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Sleep in Elite Athletes

Melanie Knufinke

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SLEEP IN ELITE ATHLETES

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Radboud Universiteit Nijmegen
op gezag van de rector magnificus prof. dr. J.H.J.M. van Krieken,
volgens besluit van het college van decanen
in het openbaar te verdedigen op maandag 1 oktober 2018
om 16.30 uur precies

Door

Melanie Knufinke
geboren op 27 mei 1989
te Gütersloh, Duitsland

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CHAPTER 1

INTRODUCTION

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The life of an elite athlete

Elite athletes are required to perform at the peak of their capabilities, and regularly push their bodies and minds to the limit. To get an idea of an athletes’ training program, road cyclist and Olympic champion Anna van der Breggen (27) shared her week schedule, depicted in Figure 1.1 The selected period displays a week in the off-season, including a training camp in Giorna, Spain, followed by a one-night stay-over in the Netherlands, after which Anna spent a couple of days on Cyprus to compete in an upcoming Mountain-bike race. Shortly thereafter, Anna started her 2018 road-season in Italy with the ‘Strade Bianche Race’, currently she is riding for the Dutch Boels-Dolmans Cycling Team.

As can be deducted from Figure 1.1, elite athletes’ can have quite demanding schedules, including high-intensity training and competition, as well as traveling and sleeping at different locations. The high physiological and psychological strain that is apparent in Anna’s schedule is not unlike what most elite athletes experience, regardless of their discipline, and makes clear how crucial it is for elite athletes to secure adequate recovery.

Sleep is renowned to be the best and most accessible recovery strategy of the human body\(^1\), \(^2\) and may be indispensable for skill acquisition and overall performance capacity\(^3\). Indeed, in 2015, the International Olympic Committee recognized the importance of rest and recovery in athletes, highlighting the importance of sleep in facilitating both mental and physiological health\(^4\). Against this background, the purpose of the current thesis is to (1) shed light on sleep quantity and quality in athletes, (2) identify potential sleep deteriorating factors, (3) extend knowledge on the effects of sleep on performance, and (4) investigate promising interventions to optimize sleep.

An introduction to sleep

From a behavioral perspective, sleep is a reversible state that is characterized by detachment and reduced responsiveness to the environment\(^5\). In spite of the behavioral quiescence, during sleep, numerous physiological and cognitive processes are actively regulated and resources are replenished, so that the body is prepared to optimally function during the subsequent day\(^6\). To date, the functions...
Figure 1.1. Week schedule.

Note. * = “I didn’t sleep well – we stay in a small, noisef apartment in the center of Giorna. Despite using earplugs, I frequently woke up during the night.” ** = “I slept very poorly, probably due to the early wake-time and because of ruminating about next day’s travel.” *** = Cyprus type (GMT + 2), that is one hour later than in The Netherlands.

Figure 1.1. Week schedule.
of sleep are still subject to discussion. Yet, sleep restriction and deprivation studies reveal a salient role of sleep in restoration of the immune and the endocrine systems, recovery from the metabolic cost imposed by the waking state, as well as in (skill-)learning, memory and synaptic plasticity.

Based on measurement of electrical brain activity during sleep, two sleep states are distinguished – rapid eye movement sleep (REM-sleep) and non-REM sleep, which constitute 20-25% and 75-80% of the night, respectively (Figure 1.2). While sleep is typically entered through non-REM sleep, throughout the night, non-REM and REM sleep alternate in cycles of approximately 90 minutes. A typical night entails 4-6 of these sleep cycles, depending on sleep duration. Non-REM sleep is further distinguished in four different sleep stages, which will be referred to in this thesis as 'light sleep' (S1 & S2) and 'deep sleep' (S3 & S4, slow-wave sleep). Sleep stages, including REM sleep, differ in terms of frequency and amplitude of electrical brain activity, depth (auditory awakening response), eye-movement, muscle tone (atonia during REM sleep), respiratory activity, and heart rate. The first part of the night is dominated by deep sleep (S3, S4, slow-wave sleep), whereas REM sleep prevails in the second part of the night.

Despite the fact that their specific function is still under debate, it is commonly accepted that each sleep stage uniquely contributes to psychological and physiological functioning. For athletes, deep sleep is considered to be an especially important stage because, during deep sleep, secretion of the growth hormone (GH) by the pituitary gland is elevated. Growth hormone is essential for protein synthesis and physiological restoration, thereby facilitating recovery from strenuous
exercise. The amount of deep sleep adapts to the body's need for recovery: in line with the restorative hypothesis of sleep, sustained periods of wakefulness or high training load are followed by higher amounts of deep sleep or changes in slow wave activity (SWA).

Figure 1.3: Sleep duration recommendations for relevant age groups as formulated by the National Sleep Foundation.

Regardless of the specific sleep stage, further areas that benefit from sleep concern aspects of athletic performance (e.g., accuracy, speed and endurance), neurocognitive function (e.g., attention, decision making, performance skill learning, memory), and physical health (e.g., higher immunity, pain tolerance, injury prevention, weight control). In order to enjoy these benefits, sleep should be undisturbed and not disordered, of good quality, appropriately and regularly timed, and of adequate duration. Optimal sleep duration is subject to individual differences and factors such as age. According to the National Sleep Foundation (NSF), a sleep duration of 7-9 hours is recommended for (young) adults (18-25 years). Figure 1.3 presents an overview of recommended sleep durations.
depending on age. For athletes, these recommended sleep durations are a good starting point. Based on their high activity profiles (e.g., see Anna van der Breggen’s schedule in Figure 1.1), however, it has been argued that elite athletes may require larger amounts of good quality sleep as compared to the non-athletic population14.

The performance costs of insufficient sleep and the benefits of sleep extension
Athletes may benefit from good sleep, but their performance may also suffer as a consequence of sleep loss. The effects of insufficient or disturbed sleep on athletic performance have mostly been assessed among non-athletes, utilizing sleep restriction (partial sleep deprivation) and total sleep deprivation protocols. Partial sleep deprivation refers to a period in which sleep is restricted to less than or equal to six hours a night, or in which sleep is experimentally disturbed by repeated awakening of the participant, whereas total sleep deprivation refers to a period of sustained wakefulness longer than 24 hours15.

Cognitive performance (e.g., reaction time) constitutes crucial aspects of overall athletic performance and deserves some mentioning. Generally, the extent to which task performance is affected by sleep loss is believed to increase with the degree of cognitive functioning that is involved and the amount of sleep that has been lost. Therefore, effects of sleep loss are expected to be stronger for cognitive performances compared to less complex aspects of athletic performance, as will be outlined below3. Cognitive performance, as for example psychomotor vigilance and reaction time, are the first to deteriorate in a dose-response relationship following sleep loss6, 16. Additional cognitive processes in the domain of executive functioning, such as decision making and accuracy, but also memory and learning are affected by sleep loss3, 18. In addition, sleep loss is associated with higher levels of irritability, bad mood, mental fatigue and reduced motivation19–21, which can increase perception of effort and hence affect performance through cognitive pathways3.

Along the lines of cognitive performance, effects of sleep loss on athletic performance are larger following total sleep deprivation as compared to partial sleep deprivation3. In addition, it is reasoned that skills with a high cognitive reliance (e.g., tennis, darts) are more susceptible to sleep loss. Based on the dependence on cognitive function, a classical distinction between skills has been made that

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Along the lines of cognitive performance, effects of sleep loss on athletic performance are larger following total sleep deprivation as compared to partial sleep deprivation3. In addition, it is reasoned that skills with a high cognitive reliance (e.g., tennis, darts) are more susceptible to sleep loss. Based on the dependence on cognitive function, a classical distinction between skills has been made that
differentiates ‘fine motor skills’ from ‘gross motor skills’\textsuperscript{22}. Fine motor skills incorporate intricate, precise movements, which use small muscle groups and involve high levels of hand-eye coordination (e.g., golf putting), whereas gross motor skills incorporate less precise, whole-body movement, which use large muscle groups and involve lower levels of hand-eye coordination (e.g., jumping, running, cycling)\textsuperscript{22}. For reasons of clarity, this distinction will be used throughout the thesis.

Finally, effects tend to be larger for sustained efforts and repeated exercise bouts than for short-duration exercises and single exercise bouts. Evidence suggests larger effects on sustained (submaximal, endurance > 30 minutes) and repeated performance efforts (e.g., series of weight training exercises), while single maximal exercise performances (e.g., single bouts of aerobic performance, such as vertical jumps, sprints, peak power output or endurance exercise of < 20-30 minutes) remained relatively unaffected by sleep loss\textsuperscript{3}.

While sleep loss is thus likely to adversely affect cognitive and athletic performance, evidence also suggests that extending sleep has the potential to improve performance\textsuperscript{23, 24}. Mah, Mah, Kezirian, and Dement\textsuperscript{23} reported that increasing objective sleep duration from 6.6 hours per night to 8.5 hours per night during a period of 5-7 weeks, resulted in faster sprint times, improved shooting accuracy, faster psychomotor reaction times and decreased daytime sleepiness among 11 healthy Collegiate Basketball players.

As yet, however, research findings of the effect of sleep on athletic performance are often ambiguous and inconclusive\textsuperscript{3}. To date, sample sizes were small, and a large variety of sleep manipulations was used that differed in, for example, the duration of sleep restriction, varied in whether sleep was restricted at the beginning or end of the night, or a protocol was used in which sleep was interrupted by awakening the participant. Additional aspects, such as a large variation in the type of performance test or exercise protocol that was used, the sequential order of multiple performance tests, the time of day on which performance was assessed, the fitness level of the participants, the test-environment (e.g., thermoregulation), as well as individual differences in sleep need and sleep history, may further account for ambiguous results\textsuperscript{3}. Accordingly and in order to obtain a more differentiated picture on the extent to which sleep impacts fine- and gross motor performance across various sports, larger studies are warranted that exhibit more control over the above mentioned factors. Nevertheless, while insight into sleep and athletic
performance can thus be strengthened, studies so far revealed a potentially significant role of sleep in (athletic) performance.

Sleep in elite athletes
Athletes have high activity profiles and thus depend rather heavily on the recovery and performance benefits that can be attained from good quality sleep. Initial studies on sleep in athletes, however, indicate that Olympic athletes show comparable sleep durations, but poorer sleep quality than non-athletic, gender and age-matched controls. Specifically, athletes prioritize sleep by spending more time in bed, but have longer sleep onset latencies, more fragmented sleep, and lower sleep efficiencies (80.6% vs. 88.7% in controls). While not reaching clinical values, these sleep estimates revealed that athletes' sleep is under pressure. Other studies have confirmed this image, showing that athletes typically get less than the recommended 7-9 hours of sleep (e.g., 6.8 hours). Athletes from individual sports (e.g., Cycling, Mountain bike, Swimming, Triathlon) generally tend to sleep worse than team sport athletes (e.g., Football, Rugby Union, Basketball), showing earlier bed- and wake times which potentially result in shorter sleep durations, and lower sleep efficiencies. Finally, a systematic review by Gupta, Morgan, and Gilchrist revealed an overall high prevalence of insomnia symptoms in athletes, such as longer sleep latencies, more fragmented sleep, non-restorative sleep, and excessive daytime sleepiness.

