEE for the three thresholds was almost identical, however when using the Low threshold, a low correlation to PSG was observed (r = 0.27), and a moderate correlation was observed for the Medium and High thresholds (r = 0.35 and 0.34).

The average amount of time athletes spent awake after sleep onset was overestimated by an average of 15.9 min using the Low threshold. Conversely, the Actical® devices underestimated wake time on the Medium and High thresholds by 4.1 and 19.3 min respectively. As with sleep efficiency, a low correlation to PSG was observed for the Low threshold (r = 0.24) and a moderate correlation was observed for the Medium and High thresholds (r = 0.33 and 0.37) and the SEE was similar across thresholds. Compared to PSG, the Actical® monitor underestimated the number of wake bouts regardless of the sleep-wake threshold employed, however these results were not significantly different from that obtained from PSG. As with the other sleep parameters, the SEE for all thresholds was practically the same, however the Low threshold produced the smallest mean bias. A low correlation with PSG was observed with r values of 0.20 for Low, 0.12 for Medium and 0.16 for High thresholds. The Actical® devices underestimated sleep latency by an average of 9.5 min with a SEE of 15.2 min. The results for this sleep parameter were the same across the three thresholds and a low correlation to PSG was observed (r = 0.24).

4. Discussion

In a sport setting, Actical® devices are commonly used to identify athletes requiring further education or intervention about their sleep hygiene, and are also used in research settings as a measure of sleep quantity and quality.[2,4] The results of this study indicate that for elite team-sport athletes the interpretation of the Actical® data, and therefore feedback to athletes, can vary widely depending on the Actiware® software threshold used to process the data. In the present study, the Medium sleep-wake threshold of the Actiware® software produced the smallest mean bias compared with PSG for sleep duration, sleep efficiency and wake after sleep onset. These findings are in contrast to that of Sargent et al.,[1] who reported that the High threshold produced the smallest differences for the same sleep parameters compared to the PSG for elite endurance-trained cyclists. Our results are also in contrast to other validation studies using the Actical® device with non-athletic populations which have recommended using the Low or very low (activity count = 10) thresholds for better overall performance compared with PSG.[6,7]

The differences between the findings of the present study conducted on elite team-sport athletes and those of other validation studies noted above may relate to the different subject groups and conditions in which studies were conducted. Sargent[1] used male endurance-trained cyclists who were measured during a six-week block of intensified training. Sargent hypothesised that the heavy training load may have reduced the immobility of subjects during sleep, with the possibility that athletes moved more in their sleep due to muscle soreness induced by their training. The validation studies conducted by Kosmadopoulos et al.[6,7] did not use an elite athlete population, rather they used healthy young adults, male and female, sleeping in a laboratory. This setting may also influence results as factors such as noise, temperature and light are regulated in a sleep laboratory, thereby potentially influencing sleep behaviour.

Collectively the results of the current and previous validation studies highlight that, compared with PSG, actigraphy has limitations when applied to different athletic or non-athletic populations and should be interpreted with caution. One limitation of the present study was that only male athletes were used and as such, similar validation studies should be conducted on female athletes. However, given the varying results of the aggregated validation studies, the data on women may also be confounded by similar factors such as the type of athlete (endurance or team-sport), training phase, and if the data is collected in a private residence or a sleep laboratory.

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The present study found that compared to PSG, the athletes' total sleep time (447 min) and sleep efficiency were underestimated on the Low threshold (~12 min) and overestimated with the Medium (~9 min) and High (~24 min) thresholds. In an applied sense, the latter error of about five percent is substantial. The practical relevance of the errors compared with PSG are larger for WASO (41 min), which was underestimated when the Medium (~37 min) and High (~22 min) thresholds were applied, and overestimated using the Low (~31 min) threshold. Indeed the value from the High threshold is approximately half that from PSG and would lead to a different interpretation of an athlete's sleep. Furthermore, regardless of the threshold applied, the Actical® devices significantly underestimated sleep onset latency by an average of 9.5 min. Considering a normal sleep latency period is 10–20 min, a bias of this magnitude is important when attempting to interpret sleep reports. In addition to these observed biases, it is important to note that in the present study the correlations between the actigraphy and PSG for all sleep parameters, other than total sleep time, are only low to moderate. One of the limitations of actigraphy is that it uses movement or lack of movement as a surrogate to infer a state of wakefulness or sleep respectively,[12] whereas PSG detects wakefulness and sleep using brain wave activity rather than subject mobility.

As well as investigating the potential systematic bias of each threshold on the different sleep parameters, another objective of the study was to understand the uncertainty of measures using the Actical® devices. These devices are often used with elite athletes to quantify sleep in research studies, and in routine servicing to identify athletes requiring sleep hygiene coaching. If the devices are used to longitudinally monitor an athlete's sleep, care must be taken when interpreting any change in measures. The standard error of the estimate (SEE) provides users with the typical 'noise' or variability of the measure. This estimate can be used to interpret changes in sleep reports for athletes. By quantifying the random uncertainty of each measure, normally distributed confidence limits (CL) can then be employed when interpreting changes in sleep parameters measured with the Actical® devices. If one wanted to be conservative, 95% CLs would be employed to help interpret a meaningful change in an individual's sleep measures, where the 95% CL for an individual change score is calculated as $\pm\sqrt{2} \times 1.96 \times \text{SEE}$. A less conservative approach might use a 52% CL for an individual change score, calculated as $\pm\sqrt{2} \times 0.71 \times \text{SEE}$.

This study found the SEE for each sleep parameter was similar regardless of the Low, Medium or High software threshold applied. For total sleep duration, the SEE across thresholds was approximately 25 min, sleep efficiency 4.5%, WASO 21 min and wake bouts approximately 8 counts. The SEE for sleep onset latency was 15.2 min. If one used 95% CLs, changes within an individual athlete would have to exceed ±69 min for sleep duration, ±12.5% for sleep efficiency, ±58 min for WASO, ±22 counts for Wake Bout, ±42 min for sleep latency. These magnitudes highlight a limitation of using actigraphy on individuals to monitor changes longitudinally. Without an understanding of the 'noise' of each measurement, changes in sleep measures may be interpreted as genuine, rather than being due to the measurement variability of the actigraphy device. In a practical sense, this may lead practitioners and researchers to believe a particular sleep intervention has been successful when in reality it has not.

5. Conclusions

Results from the present study suggest that whilst the 'noise' or imprecision of measures from the Actical® devices is similar for the different sleep-wake thresholds, there is less bias associated with the Medium threshold for sleep duration, sleep efficiency and WASO. Therefore, scientists using Actical® devices to monitor sleep in elite team-sport athletes should consider using thresholds that are moderately sensitive to sleep (Medium threshold) where activity counts are above 40. Additional validation studies of the Actical® devices with elite athlete populations, including female athletes, should be undertaken to understand the bias and imprecision of the different sleep-wake threshold settings on data analysis.

6. Practical implications

- Sleep reports and research using the Actical® devices should indicate which sleep-wake threshold was used to process the data.
- A Medium sleep-wake threshold (activity counts above 40) should be used to process sleep data for team sport athletes.
- The imprecision of actigraphy highlights the importance of utilising confidence limits to assess the likelihood of a real change between sleep measures over time.

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