Disturbed sleep or sleep loss may negatively affect performance (as described above) and increases the chance for injury, ‘under-recovery’ and non-functional overreaching, which can be a precursor for the overtraining syndrome. In this regard, it is important to understand why sleep tends to be compromised in (elite) athletes and to find ways in which this may be improved.

Regulation of sleep and wakefulness
In order to understand what drives compromised sleep in athletes and to develop promising interventions, it is essential to understand the basis of sleep-wake regulation.

Sleep and wakefulness are regulated by two distinct processes, a homeostatic drive ‘process S’ and a circadian drive ‘process C’. Process S depicts a steady increase in sleep pressure throughout sustained wakefulness that decreases once...
sleep is initiated. Therefore, process S is sleep-dependent. Process C depicts a sleep-independent circadian oscillation in arousal during approximately 24 hours (i.e., circadian rhythm)\textsuperscript{30, 31}. Thereby, hormonal changes orchestrated by process C determine the best time for alert wakefulness and consolidated sleep, which corresponds to day- and nighttime in humans. Sleep is easiest initiated and maintained when both processes align. That is when sleep pressure is highest and the circadian drive for arousal is lowest ('beginning of the sleep window'; Figure 1.4).

Misalignment of the processes can result in sleep problems\textsuperscript{32}. A common example of misalignment is shiftwork (i.e., when sleep is scheduled during daytime), and (social-) jet lag, where sleep-wake patterns are irregular or shifted.

Importantly, process S and process C do not operate in isolation, but are susceptible to interference by exogenous factors. For example, (evening) light exposure\textsuperscript{33}, extreme ambient temperatures\textsuperscript{34}, elevated core body temperature as a result of late evening trainings\textsuperscript{35, 36}, and also stimulants such as caffeine\textsuperscript{37} can interfere with sleep regulation. Additionally, daytime behaviors, such as extended daytime naps (> 30 minutes) in the late afternoon\textsuperscript{38}, or sedentary behavior during the day\textsuperscript{39}, can decrease sleep pressure, and thus interfere with sleep regulation. Another component that can interfere with sleep initiation and continuation is increased allostatic load, as for example behavioral stress\textsuperscript{40}. Pre-sleep arousal and stress can lead to a coactivation of sleep and arousal centers in the brain, the resulting instability of the sleep-switch can cause insomnia\textsuperscript{41, 42}.

Figure 1.4. The two-process model of sleep regulation, based on Borbely\textsuperscript{30}.
Interference with the sleep regulating processes in elite athletes

Based on knowledge about the regulation of sleep and wakefulness, numerous potentially disturbing factors can be identified by looking at Anna van der Breggen’s week schedule (Figure 1.1). Indeed, researchers have identified a whole range of factors that are more or less inherent to elite sports, but which potentially disturb the adequate regulation of their sleep. A non-exhaustive overview of these factors includes travel\(^{43}\), jet lag\(^{44}\), training and rest schedules\(^{45-47}\), training load\(^{48, 49}\), timing of training and competition\(^{15, 46, 50, 51}\), and anticipatory stress or pre-competitive arousal\(^{15, 52, 53}\). In addition, athletes may experience disturbed sleep due to muscle soreness, pain and injury, as well as the need to use the bathroom at night given their elevated need to hydrate\(^{41}\).

In sum, elite athletes sleep is under pressure, particularly during competitions but also at times of habitual training. In the light of potential interventions, it is important to better understand these factors with regard to sleep, and identify how they can be modified such that sleep can be optimized.

Limitations of previous research and contribution of this thesis

Sleep research among elite athletes is an emerging field. This thesis sought to add to the current understanding of sleep and performance among elite athletes by addressing the four research aims outlined below.

Aim 1: Characterizing sleep of elite athletes

Initial evidence of sleep quantity and sleep quality indicated that athletes’ sleep estimates are inferior to those of non-athletic controls and potentially insufficient for adequate recovery and optimal performance\(^{25}\). The vast majority of these studies utilized actigraphy-based sleep estimates. In order to provide a more complete picture, the current thesis sought to extend this information by also providing subjective sleep estimates. This is important, especially because it appears that some individuals may report poor sleep quality despite of adequate objective markers of sleep, and vice versa\(^{54}\).

Another methodological aspect that will be addressed in this thesis concerns the sleep-wake detection threshold for actigraphy that is commonly used among athletes. Recent evidence suggests that the default actigraphy sleep-wake detection threshold may underestimate sleep in athletes, because athletes exhibit more...
limb-movement during the night (e.g., due to muscle soreness). This could bias actigraphy-estimates towards higher amounts of wakefulness, which means that sleep may be underestimated\(^5\). Recently, a higher sensitivity to sleep setting has reflected better agreement with polysomnography (PSG) in athletes\(^5\), suggesting that employing such a threshold can further contribute to accuracy and validity of sleep-wake estimates in athletes.

Lastly, despite research highlighting that a healthy distribution of sleep stages is crucial for psychological and physiological functioning\(^6\), very little information is available about sleep stage distribution in athletes. Athletes may have an altered sleep architecture, as for example featuring higher amounts of deep sleep following intensified training periods\(^10, 56\), or as a consequence of suboptimal sleep-wake behavior (e.g., sleep restriction, fragmentation, overtraining, and stress)\(^57, 58\). In this regard, capturing a broad and representative image of sleep stage distributions among elite athletes will further add to an understanding of their recovery status and help to identify potential areas of improvement.

In sum, this thesis sought to add to the current understanding of sleep in elite athletes by (1) providing subjective (questionnaire and diary) sleep estimates, (2) using a refined actigraphy sensitivity threshold, and (3) assessing sleep stage distributions (Aim 1).

**Aim 2: Identifying sleep jeopardizing factors**

Alarmed by the relatively poor sleep estimates and potential insufficient recovery measures among athletes, various ‘sleep thieves’ have been identified. Factors such as jet lag\(^14\), psychological and physiological pre-sleep arousal\(^15, 52, 63\), training and competition schedules\(^15, 46, 50, 51\) have been held accountable for compromised sleep quantity and quality in athletes. Adequate sleep hygiene has repeatedly been suggested as a remedy for poor sleep quality\(^44\). In order to provide more specified sleep hygiene guidelines for athletes, a detailed quantification of athletes’ daytime behaviors and environmental conditions is warranted as well as providing information on how sleep hygiene is associated with sleep among athletes (Aim 2).

Another factor that comes to mind when evaluating potentially sleep disturbing and facilitating factors in elite athletes, is training load. Athletes follow intense training programs that are designed to stimulate psychophysiological adaptation,

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Another factor that comes to mind when evaluating potentially sleep disturbing and facilitating factors in elite athletes, is training load. Athletes follow intense training programs that are designed to stimulate psychophysiological adaptation,
so that performance capacity can be enhanced. However, the relation between exercise and sleep appears to be reciprocal. One the one hand, exercise can improve sleep quality, as reflected in shorter sleep onset latencies, fewer occurrences of wake after sleep onset, longer sleep durations, fewer sleep stage changes, and more regular REM to non-REM transitions. On the other hand, there is evidence suggesting that prolonged periods of extreme exercise intensity may worsen sleep quantity and quality, as is reflected in increased wakefulness and decreased proportions of REM sleep. While sleep may thus be deteriorated under extreme training regimes, the current thesis sought to extend this knowledge by assessing how day-to-day variations in self-reported training load during habitual training periods are reflected in actigraphy-based sleep estimates and one-channel EEG-based sleep staging (Aim 2).

**Aim 3: Establishing the effects of sleep on athletic performance**
Similar to cognitive performance, athletic performance is believed to deteriorate following (partial) sleep deprivation and to improve following sleep extension. However, most of the studies to date employed non-elite populations and featured small samples sizes. In addition, the magnitude of sleep restriction employed in previous studies appears to be larger (e.g., ± 4 hours) than the amount of sleep loss or gain that is routinely encountered by elite athletes. Therefore, a study is conducted to investigate the extent to which rather mild, naturally occurring day-to-day variations in sleep are reflected in cognitive and sport-specific performances among a large cohort of elite athletes from individual and team sports (Aim 3).

**Aim 4: Optimizing sleep**
Lastly, while there is good reason to believe that optimized sleep may greatly benefit recovery, overall health and well-being, and performance capacity in athletes, the number of interventions tested among a healthy population such as elite athletes, is limited. Thus far, the few studies aiming at sleep optimization in athletes concern interventions focusing on nutrition, selective sleep hygiene practises, brain-wave entrainment, or sleep extension. In this light, a last aim of this thesis (Aim 4) was to develop and test evidence-based sleep optimization strategies in athletes that specifically target potential sleep deficiencies and that focus on sleep disruptive components that we identified.
### Table 1.1. Overview of research aims and chapters.

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<td>4. Optimizing sleep in elite athletes. Interventions are desired that aim at improving the identified sleep deficiencies (results of Aim 1), and that focus on the sleep disruptive components that were previously identified (results of Aim 2).</td>
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### Outline of this thesis

In line with the above, Table 1.1 depicts an overview of the research aims of this thesis and the chapters in which they are addressed.

The first two research aims, that is characterizing sleep of elite athletes (Aim 1), and identifying sleep jeopardizing factors (Aim 2), are addressed in Chapters 2 and 3. More specifically, Chapter 2 provides insight into self-reported sleep quantity, sleep quality and sleep hygiene practices and their underlying association among a large cohort of 98 Dutch elite athletes. Sleep quantity, quality and sleep hygiene were assessed once covering a 1-month period by using established (sub)clinical questionnaires, and repeatedly during seven consecutive days of training using morning and evening diaries. Associations between sleep hygiene practices and various sleep estimates were calculated. In Chapter 3, insight into sleep among elite athletes is extended by assessing actigraphy-based sleep estimates, and for the first time, by providing information on EEG-based sleep stage distributions. In order to assess whether variations in training load are reflected in sleep, self-reported training load and sleep estimates were assessed continuously during seven days of training.
habitual training. The effects of training load on sleep have been calculated using linear mixed-effects models.

The third aim of this thesis was to shed light on the effects of mild (day-to-day) variation in sleep on performance. Therefore, Chapter 4 presents unprecedented information on the effects of actigraphy-based sleep estimates and EEG-based sleep stage durations on cognitive (psychomotor) and athletic performance. As part of the same data collection reported in Chapters 2 and 3, performance of 98 elite athletes was assessed on three nonconsecutive occasions and included tests of psychomotor performance (10-minute psychomotor vigilance task) and sport-specific tests of fine (e.g., accuracy) and gross motor skills (e.g., endurance, power). By employing linear mixed-effects models, the effect of day-to-day variation in actigraphy-based sleep estimates and sleep stage duration (light, deep, REM) on performance were assessed, while taking into account the nested structure of the data (i.e., repeated measurements within individuals).

The fourth and final aim of this thesis was to optimize sleep in athletes. Based on the analyses of elite athletes sleep and potential sleep-disturbing factors reported in Chapters 2 and 3, Chapter 5a, provides an evidence-based sleep hygiene protocol for elite athletes (including a sleep hygiene monitoring smartphone application), and presents the results of two intervention pilot studies (Chapters 5b and 5c). Chapter 5b provides insight in the effectiveness of distal skin warming on sleep onset latency. In Chapter 5c, the effect of evening restriction of short-wavelength light (blue-light) on various subjective and objective sleep estimates is presented. Next, based on these pilot studies, Chapter 6 presents an intervention study in which the combined effect of bright morning light exposure and evening light restriction on sleep estimates was investigated among 26 recreational athletes. The study had a within-subject cross-over design and sleep was monitored for three continuous weeks using sleep diaries and wrist-worn actigraphy.

Finally, in Chapter 7, a summary and general discussion of the empirical findings regarding sleep and performance in (elite) athletes, alongside a discussion concerning the effectiveness of light-dark regulation in optimizing sleep among recreational athletes, is provided. The chapter ends with future research prospects, practical implications, and a general conclusion.
CHAPTER 2

SELF-REPORTED SLEEP QUANTITY, QUALITY AND SLEEP HYGIENE IN ELITE ATHLETES

Published as:
ABSTRACT — Sleep is essential for recovery and performance in elite athletes. While actigraphy-based studies revealed suboptimal sleep in athletes, information on their subjective experience of sleep is scarce. Relatively unexplored is also the extent to which athletes’ sleep is adversely affected by environmental conditions and daytime behaviors, that is sleep hygiene. This study aimed to provide insight in sleep quantity, quality and its putative association with sleep hygiene.

Participants were 98 elite (youth) athletes competing at the highest (inter-)national level. Sleep quantity, quality and sleep hygiene were assessed once covering a 1-month period by using established (sub) clinical questionnaires, and repeatedly during 7 consecutive days. Sleep quality was generally healthy, although 41% of all athletes could be classified as “poor sleeper”, and 12% were identified as having a sleep disorder. Daily self-monitoring revealed sleep durations of 8:11 ± 0:45 hours, but elevated wake after sleep onset of 13 ± 18 minutes. Sleep quality, feeling refreshed, and morning vigor were moderate at best. Regarding sleep hygiene, general measures revealed irregular sleep-wake patterns, psychological strain and activating pre-sleep behaviors. At the daily level, blue-light exposure and late-evening consumption of heavy meals were frequently reported. General sleep hygiene revealed significant associations with sleep quality \((.45 < r > .50; p's < .001)\).

Results indicate that there is ample room for optimization, specifically in onset latency and in wake after sleep onset. Subtle improvements in sleep seem possible and optimizing sleep hygiene, such as regular sleep-wake patterns and reducing psychological strain, may facilitate this sleep upgrading process.
INTRODUCTION

Sleep is crucial for recovery and performance capacity in elite athletes. This implies that suboptimal sleep can hamper the ability to reach full athletic potential. Assessing sleep quantity, sleep quality and identifying potential threats to adequate sleep in elite athletes is important in order to identify potential areas for sleep optimization.

Actigraphy-based sleep estimates indeed reveal suboptimal sleep in athletes, expressed in relatively high sleep fragmentation, low sleep efficiency and consequently low sleep durations. However, the extent to which athletes also experience their sleep as suboptimal remains unclear. This may be important since the need for sleep varies between individuals: some may complain about poor sleep quality although objective markers indicate sufficient sleep quality, while others report good sleep quality despite objective markers of poor sleep. Hence, assessing subjective sleep quantity and quality is a valuable extension to the current actigraphy-based sleep estimates. Insight in subjective markers of sleep sheds light on sleep need and recovery status in elite athletes, and importantly, it highlights areas for sleep optimization.

In order to optimize elite athletes’ sleep, it has been suggested to improve their sleep hygiene. Sleep hygiene encompasses all conditions and practices that promote continuous and effective sleep, including regularity of bed- and rise times, restriction of alcohol and caffeine beverages, regular exercise, nutrition, and environmental factors that enhance restful sleep. Evidence suggests that anxiety, noise, the need to use the bathroom, and unfavorable competition times disrupt sleep in athletes. Unsurprisingly, adherence to sleep hygiene is especially challenging in athletes due to factors as inter-meridian travel, unfavorable training schedules and late competition times. Therefore, it is important to have a complete picture of elite athletes’ sleep hygiene practices and to which extent specific daytime behaviors and environmental conditions are related to sleep. Apart from few studies which have investigated the prevalence and impact of selected sleep hygiene factors such as blue-light exposure and pre-competitive anxiety, such information is currently lacking.

Working towards future interventions, the present study aimed first, to shed light on subjective sleep quantity and sleep quality in elite athletes; second, to identify...
their sleep hygiene practices; and third, to investigate associations between sleep hygiene, sleep quantity and sleep quality. Thereby, this study aims to identify areas for sleep optimization in athletes. To provide a robust answer for these aims, a large group of elite athletes was recruited and their subjective sleep quantity and quality, as well as their current sleep hygiene practices were assessed. All measures were obtained by using (sub)clinical questionnaires providing insight in general sleep and sleep hygiene behaviors, as well as day-to-day measurements over a representative 7-day self-monitoring period, providing insight in daily-monitored sleep and sleep hygiene behaviors. Associations between general and daily-monitored measures were calculated to indicate converging or diverging evidence. It was hypothesized that subjective measures of sleep quantity and quality resemble sleep insufficiencies based on actigraphy (e.g., 25). Because sleep hygiene generally concerns “conditions and practices that promote continuous and effective sleep” (p. 34726), associations between sleep hygiene, sleep quantity and quality, both at the general and daily-monitored level, were expected. Results of the present study are expected to aid the development of interventions that directly target sleep and to identify critical sleep hygiene aspects that can be integrated into sleep hygiene protocols for athletes.

**METHODS**

**Participants**

Participants were recruited through the Netherlands Olympic Committee * Netherlands Sport Federation (NOC*NSF) or through the coaches of the national associations. Participants were 98 Dutch elite (youth) athletes aged 18.9 ± 3.2 years (range 15-32), including 56 females, who were all part of the national (youth) selection team in their respective sports and competed on the highest national and international (youth) level. Athletes competed either in individual sports (n = 38; Road Cycling, n = 26, Triathlon n = 8, Mountain Bike n = 4), or team sports (n = 60; Handball n = 13, Volleyball n = 30, Soccer n = 17). Participants had an average Body Mass Index (BMI) of 21.2 ± 0.2, had practiced their sport for an average of 10.0 ± 0.4 years, and spent on average 19.3 ± 0.5 hours per week on training and competition. The study was approved by the faculty’s ethical committee and all participants or responsible parents or caregivers signed informed consent.
Measures and Procedure
With respect to the current study, data collection consisted of two parts: a) general sleep measurements, and b) daily-monitored sleep measures. General sleep was assessed once using an online survey which consisted of well validated questionnaires on sleep quality, sleep disturbances, and sleep hygiene. Subsequently, these sleep parameters were also assessed for 10 consecutive days using pen-and-paper based diaries. This was done just before sleep and upon awakening. Athletes slept in their habitual or training environment and the self-monitoring period was free from competition with the exception of exhibition matches. Road cyclists and footballers were assessed during a training-camp abroad, with inter-meridian travel for the female cyclists only (n = 9). In the latter case, the ten-day self-monitoring period started after an adaptation period of 3 days.

Sleep Quantity and Quality
General Measures. General sleep quantity and quality were measured with the Pittsburgh Sleep Quality Index (PSQI(69)) and the Holland Sleep Disorder Questionnaire (HSDQ(70)). The PSQI is a 19-item self-report questionnaire assessing sleep quantity and quality over a 1-month period. Seven component scores were assessed: (1) subjective sleep quality, (2) sleep latency, (3) sleep duration, (4) habitual sleep efficiency, (5) sleep disturbances, (6) use of sleep medication, and (7) daytime dysfunctioning. Answer scores ranged from 0-3 (“not during the past month” – “three or more times a week”), which were assessed for each component and combined into a Global Sleep Quality Score ranging from 0-21. A global score ≥ 5 was taken as indicator of poor sleep quality(2). Treating each of the component scores as items, a Cronbach’s α of .45 was observed in the current sample, which reflects the heterogeneous nature of the different components.

The HSDQ consists of 32-items, which were used to screen for six potential sleep disorders: (1) insomnia, (2) parasomnia, (3) circadian rhythm sleep disorder (CRSD), (4) hypersomnia, (5) restless legs/periodic limb movement disorder (RSL/PLMD), and (6) sleep related breathing disorder (SBD). Each item was rated on a 5-point Likert scale with averaged sum scores ranging from 1-5 (“not at all applicable” – “applicable”). A higher score indicate more serious sleep complaints. In addition to the subscale-cutoff scores displayed in Table 2.1, a clinical cutoff of

Measures and Procedure
With respect to the current study, data collection consisted of two parts: a) general sleep measurements, and b) daily-monitored sleep measures. General sleep was assessed once using an online survey which consisted of well validated questionnaires on sleep quality, sleep disturbances, and sleep hygiene. Subsequently, these sleep parameters were also assessed for 10 consecutive days using pen-and-paper based diaries. This was done just before sleep and upon awakening. Athletes slept in their habitual or training environment and the self-monitoring period was free from competition with the exception of exhibition matches. Road cyclists and footballers were assessed during a training-camp abroad, with inter-meridian travel for the female cyclists only (n = 9). In the latter case, the ten-day self-monitoring period started after an adaptation period of 3 days.

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2.02 was used as an indication of a self-reported sleep disorder based on the entire questionnaire. Cronbach's $\alpha$ was .85 in the current sample.

**Daily-Monitored Measures.** Daily-monitored sleep quantity was assessed using the following aspects of the morning section of the Expanded Consensus Sleep Diary (CSD-E\(^7\)). The CSD-E assesses bedtime (hh:mm), lights-off time (hh:mm), sleep onset latency (min), frequency of wake after sleep onset (#), wake after sleep onset (min), rise time (hh:mm), total sleep time (hh:mm), as well as quality and refreshment of sleep, with scores ranging from 1-10, and 10 indicating high sleep quality/refreshment. Daily monitored sleep quality was assessed using the Groningen Sleep Quality Scale (GSQS\(^7\)). The GSQS assessed sleep quality on a 14-item scale. Scores range from 0-14, with scores between 0-2 indicating normal, refreshing sleep, and scores $\geq$ 6 indicating disturbed sleep\(^7\). Cronbach's $\alpha$ for the current sample was .82.

The Global Vigor and Affect Scale (GVA\(^7\)) was used to assess vigor and affect just before going to sleep and upon awakening. The subscale Vigor was based on four items concerning alertness, sleepiness, motivation loss (effort) and weariness. The subscale Affect was based on four items concerning happiness, sadness, calmness and tension. Scores were calculated using an established algorithm and range from 0 to 100\(^7\). Additionally, one question concerning the perceived level of fitness was added. Higher GVA scores indicate higher arousal/alertness/fitness and greater positive affect. Cronbach's alpha's for global Vigor and global Affect, were $\alpha = .90$ and $\alpha = .71$ for the morning measurements, and $\alpha = .85$ and $\alpha = .75$ for the evening measurements.

The Karolinska Sleepiness Scale (KSS)\(^7\) was used to assess alertness/sleepiness upon awakening and before sleep. A 9-point verbally anchored scale ranging from 1-9 ("extremely alert" - "extremely sleepy" - "fighting sleep") was used. Higher scores indicate higher sleepiness.

**Sleep Hygiene**

**General Measures.** General sleep hygiene was measured with the Sleep Hygiene Index (SHI\(^7\)). The SHI consists of 13 items, covering the occurrence of inappropriate sleep behavior and is based on criteria set forth in the International Classification of Sleep Disorders\(^46\). Each item is rated on a 5-point Likert scale ("never" - "always").
Item scores were summed to a total score ranging from 13-65, with higher sum scores indicating poorer sleep hygiene. Cronbach’s α was .61 in the present sample. For analysis purpose, the 13 SHI items were grouped into six broader categories adopted from Storfer-Isser et al. (2013), including: regularity (item #2, #3, #5); environment (item #10, #11); psychological strain (item #8, #13); active behavior (item #4, #7, #9, #12); naps (item #1) and substances (item #6). For each category, item scores were averaged.

Daily-Monitored Measures. Daily-monitored sleep hygiene (10 items) was assessed by the evening section of the CSD-E (CSD-E71). This section asked for daytime naps (length and timing), alcoholic and caffeinated consumptions (amount, sort and timing), and sleep medication. In addition, items on sleep location, bed-/room partner, nutrient intake 2-3 hours before bedtime, activities within one hour before bedtime, and bedtime routine were added to match SHI subcategories. Daily-monitored sleep hygiene practices were dummy coded (yes/no) for each day, summed and averaged by the number of monitoring days, resulting in a score between 0 and 100. This score expressed the percentage of nights that individuals engaged in certain sleep hygiene behaviors.

Data Processing
General sleep quantity, sleep quality and sleep hygiene measures were processed as described in the original validation papers. Total scores for the PSQI could not be calculated for two participants, due to missing values on one or more items.

Daily-monitored sleep quantity, sleep quality and sleep hygiene measures were also processed as described in the original validation papers. In the self-monitoring study, the first three days of the 10-day self-monitoring period served as habituation time and were excluded from further analysis. Data of the remaining 7 days were averaged1. Because morning- and evening measures of vigor, affect and sleepiness (KSS) were highly correlated (r’s ranging between .48 and 1.00), only morning measures are reported. One participant was excluded because of invalid diary entries.
Statistical Analysis
To assess elite athletes’ subjective sleep quantity and quality, descriptive statistics were performed for both general and daily-monitored measures of sleep. All measures were compared to cutoff values obtained from the original validation papers or other meaningful reference values. Pearson correlation coefficients were calculated to investigate associations between general and daily-monitored sleep.

To assess sleep hygiene behaviors in elite athletes, descriptive statistics were performed for general and daily-monitored sleep hygiene. Again, to investigate associations between general and daily-monitored sleep hygiene, Pearson correlation coefficients were calculated.

Finally, to investigate associations between sleep hygiene and sleep quantity and sleep quality, Pearson correlation coefficients were calculated. All analyses were performed using SPSS (version 22). Significance levels were set at $\alpha = .05$.

RESULTS
Sleep Quantity and Quality
General Sleep. Table 2.1 provides an overview of general sleep quality, sleep disturbances and the number of athletes scoring above clinical cutoff values. Based on the PSQI, 58 out of 98 athletes reported “healthy sleep quality”, while 40 athletes (41%) were classified as “poor sleepers” (cutoff ≥ 5) (Table 2.1). These 40 “poor sleepers” scored rather close to the cut-off values indicating that their sleep was suboptimal but not too worrisome. With regard to the HSDQ, 12 athletes (12%) scored above the clinical cutoff ($\geq 2.02$), indicating the potential presence of one or more sleep disorders. Sixteen athletes (16%) scored above the clinical cutoff on one or more of the HSDQ subscales. The HSDQ subscale “restless leg syndrome/periodic limb movement disorder” was most prevalent, with six athletes (6%) scoring above cutoff. Nine athletes (9%) scored above the cutoff of both PSQI and HSDQ.

Daily-Monitored Sleep. Table 2.1 also provides an overview of daily-monitored sleep quantity, sleep quality and morning state measures. On average, athletes reported a total sleep time of 8.11 ± 0.44 hours, a sleep onset latency of 20.17 ± 13.70 minutes.
and a number of 1.19 ± 0.90 awakenings after sleep onset. Wake after sleep onset was 12.56 ± 19.19 minutes with large standard deviations, thus indicating large individual differences.

Table 2.1. Mean, standard deviation, cutoff values and scale properties for all sleep quality and quantity measures. Daily-monitored values reflect averages over the 7-day monitoring period.

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th># Athletes</th>
<th>≥ [cutoff]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demographics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>18.72 (3.02)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>56</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>General Sleep Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSQI total (0-21)</td>
<td>4.61 (2.04)</td>
<td>40 [5]</td>
<td></td>
</tr>
<tr>
<td>HSDQ total (0-5)</td>
<td>1.64 (0.35)</td>
<td>12 [2.02]</td>
<td></td>
</tr>
<tr>
<td><strong>Daily-monitored Sleep Measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sleep Quantity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bed Time (hh:min)</td>
<td>23:11 (0:47)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wakeup Time (hh:min)</td>
<td>7:57 (0:37)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Sleep Time (hh:min)</td>
<td>8:11 (0:44)</td>
<td>6 [≤ 7]</td>
<td></td>
</tr>
<tr>
<td>Sleep Onset Latency (min)</td>
<td>20.17 (13.70)</td>
<td>18 [≥ 30]</td>
<td></td>
</tr>
<tr>
<td>Awakenings (#)</td>
<td>1.19 (0.90)</td>
<td>4 [≥ 3]</td>
<td></td>
</tr>
<tr>
<td>Wake After Sleep Onset (min)</td>
<td>12.56 (19.19)</td>
<td>18 [≥ 20]</td>
<td></td>
</tr>
<tr>
<td><strong>Sleep Quality &amp; Morning State</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GSQS (0-14)</td>
<td>2.93 (1.68)</td>
<td>47 [≥ 3]</td>
<td></td>
</tr>
<tr>
<td>Quality (1-10)</td>
<td>6.84 (0.92)</td>
<td>16 [≥ 6]</td>
<td></td>
</tr>
<tr>
<td>Refreshed (1-10)</td>
<td>6.13 (1.12)</td>
<td>39 [≥ 6]</td>
<td></td>
</tr>
<tr>
<td>Vigor AM (0-100)</td>
<td>53.70 (13.98)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Affect AM (0-100)</td>
<td>67.98 (13.65)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KSS AM (1-9)</td>
<td>4.79 (1.30)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. PSQI = Pittsburgh Sleep Quality Index; HSDQ, Holland Sleep Disorder Questionnaire; CRSD = Circadian Rhythm Sleep Disorder; RLS / PLMD = Restless Leg Syndrome/Periodic Limb Movement Disorder; SBD = Sleep Related Breathing Disorder.
Self-reported sleep quality was on average 6.84 ± 0.92 (1-10 scale). More specifically, athletes experienced a weekly average of 2.93 ± 1.68 sleep disturbances per night (GSQS) and reported an average score of 6.13 ± 1.12 on feeling refreshed, 4.79 ± 1.30 on sleepiness (KSS; scale 1-9), 53.70 ± 13.98 on vigor (GVA; scale 0-100), and 67.98 ± 13.65 (GVA; scale 0-100) on affect in the morning.

Associations between General and Daily-Monitored Sleep. As displayed in Table 2.3, half (i.e., 4 out of 8) of the general sleep measures were significantly associated with daily-monitored sleep quantity measures, with moderate effect sizes (.26 < r > .48). All general sleep measures were significantly associated with almost all daily-monitored sleep quality measures, with moderate effect sizes (.24 < r > .45).

Sleep Hygiene

General Sleep Hygiene. Table 2.2 provides overall and subscale scores for the SHI. Athletes’ sleep hygiene scores ranged between “rarely” and “sometimes” (i.e., 30.94 ± 5.21). Grouping items into different categories revealed that “regularity”, “psychological strain” and “active behavior” contributed the most to the overall SHI score (Table 2.2).

Daily-Monitored Sleep Hygiene. Table 2.2 also displays the percentage of nights that athletes were engaged in specific sleep hygiene practices. To facilitate interpretation, these practices are reported based on the same grouping that was used for the general sleep hygiene. “Substances” were regularly consumed before bedtime (meal 26%; caffeine 22%), with an exception for alcohol (2%) and sleep medication (3%). Athletes indicated “active behavior” within one hour before bedtime in 2% of the nights, and “naps” were taken on 18% of the monitored days. A bedtime routine was followed in 25% of the nights. In 70% of the monitored nights, athletes engaged in sedentary (blue-light emitting) activities within the last hour before bedtime.

Associations between General and Daily-Monitored Sleep Hygiene. As displayed in Table 2.3, general sleep hygiene was poorly associated with daily-monitored sleep hygiene. None of the 10 associations reached significance and effect sizes were low (.04 < r > .18).
### Table 2.2. Mean, standard deviation, cutoff values and scale properties for all sleep hygiene measures. Daily-monitored values reflect average occurrence of sleep hygiene behaviors (% of nights) during the 7-day monitoring period.

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th># Athletes ≥ [cutoff]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 98</td>
<td>M (SD)</td>
</tr>
<tr>
<td><strong>General Sleep Hygiene</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHI total (13-65)</td>
<td>30.94 (5.21)</td>
<td>0 [ 4]</td>
</tr>
<tr>
<td>Regularity (1-5)</td>
<td>2.59 (0.67)</td>
<td>3 [ 4]</td>
</tr>
<tr>
<td>Environment (1-5)</td>
<td>1.71 (0.79)</td>
<td>1 [ 4]</td>
</tr>
<tr>
<td>Psychological Strain (1-5)</td>
<td>2.75 (0.78)</td>
<td>6 [ 4]</td>
</tr>
<tr>
<td>Active Behavior (1-5)</td>
<td>2.67 (0.60)</td>
<td>0 [ 4]</td>
</tr>
<tr>
<td>Naps (1-5)</td>
<td>1.77 (0.78)</td>
<td>1 [ 4]</td>
</tr>
<tr>
<td>Substances (1-5)</td>
<td>1.91 (1.00)</td>
<td>9 [ 4]</td>
</tr>
<tr>
<td><strong>Daily-monitored Sleep Hygiene</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy Meal (%)</td>
<td>26 (33)</td>
<td>10 [ 80]</td>
</tr>
<tr>
<td>Caffeine After 6 PM (%)</td>
<td>22 (28)</td>
<td>7 [ 80]</td>
</tr>
<tr>
<td>Alcohol After 8 PM (%)</td>
<td>2 (6)</td>
<td>0 [ 80]</td>
</tr>
<tr>
<td>Sleep Medication (%)</td>
<td>3 (1.3)</td>
<td>1 [ 80]</td>
</tr>
<tr>
<td>Bed partner/ Roommate (%)</td>
<td>49 (46)</td>
<td>40 [ 80]</td>
</tr>
<tr>
<td>Bedtime Routine (%)</td>
<td>25 (38)</td>
<td>16 [ 80]</td>
</tr>
<tr>
<td>Nap (%)</td>
<td>18 (20)</td>
<td>1 [ 80]</td>
</tr>
<tr>
<td>Intense Activity (%)</td>
<td>2 (11)</td>
<td>1 [ 80]</td>
</tr>
<tr>
<td>Blue Light (%)</td>
<td>70 (29)</td>
<td>51 [ 80]</td>
</tr>
</tbody>
</table>

Note: SHI = Sleep Hygiene Index. Melatonin was the only sleep aid encountered.

### Associations between Sleep Hygiene, Sleep Quantity and Sleep Quality

**Associations between General Sleep Hygiene and Sleep Quality and Disturbances.**

Moderate correlations were observed between SHI and PSQI, with $r(94) = .45$, $p < .001$, and high correlations between SHI and HSDQ, with $r(96) = .50$, $p < .001$ (Cohen, 1992), thereby confirming an association between general sleep hygiene and general sleep quality (Table 2.3).

**Associations between Sleep Hygiene, Sleep Quantity and Sleep Quality**

Moderate correlations were observed between SHI and PSQI, with $r(94) = .45$, $p < .001$, and high correlations between SHI and HSDQ, with $r(96) = .50$, $p < .001$ (Cohen, 1992), thereby confirming an association between general sleep hygiene and general sleep quality (Table 2.3).
Associations between Daily-Monitored Sleep Hygiene and Sleep Quantity and Quality.
Daily-monitored sleep hygiene was associated with sleep quantity in 8 out of 40 possible cases, with correlations ranging between .20 < \( r \) < .36 (Table 2.3). Consuming a heavy meal within the last three hours before bedtime was associated with longer sleep durations and more frequent wake after sleep onset. The use of sleep medication was associated with longer sleep onset latencies and higher frequencies of wake after sleep onset. Having a bed-/room partner was associated with longer sleep duration. The presence of a bedtime routine was associated with higher frequencies and longer durations of wake after sleep onset. Contrary to expectations, exposure to blue-light was associated with shorter sleep onset latency. No significant correlations were observed for caffeine, alcohol, napping, and intense physical activity before bedtime.

In addition to its associations with sleep quantity, daily-monitored sleep hygiene was associated with sleep quality in 4 out of 60 possible cases, with significant correlations ranging between .21 < \( r \) < .28. Sleep medication was related to higher sleepiness (KSS); having a bed-/room partner was related to more positive affect in the morning; and having a bedtime routine was related to poorer sleep quality (GSQS). Intense activity during the last hour before bedtime was related to lower morning vigor. No significant correlations were observed for meal, caffeine and alcohol consumptions, naps, and sedentary activities in which blue-light was emitted.

In summary, significant correlations between sleep hygiene, sleep quantity and sleep quality were indicated at the general level as well as at the daily-monitored level. It is remarkable, however, that associations were medium to large at the general level but only incidental and weak at the daily monitored level.
### Table 2.3. Pearson correlations between general and daily-monitored sleep quantity, sleep quality and sleep hygiene ($n = 97$).

<table>
<thead>
<tr>
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### Table 2.3. Pearson correlations between general and daily-monitored sleep quantity, sleep quality and sleep hygiene ($n = 97$).

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pearson correlations between general and daily-monitored sleep quantity, sleep quality and sleep hygiene ($n = 97$).
DISCUSSION

The present study had three research aims. First, to shed light on subjective sleep quantity and sleep quality of elite athletes; second, to identify their sleep hygiene practices; and third, to establish associations between sleep hygiene, sleep quantity and sleep quality. All measures were first assessed once to retrospectively capture typical behavior over a 1-month period (“general sleep measures”) and, subsequently, were also monitored on a day-to-day basis to indicate more specific behavior during a representative period of training (“daily-self-monitoring”).

Subjective Sleep Quantity and Quality

Based on the PSQI, analyses of general sleep quantity and quality revealed that the sleep of elite athletes is generally of appropriate quality, although a substantial minority of 41% athletes must be regarded as “poor sleepers”. Although there is empirical discussion about which PSQI cutoff scores best reflect sleep problems in elite athletes\textsuperscript{2, 78}, performance margins are small and every gain that may result from optimized sleep, particularly in poor sleepers but perhaps also in moderate sleepers, could be crucial\textsuperscript{79}. That sleep of elite athletes indeed deserves improvement is further emphasized by scores on the HSDQ, which indicate that 12% of athletes could be identified as having a potential sleep disorder. More specifically, a small but notable number of athletes was identified with “restless leg symptom” (RLS/PLMD). The current prevalence of potential sleep disorders compares to the general population and is in accordance with previous findings among athletes\textsuperscript{80, 81}, thereby highlighting the need for sleep monitoring and potentially treatment of sleep disorders in elite athletes.

Daily-monitored sleep quantity and sleep quality largely resembled the results obtained at the general level. Average sleep duration was eight hours and thereby longer than the recommended seven hours\textsuperscript{12}. Nevertheless, self-reported sleep onset latencies and wake after sleep onset were slightly elevated and indicate room for improvement. In interpreting these data, it is important to note that while subjective ratings are considered reliable instruments for sleep-wake estimation\textsuperscript{82}, they often diverge from objective (e.g., actigraphy-based) values due to an overestimation of sleep onset latency and an underestimation of nocturnal awakenings in subjective reports\textsuperscript{83, 84}. Although wake after sleep onset was found to be longer than the recommended seven hours\textsuperscript{12}, thereby highlighting the need for sleep monitoring and potentially treatment of sleep disorders in elite athletes.

DISCUSSION

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to be elevated more distinctively in previous actigraphy-based studies, our results are in line with existing literature\textsuperscript{25, 26} and provide further indication that the sleep of many athletes may indeed be suboptimal.

Moving beyond sleep quantity, analyses of daily monitored sleep quality revealed that with the given amount of sleep, athletes felt only moderately refreshed, alert and vigorous in the morning. While in our study, these measures were explicitly taken to reflect sleepiness and sleep quality, it is important to note that, given the activity level of elite athletes, feelings of (physical) fatigue may be considered fairly normal. Nevertheless, knowing that subjective experiences of sleepiness can influence motivation and daytime functioning\textsuperscript{85}, these results underline the importance of understanding how these experiences are brought about and how they may be improved. In this respect, strong associations between wake after sleep onset and most sleep quality variables (Table 2.3; see also\textsuperscript{55}) suggest that besides increasing overall sleep duration\textsuperscript{86}, targeting augmented wake after sleep onset, may prove to be critical.

**Elite Athletes Sleep Hygiene Practices**

General sleep hygiene was acceptable, however, regularity in sleep-wake patterns, psychological strain and activating pre-sleep behavior are subcategories that could deserve some improvements (Table 2.2).

Daily-monitored sleep hygiene appeared to be adequate, with only few suboptimal behaviors. Notable exceptions include frequent engagement in sedentary activities that involve artificial light exposure (i.e., 70% of nights; Table 2.2). Although the current study indicates an association in the opposite direction (see below), blue-light, as emitted by screens, could delay sleep onset\textsuperscript{87}. Other behaviors that may interfere with sleep were frequent late-evening consumptions of heavy meats and caffeinated beverages\textsuperscript{86}. Finally, and in line with Lastella, Roach, Halson, and Sargent\textsuperscript{26}, daytime naps were taken relatively infrequently (i.e., 18% of days). Whilst ensuring that naps do not interfere with nighttime sleep, athletes may thus be encouraged to increase their napping behavior with the potential benefit to improve daytime recovery and performance\textsuperscript{88}.

In comparing general and daily-monitored sleep hygiene, no significant associations were observed. Although daily-monitored items largely resembled the items included in the SHI, it is important to note that the SHI asks for broad
categories of behavior, while daily-monitored items asked for specific behaviors. As such, both types of measures should be regarded as complementary rather than being identical. This approach offers a broader insight in elite athletes’ sleep hygiene.

In conclusion, the present study indicated adequate overall sleep hygiene behavior in elite athletes, while certain daytime behaviors such as irregular bedtimes, psychological strain, pre-sleep activities and taking late-evening consumptions, can be improved. Consequently, it is suggested here to critically assess the possibility to adjust training times, to reduce evening activities and to introduce stress-reduction strategies to further optimizing sleep hygiene and facilitate sleep.

Associations between Sleep Hygiene, Sleep Quantity and Sleep Quality

General measures showed a moderate to strong association between poor sleep hygiene and poor sleep quality, thereby confirming findings with non-athletes. Daily-monitored sleep hygiene was also associated with sleep quantity and sleep quality, but to a lesser extent and with smaller effect sizes. Some associations were in line with expectations (e.g., active pre-sleep behavior was associated with reduced morning vigor), while others were less straightforward. For instance, the present study showed a shortening of sleep onset latency to be associated with sedentary behavior that encompasses blue-light exposure, while it has been reported that blue-light, as emitted by screens, could delay sleep onset (cf. 87). Potentially, the negative effect of the blue-light exposure on sleep was outweighed by the arousal reducing nature of the accompanying activity (e.g., watching a movie, engaging in social media). Another unexpected finding concerns the negative relation between bedtime routine and the duration and frequency of wake after sleep onset. A potential explanation for this may be that athletes with sleep problems tend to engage in bedtime routines, while undisturbed sleepers do not. In general, associations between sleep hygiene, sleep quantity and sleep quality – both at the general and daily-measured level – indicate that specific daytime behaviors and environmental circumstances may bear relevance for sleep. Although the correlational design used in this study prevents conclusions regarding causality, practical strategies such as regularity in sleep-wake patterns, and practices that target sleep more directly, such as relaxation strategies in the categories of behavior, while daily-monitored items asked for specific behaviors. As such, both types of measures should be regarded as complementary rather than being identical. This approach offers a broader insight in elite athletes’ sleep hygiene.

In conclusion, the present study indicated adequate overall sleep hygiene behavior in elite athletes, while certain daytime behaviors such as irregular bedtimes, psychological strain, pre-sleep activities and taking late-evening consumptions, can be improved. Consequently, it is suggested here to critically assess the possibility to adjust training times, to reduce evening activities and to introduce stress-reduction strategies to further optimizing sleep hygiene and facilitate sleep.

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evening are suggested to facilitate sleep in athletes. Future research is required to test actual implications of such strategies.

CONCLUSION

The current study provided a detailed overview of self-reported sleep quantity, sleep quality and sleep hygiene practices in a large cohort of elite athletes. Although on average sleep quality appeared to be appropriate, a substantial minority of athletes could be classified as poor sleeper and morning states were moderate at best. These results imply substantial room for improvement. Sleep hygiene appeared to be adequate overall, but adjustments with respect to specific behaviors, such as in reducing irregularity in sleep-wake patterns, decreasing high psychological strain and avoiding activating behaviors in evening hours may prove fruitful. Based on associations between sleep hygiene, sleep quantity and sleep quality it is suggested that improvement in critical sleep hygiene practices (such as regular sleep-wake patterns and reducing psychological strain) may help to further optimize sleep in elite athletes.
ABSTRACT — Sleep is essential for recovery and performance in elite athletes. While it is generally assumed that exercise benefits sleep, high training load may jeopardize sleep and hence limit adequate recovery. To examine this, the current study assessed objective sleep quantity and sleep stage distributions in elite athletes and calculated their association with perceived training load.

Perceived training load, actigraphy and one-channel EEG recordings were collected among 98 elite athletes during 7 consecutive days of regular training.

Actigraphy revealed total sleep durations of 7.50 ± 1.08 hours, sleep onset latencies of 13 ± 15 minutes, wake after sleep onset of 33 ± 17 minutes and sleep efficiencies of 88 ± 5%. Distribution of sleep stages indicated 51 ± 9% light sleep, 21 ± 8% deep sleep, and 27 ± 7% REM sleep. On average, perceived training load was 5.40 ± 2.50 (scale 1-10), showing large daily variability. Mixed-effects models revealed no alteration in sleep quantity or sleep stage distributions as a function of day-to-day variation in preceding training load (all p's > .05).

Results indicate healthy sleep durations, but elevated wake after sleep onset, suggesting a potential need for sleep optimization. Large proportions of deep sleep potentially reflect an elevated recovery need. With sleep quantity and sleep stage distributions remaining unresponsive to variations in perceived training load, it is questionable whether athletes’ current sleep provides sufficient recovery after strenuous exercise.
INTRODUCTION

Athletes consider sleep as being essential for their health, recovery and performance. Despite its perceived importance, elite athletes appear to sleep worse compared to gender and age matched, non-exercising controls, which is reflected in shorter sleep duration, elevated wake after sleep onset and lower sleep efficiency. Despite the importance of sleep, systematic research on sleep-wake behaviour in elite athletes is still scarce and much can be gained by improving methodological approaches. Commonly, representative sleep quantity estimates are based on default actigraphy settings, whereas for athletes – higher sensitivity to sleep settings have recently been shown to reflect better agreement with polysomnography (PSG). In this respect, replicating previous studies among elite athletes while using a higher sensitivity to sleep threshold can further contribute to accuracy and validity of sleep-wake estimates.

Besides sleep quantity, a healthy distribution of sleep stages is considered crucial for psychological and physiological functioning. Sleep stage distribution is modified by physical exercise, as sleep adjusts to the body’s daily need for recovery, but may also be negatively affected by suboptimal sleep-wake behavior (e.g., sleep restriction, fragmentation, overtraining, and (anticipatory) stress). In general, it is assumed that exercise benefits sleep, as is expressed in shorter sleep onset latencies, fewer occurrences of wake after sleep onset, longer sleep durations, fewer sleep stage changes and more regular REM to non-REM transitions. In particular, and in line with the restoration hypothesis of sleep, proportions of deep sleep tend to be higher in active versus non-active individuals and have been shown to increase following a day of strenuous exercise. At the same time, however, there is evidence suggesting that in specific cases, athletes’ training demands may also jeopardize sleep (for a comprehensive review see ). For example, prolonged periods of extreme exercise intensity may worsen sleep quantity and quality, as is reflected in increased wakefulness and decreased proportions of REM sleep.

Despite its relevance for recovery and performance in elite athletes, a representative field-based indication of sleep stage distributions in elite athletes (e.g., proportions of light sleep, deep sleep, REM sleep) is currently not available. Furthermore, no studies have examined the extent to which naturally occurring
day-to-day variation in training load is indeed associated with (mal)adaptive changes in sleep. To address these issues, the current study aimed to target the following research questions. First, what is the objective sleep quantity and how sleep stages are distributed; and second, are sleep quantity and sleep stage distributions associated with (day-to-day variation in) preceding perceived training load? To provide a robust answer to these questions, a mixed-method approach was employed in which actigraphy-based sleep quantity, EEG-based sleep staging, and perceived training load were monitored in a large cohort of elite athletes during seven consecutive days of regular training. With respect to objective sleep quantity and sleep stage distributions, it was expected to replicate previously reported sleep insufficiencies (i.e., elevated wake after sleep onset, and relatively low sleep efficiency) and – given the activity profile of the sample – to observe relatively high proportions of deep sleep. With regard to associations between sleep quantity and sleep stage distributions and day-to-day variation in training load, it was expected that proportions of deep sleep would increase following days with moderate to high training load, but that sleep onset latencies and wake after sleep onset would increase when training load would be more extreme.

**METHODS**

Participants were recruited via the Netherlands Olympic Committee* Netherlands Sport Federation (NOC*NSF) or via the head coaches of the respective sports federations. A total number of 98 elite athletes (56 female; 42 male), competing at the highest national and international (youth or senior) level, participated in the study. Athletes were aged 18.8 ± 3.0 years (range 15-31), had an average Body Mass Index of 21.3 ± 1.6, had practiced their sport on average for 10.0 ± 3.5 years, and spent on average 19.3 ± 5.1 hours per week on training and competition. Athletes competed in different individual and team sports (Road Cycling n = 26, Triathlon n = 8, Mountain Bike n = 4; Handball n = 13, Volleyball n = 30, Soccer n = 17). Ethical approval was obtained from the faculty’s ethical committee [ECSW2013-1612-170] and all participants or responsible guardians signed informed consent.

Data were collected as part of a larger project assessing subjective sleep quantity, quality, and sleep hygiene practices among Dutch elite athletes. In the current project, sleep quantity, sleep stage distributions and perceived training load were monitored in a large cohort of elite athletes during seven consecutive days of regular training. With respect to objective sleep quantity and sleep stage distributions, it was expected to replicate previously reported sleep insufficiencies (i.e., elevated wake after sleep onset, and relatively low sleep efficiency) and – given the activity profile of the sample – to observe relatively high proportions of deep sleep. With regard to associations between sleep quantity and sleep stage distributions and day-to-day variation in training load, it was expected that proportions of deep sleep would increase following days with moderate to high training load, but that sleep onset latencies and wake after sleep onset would increase when training load would be more extreme.

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Sleep stages were recorded by means of a wireless, self-logging headband sensor (Wireless System, WS; Zeo Inc., Newton, USA). The wireless system (WS) has been validated for sleep registration in healthy adults and performs an automatic classification of sleep stages based on recordings of a single bi-polar channel, which is located at the forehead (EEG position approximately at Fp1-Fpz) and integrated into an elastic headband. Based on analysis of 30-second epochs the WS distinguishes between episodes of wakefulness, light sleep (comparable to stage 1 and 2), deep sleep (comparable to stage 3 and 4) and Rapid Eye Movement (REM) sleep. As reported by Shambroom, Fabregas, and Johnstone, agreement between WS and PSG is 98.5% for scoring sleep / wakefulness and 83.6% for sleep stage classification. In the current study, WS recordings were used to calculate both absolute (h:min) and relative (% of TST) proportions of light sleep, deep sleep, and REM sleep. The WS was attached before lights-off and removed following lights-on.
To acquire a coherent measure of training load that would capture self-perceived load across an entire day (including one or more training sessions), self-perceived training load was measured every evening, using a single-item question: “How high was today’s training load?” All athletes were familiar with this, or very similar questions. In accordance with the Dutch grading system, a 10-point rating scale (i.e., 1 = ‘very low training load’; 10 = ‘very high training load’) was employed.

Data was processed as follows: Actigraphy data were analysed using Respironics Actiware 5 (Philips Respironics, Murrysville, USA). Data were visually inspected and excluded when activity counts and light values indicated detachment of the sensor. In all other cases, rest intervals were manually set when (i) event markers identified bed- and rise time, or – in case event markers were missing – when (ii) light and activity was absent. If light and activity values were ambiguous, (iii) WS data and diary entries were used to set rest intervals. The default setting (10-minutes immobility parameter) was used to identify sleep onset and sleep offset. Following Sargent, Lastella, Halson, and Roach, episodes of sleep / wakefulness were identified using a high sleep-wake threshold (i.e., AW > 80; epochs are scored as wake if activity counts are above 80). TIB, TST and fragmentation were derived from the “rest” interval. SOL, WASO and SE were derived from “sleep” interval.

Sleep stages were automatically classified by the WS. Consecutively, data were processed as follows: First, to determine lights-off and lights-on times, actigraphy and diary entries were taken as a reference. Second, in order to match TIB values with actigraphy and diary reports, missing epochs were manually added at the beginning and end of a night and classified as “undefined” when necessary. Third, nights with more than 15% “undefined” epochs were excluded from further analysis, which was the case for 31.5% of all possible recordings (e.g., losing the headband, equipment malfunctioning). Little’s MCAR test revealed that data was missing at random ($\chi^2(193) = 226.225, p = .051$), indicating that available data (i.e., 68.5% of all possible recordings) may be taken as representative. Fourth, sleep onset was operationalized as the first of three consecutive epochs of “light sleep”. Compared to PSG, the WS overestimates REM at the cost of “wake”. Therefore, all “undefined” or “REM” epochs that preceded sleep onset were manually scored as “wake”. Finally, based on the normative range of REM sleep latency (49.5-278.5 min) provided by Mitterling, Högl, Schoenwald, et al., “REM” epochs within the first 30 minutes of the night and without succeeding “deep sleep” were also manually scored as “wake”.

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To assess objective sleep quantity and sleep stage distributions, descriptive statistics were performed on actigraphy (sleep quantity) and WS (sleep stage distributions) data. To investigate how day-to-day variation in preceding training load affects objectively measured sleep quantity and sleep stage distributions, linear mixed-effect models were employed. Linear mixed-effect models are an extension to linear regression, that take the nested structure of the data into account (i.e., repeated measurements within participants). We used the lmer function of the lme4 package (version 1.1-1) in R (R Core Team, 2015). All dependent measures (TST, SOL, WASO and SE – obtained from actigraphy; % Light, % Deep, and % REM – obtained from the WS) were analysed in separate models. Each model included a fixed intercept and fixed effects for gender (with contrast set as 1 for male and -1 for female), age, a lag variable for the dependent (sleep-)variable in question as covariates, and training load. To dissociate changes in sleep stage distribution from possible changes in sleep quantity, the statistical models for sleep stage distribution only included the relative (i.e., %) proportions of light sleep, deep sleep and REM sleep. Variables were scaled before entering the model. Following Barr, Levy, Scheepers, et al., a maximal random-effects structure was used, by including a per-participant random intercept, as well as per-participant random slope for training load and the lag variable. For convergence reasons, we excluded all possible random correlation terms among the random effects. P-values were determined using the function ‘mixed’ from the package, using type 3 tests and the parametric bootstrap method (with 1000 simulations), which in turn calls the function PBmodcomp from the package pbkrtest (version 0.4.6). Confidence intervals were calculated using parametric bootstrapping as implemented in lme4’s bootMer function, with 10000 simulations and deriving 95% confidence intervals using the function boot.ci of the package boot (version 1.3.17).

RESULTS

Table 3.1 provides an overview of actigraphy-based sleep quantity measures over the 7-day monitoring period (means and standard deviations). On average, athletes lay in bed for 8:32 ± 01:10 (M ± SD) hours and had a total sleep time of 7:50 ± 01:08 (M ± SD) hours. Sleep onset latency was 13.92 ± 15.69 (M ± SD) minutes. Wake after sleep onset was 33.03 ± 17.00 (M ± SD) minutes, and was distributed over 33.44 ±
11.07 (M ± SD) nocturnal awakenings. Sleep efficiency was 88.47 ± 5.46% (M ± SD). In addition, Table 3.1 displays the percentage of nights on which athletes slept less than 6 hours (5.25%), on which it took them longer than 30 minutes to fall asleep (14.24%), on which their wake after sleep onset was longer than 60 minutes (7.35%) and on which their sleep efficiency was below 85% (22.35%).

For reason of comparison, the same analysis was run with sleep estimates derived from the default actigraphy settings (i.e., AW > 40 instead of AW > 80)\textsuperscript{55}. This analysis revealed the same general picture but – primarily due to an increase in wake after sleep onset – caused the incidence of poor sleep among athletes to become more pronounced (i.e., 10.94% of nights with TST ≤ 6hrs; 14.24% of nights with sleep onset latency ≥ 30 minutes; 42.28% of nights with wake after sleep onset ≥ 60 minutes; and 52.47% of nights with SE ≤ 85%).

Table 3.1. Descriptive statistics for all sleep quantity and sleep stage distribution measures.

<table>
<thead>
<tr>
<th>Sleep Quantity (Actigraphy)</th>
<th>M (SD)</th>
<th>% of nights scored ≥ (cutoff)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in Bed (h:min)</td>
<td>8:32 (01:10)</td>
<td></td>
</tr>
<tr>
<td>Total Sleep Time (h:min)</td>
<td>7:50 (01:08)</td>
<td>5.25 (≤ 6hrs)</td>
</tr>
<tr>
<td>Sleep Onset Latency (min)</td>
<td>13.92 (15.69)</td>
<td>14.24 (≥ 30 min)</td>
</tr>
<tr>
<td>Wake After Sleep Onset (min)</td>
<td>33.03 (17.00)</td>
<td>7.35 (≥ 60 min)</td>
</tr>
<tr>
<td>Fragmentation (%)</td>
<td>33.44 (11.07)</td>
<td>-</td>
</tr>
<tr>
<td>Sleep Efficiency (%)</td>
<td>88.47 (5.46)</td>
<td>22.34 (≤ 85%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sleep Stage Distribution (WS)</th>
<th>M (SD)</th>
<th>% of nights scored ≥ (cutoff)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light (h:min)</td>
<td>4:02 (0:52)</td>
<td></td>
</tr>
<tr>
<td>Deep (h:min)</td>
<td>1:36 (0:32)</td>
<td></td>
</tr>
<tr>
<td>REM (h:min)</td>
<td>2:10 (0:46)</td>
<td></td>
</tr>
<tr>
<td>Light (%)</td>
<td>51.36 (8.54)</td>
<td></td>
</tr>
<tr>
<td>Deep (%)</td>
<td>20.99 (7.73)</td>
<td></td>
</tr>
<tr>
<td>REM (%)</td>
<td>27.36 (7.39)</td>
<td></td>
</tr>
</tbody>
</table>

Note. WS = wireless system

Table 3.1 also provides an overview of absolute (minutes) and relative (percentages) sleep stage distributions over the 7-day monitoring period. Averaged
distribution of sleep stages reflected $4.02 \pm 0.52$ h:min (51.36 ± 8.54%) light sleep, $1.36 \pm 0.32$ h:min (20.99 ± 7.73%) deep sleep, and $2.10 \pm 0.46$ h:min (27.36 ± 7.39%) REM sleep.

Table 3.2 and 3.3 show an overview of the results of the mixed-effects model analyses that tested the impact of day-to-day variation in perceived training load on sleep quantity and sleep stage distribution, respectively. In both Tables, statistical outcomes (i.e., small point estimates [6], confidence intervals [CI] and $p$-values; see Methods) concerning the impact of training load are reported in the fifth row (labelled: “Training load”). Outcomes regarding the control variables (i.e., gender, age, and a lag variable of the dependent variable in question; see Methods) are reported in the first three rows.

On average, training load was experienced as moderate, with large between-subject variability (range = 9; 5.40 ± 2.50 M ± SD; scale 1-10) and within-subject variability (mean range of 5.65 ± 1.96). Despite the fact that available data thus covered a wide range of low, moderate and high levels of perceived training load, linear mixed-effects modelling showed that day-to-day variation in training load had no significant effect on sleep quantity (Table 3.2). That is, variation in perceived training load was not significantly associated with time in bed ($B = -0.90$ (2.96), $p = .78$), total sleep time ($B = 0.83$ (2.86), $p = .75$), sleep onset latency ($B = -1.00$ (0.69), $p = .15$), wake after sleep onset ($B = -0.79$ (0.06), $p = .15$), or sleep efficiency ($B = 0.30$ (0.21), $p = .15$). In addition, mixed-effects modelling also showed that day-to-day variation in training load had no significant effect on sleep stage distribution (Table 3.3). As such, day-to-day variation in training load was not significantly associated with light sleep ($B = 0.23$ (0.37), $p = .56$), REM sleep ($B = -0.23$ (0.44), $p = .62$), or deep sleep ($B = -0.10$ (0.37), $p = .66$). Confirming the robustness of the results, the confidence intervals displayed in Table 3.2 and 3.3 are narrow, indicating good model precision. Furthermore, regression lines are flat and, in line with the non-significant $p$-values, small point estimates ($B$, comparable to $\hat{\beta}$ values in regression) suggest small effect sizes.

To further indicate the robustness of the findings, post-hoc analyses using the more conservative default actigraphy settings (i.e., AW > 40) were run. Again, none of the analyses reached significance (all $p$’s > .13), thereby confirming that day-to-day variation in perceived training load was not significantly associated with (changes in) sleep quantity and the distribution of sleep stages.
Table 3.2. Mixed-effects models testing the effect of training load on sleep quantity.

<table>
<thead>
<tr>
<th>Time in Bed</th>
<th>Total Sleep Time</th>
<th>Sleep Onset Latency</th>
<th>Wake After Sleep Onset</th>
<th>Sleep Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>CI</td>
<td>p</td>
<td>B</td>
<td>CI</td>
</tr>
<tr>
<td>Fixed Effects</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intercept)</td>
<td>514.64</td>
<td>[505.30, 524.10]</td>
<td>471.68</td>
<td>[463.00, 480.40]</td>
</tr>
<tr>
<td>Gender</td>
<td>-13.12</td>
<td>[-22.55, -3.69]</td>
<td>-15.34</td>
<td>[-24.10, -6.57]</td>
</tr>
<tr>
<td>Age</td>
<td>9.72</td>
<td>[0.68, 18.82]</td>
<td>8.06</td>
<td>[-0.22, 16.36]</td>
</tr>
<tr>
<td>Lag variable</td>
<td>1.32</td>
<td>[-5.35, 8.05]</td>
<td>3.85</td>
<td>[-2.47, 10.28]</td>
</tr>
<tr>
<td>Training load</td>
<td>-0.90</td>
<td>[-6.75, 4.95]</td>
<td>0.83</td>
<td>[-4.73, 6.37]</td>
</tr>
<tr>
<td>Random Parts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ngrp</td>
<td>96</td>
<td>96</td>
<td>96</td>
<td>96</td>
</tr>
<tr>
<td>Observations</td>
<td>495</td>
<td>495</td>
<td>495</td>
<td>495</td>
</tr>
</tbody>
</table>
Table 3.3. Mixed-effects models testing the effect of training load on sleep stage distributions.

<table>
<thead>
<tr>
<th>Light sleep %</th>
<th>Deep sleep %</th>
<th>REM sleep %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Effects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Intercept)</td>
<td>52.05</td>
<td>[51.08, 53.00]</td>
</tr>
<tr>
<td>Gender</td>
<td>0.34</td>
<td>[-0.62, 1.28]</td>
</tr>
<tr>
<td>Age</td>
<td>1.25</td>
<td>[0.35, 2.13]</td>
</tr>
<tr>
<td>Lag variable</td>
<td>3.76</td>
<td>[2.67, 4.86]</td>
</tr>
<tr>
<td>Training load</td>
<td>0.23</td>
<td>[-0.51, 0.97]</td>
</tr>
</tbody>
</table>

Random Parts

N grp | 80 | 80 | 80
Observations | 309 | 309 | 309

DISCUSSION

The present study aimed to shed light on objective sleep quantity and sleep stage distributions in elite athletes and how these sleep measures are associated with day-to-day variation in preceding training load. All measures were assessed during seven consecutive days of regular training.

With regard to sleep quantity, the current study revealed an average sleep duration of almost eight hours. Likely due to the use of more liberal actigraphy settings (i.e., AW > 80) athletes’ sleep quantity thus turned out to be slightly more favourable than observed in previous reports. Nevertheless, the picture of restless sleep in athletes persists, as was for instance reflected in elevated values for wake after sleep onset. Also, the average sleep efficiency of 88% appears to be relatively low when compared to reference values for the current age group (i.e., 92%). More specifically, on 22% of the nights, sleep efficiency was below 85%.
which is considered the upper limit for poor sleep\textsuperscript{55}. Post-hoc analysis using the default actigraphy settings (i.e., \( AW > 40 \); as in\textsuperscript{25, 26}) revealed a similar picture, but led to a higher estimation of wake after sleep onset and – consequently – a higher percentages of nights (i.e., 53\%) on with sleep efficiency was below 85\%. All in all, these data indicate that while elite athletes sleep almost eight hours per night, their sleep is fragmented, thereby pointing towards a clear need for sleep optimization strategies.

Assessment of sleep stage distributions indicated that REM sleep and light sleep remained within healthy ranges\textsuperscript{5, 94}. Yet, in line with the activity level of the current sample (i.e., elite athletes), deep sleep was at the higher end of the optimum (21\%)\textsuperscript{56}, thereby suggesting an elevated need for recovery.

Contradicting expectations, sleep quantity and sleep stage distributions were not associated with day-to-day variation in perceived training load. That is, high training load was not associated with longer sleep onset latencies and wake after sleep onset (e.g., \textsuperscript{49}) and did not lead to increases in the proportion of deep sleep\textsuperscript{10, 56}. Re-running theses analyses with data obtained from the default actigraphy settings (i.e., \( AW > 40 \); as in\textsuperscript{25, 26}) did not lead to different conclusions. The absence of an adverse sleep quantity effect may be explained by an underrepresentation of extremely high values of training load (e.g., perceived training load \( \geq 9 \)). Furthermore, the fact that in all cases, training sessions were finalized at least 3 hours before bedtime may have limited potential sleep-disturbing effects of elevated core body temperature\textsuperscript{25}, high (physiological) arousal\textsuperscript{56}, or increased metabolism\textsuperscript{96}. The absence of an association between training load and the proportion of deep sleep is perhaps more surprising. Deep sleep is known to adapt to the body’s daily need for recovery and the proportion of deep sleep has been shown to increase following strenuous exercise\textsuperscript{15} and to decrease following a sedentary day\textsuperscript{29}. Potentially, the high mean value for deep sleep (21\%) that we observed in the current sample indicates a ceiling effect, which would explain why the proportion of deep sleep could not increase any further with increases in training load. In this case, it is also plausible that subtle adaptations to training load were not manifested in the macro structure of sleep, but appeared in the micro structure of sleep (slow-wave activity)\textsuperscript{39}. To make such adaptation visible, future research should employ measures that capture more fine-grained cortical activity (slow-wave activity, sleep spindles) as well as the temporal distribution of sleep stages\textsuperscript{96}. Alternatively, and

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given that the current study was performed in a field setting, it is also plausible that sleep hygiene aspects such as circadian timing of activity and sleep^97, (sun-) light exposure, lifestyle practises, daily hassles, but also physiological aspects such as fitness had a profound impact on athletes’ sleep and confounded a potential impact of training load on the proportion of deep sleep^98. If general sleep hygiene factors indeed intervene with the natural adaptation of sleep to increased or decreased recovery need^10, 39, 99, optimizing conditions and practices that promote continuous and effective sleep in elite athletes, is strongly recommended (e.g.^26, 89).

Finally, a number of important limitations need to be considered. Measuring elite athletes’ perceived training load, sleep quantity and sleep stage distributions in a field setting provides a representative image of actual sleep-wake behaviour, but – at the same time – comes at the cost of small losses in measurement sensitivity. For example, in the current study, field measurements of sleep stage distributions were based on a one-channel EEG device instead of multichannel EEG or PSG, which are preferred in lab settings. For the current device, agreement with PSG has been reported to be 98.5% and 83.6% for scoring sleep / wakefulness and sleep stage classification, respectively (also see Methods^99). As such, while some caution is warranted in comparing absolute values to (lab-based) PSG estimates, we believe that the current study does give representative (and unprecedented) insight in general sleep stage distributions in elite athletes in the field. Furthermore, given the consistency of the measurement bias, results with regard to the association between perceived training load and sleep stage distributions should not be affected. Another methodological issue that should be mentioned concerns our measurement of perceived training load. While 1-item measures of daily load have high face-validity, show fair correlations with objective indicators of training load (e.g., heart rate^100), and have successfully been correlated with sleep in previous studies^101, distinguishing between intensity, duration and frequency and timing of training sessions would arguably give more precise results. In this respect, future research should assess the robustness of the current results by utilizing more precise and potentially also objective measures of training load.

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CONCLUSION

In conclusion, the current study provides a detailed overview of objective sleep quantity, sleep stage distributions and their association with perceived training load in a large cohort of elite athletes. While athletes appear to sleep an average of almost eight hours per night, their sleep is fragmented, thereby suggesting a potential need for sleep optimization. Furthermore, observed proportions of deep sleep suggest a high need for recovery. With respect to training load, the current study found no evidence for adaptations in sleep quantity and sleep stage distribution following day-to-day variation in perceived training load. On the one hand, this suggests that sleep is not jeopardized by high training load. On the other hand, the fact that increases in training load are not accompanied by noticeable increases in the proportion of deep sleep (i.e., restoration hypothesis of sleep) suggests that elite athletes may recover insufficiently. Optimizing the conditions and practices that promote continuous and effective sleep (i.e., sleep hygiene) may help to maintain naturally adaptive responses of sleep to fluctuations in physical activity, and thus facilitate adequate recovery.
CHAPTER 4

EFFECTS OF DAY-TO-DAY VARIATION IN SLEEP ON ELITE ATHLETES’ PSYCHOMOTOR VIGILANCE AND SPORT-SPECIFIC MEASURES OF PERFORMANCE

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ABSTRACT — Performance capacity in athletes depends on the ability to recover from past exercise. While evidence suggests that athletic performance decreases following (partial) sleep deprivation and increases following sleep extension, it is unclear to which extent day-to-day variation in sleep impacts performance.

Sleep quantity and sleep stages were assessed among 98 elite athletes on three non-consecutive nights, along with performance tests that were taken on standardized times each following morning. Performance assessment included psychomotor performance (10-minute psychomotor vigilance task) and sport-specific tests of fine (e.g., accuracy) and gross motor skills (e.g., endurance, power). Mixed-effects models were employed to assess the effect of sleep quantity (total sleep time (TST), sleep onset latency (SOL), wake after sleep onset, sleep efficiency) and sleep stage duration (light, deep, REM) on performance.

Average TST was 7:30 ± 1:05 hours, with a mean day-to-day variation of 57 minutes (mean within-person ∆ TST). Longer TSTs were associated with faster reaction times on the psychomotor vigilance task ($p = .04$). Analyses of sport-specific performance indicated small and inconsistent effects of sleep quantity (TST, SOL) and sleep staging (light sleep) on gross motor performance, and no effects on fine motor skill performance.

Results indicate that day-to-day variation in sleep quantity impacts psychomotor performance to a greater extent than athletic performance. The fact that effects were small and limited in number may be explained by day-to-day variation in sleep being typically small as well. It is suggested that one night of compromised sleep may not be immediately problematic, but that more extreme sleep loss or accumulated sleep debt may prove to have more severe consequences.

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INTRODUCTION

The importance of sleep for athletic performance and recovery is widely acknowledged\(^\text{102}\). Despite this importance, however, it appears that particularly elite athletes are facing compromised sleep quantity and quality\(^\text{25}\). Studies on partial and total sleep deprivation have highlighted the adverse effects of sleep loss on athletic performance\(^\text{3}\), while other studies show that sleep extension may actually benefit performance\(^\text{23}\). Yet, the minimal magnitude of sleep deprivation or extension required to impact athletic performance is unknown. Routinely, extreme changes in sleep duration (± 4 hours) are fairly rare among elite athletes. Minor variations, however, are more frequently encountered. For example, literature indicates that unfavourable training schedules\(^\text{45}\), competition times\(^\text{50}\), and (inter-meridian) travel\(^\text{103}\), may all cause small, but significant reductions in sleep quantity, especially when compared to sleep on rest days\(^\text{45}\). Against this background, the current study aimed to assess the extent to which such mild (day-to-day) variations in sleep are reflected in the performance of elite athletes.

![](image)

Regarding athletic performance, a classical distinction is often made between ‘fine motor skills’ and ‘gross motor skills’\(^\text{3, 22}\). Fine motor skills are skills that incorporate intricate, precise movements, which use small muscle groups and involve high levels of hand-eye coordination (e.g., golf putting). In contrast, gross motor skills are skills that incorporate less precise, whole-body movement, which use large muscle groups and involve lower levels of hand-eye coordination (e.g., jumping, running, cycling)\(^\text{22}\). As such, an important aspect that distinguishes fine motor skills and gross motor skills is the extent to which they rely on cognitive functions to accurately coordinate the movement. Given the well-documented effect of sleep on cognitive functioning (e.g., reduced behavioral alertness and more cognitive errors after sleep loss)\(^\text{17, 104}\), it is often proposed that fine motor skills are more strongly affected by sleep loss than gross motor skills\(^\text{3}\). Yet, empirical research is scarce, findings remain equivocal, and the effect of sleep on athletic performance is still poorly understood\(^\text{3}\). To produce more insight in this matter, the current study tested the impact of sleep on elite athletes’ psychomotor performance as well as their performance on sport-specific fine and gross motor skills.

Furthermore, while most studies have focused on implications of reduced sleep duration (i.e., sleeping fewer hours), to our knowledge, no studies have investigated...
how day-to-day variations in sleep staging (e.g., differences in the proportion of light, deep or REM sleep) may affect athletic performance. Still, specific recovery functions associated with different sleep stages make it likely that (day-to-day) variation in the absolute time spent in a certain sleep stage might influence performance. For example, deep sleep (also referred to as Slow Wave Sleep or S3/S4, or N3) has been associated with the release of growth hormone and, hence, is believed to contribute specifically to muscle restoration and physiological recovery. With regard to psychomotor performance, studies indicate that sheer reductions in sleep quantity rather than variations in the time spent in a certain deep sleep stage (e.g., more time spent in deep sleep) are responsible for observed effects (e.g., 105, 106). With regard to athletic performance, however, such information is currently lacking. Therefore, in assessing the impact of sleep on psychomotor and athletic performance, the current study assessed effects of (changes in) sleep quantity as well as sleep staging (i.e., absolute time spent in light sleep, deep sleep, and REM sleep).

In view of the considerations above, the aim of the current study was to investigate the effect of natural, day-to-day variations in sleep quantity and the absolute time spent in different sleep stages on (sport-specific) performance in elite athletes. In particular, effects of sleep were assessed on a general measure of, i) psychomotor performance, and sport-specific measures of, ii) fine motor skill performance, and iii) gross motor skill performance. To provide a robust answer, objective measures of sleep and performance were taken on three non-consecutive occasions on uniform times among a large cohort of elite athletes (i.e., within-subject, repeated measures design). The overarching hypothesis was that variations in sleep (i.e., increase or decrease in sleep from one day to the next) would impact psychomotor performance more strongly than sport-specific performance and that fine motor skill performance would be more impacted than gross motor skill performance. We had no a priori expectation with regard to which distinct sleep characteristic (i.e., sleep quantity or sleep staging) would impact performance most.
**METHODS**

**Participants**

Athletes were recruited via the Netherlands Olympic Committee*Netherlands Sport Federation (NOC*NSF) or via the head coaches of the respective Dutch sport associations. In total 98 elite athletes (56 female) participated. All participants were part of the national (youth) selection in their respective sport and competed at the highest national and international (youth) level. Athletes were aged 18.8 ± 3.0 (range 15-32) years, had an average Body Mass Index of 21.3 ± 1.6, had practiced their sport on average for 10 ± 3.5 years, and spent on average 19.3 ± 5.1 hours per week on training and competition. Athletes competed in different individual and team sports (Table 4.1). Athletes were screened for overall sleep quality (PSQI[89], 4.61 ± 2.04, M ± SD) and subjective sleep complaints (HSDQ[90]: 1.64 ± 0.35, M ± SD). A detailed sleep history can be found elsewhere[89]. No athletes were excluded based on their sleep history. Ethical approval was obtained from the faculty’s ethical committee and all participants or responsible guardians signed informed consent [ECSW2013-1612-170].

**Measures and Procedures**

As part of a larger project assessing sleep among Dutch elite athletes, sleep was assessed for seven consecutive nights. Within this period, measures of (sport-specific) performance were taken on three occasions, typically scheduled 48 hours apart (i.e., on day 1, 4, and 7)[4]. Before starting the initial study protocol, athletes underwent three nights of habituation to sleep-wake assessment and one performance test practice session, to become familiar with the performance tests and to get used to the sleep monitoring. All athletes slept at home or in a (training) environment that was highly familiar to them and sleep-wake schedules were habitual (self-chosen). In all cases, the monitoring period was free from competition, with the exception of exhibition matches. Handball and volleyball players, triathletes and mountain bikers were monitored during a training period at their home-base. Road cyclists and soccer players were monitored during one of their annual training camps abroad. The female cyclists (n = 9) crossed six time-zones in a west-ward inter-meridian travel. For those athletes, data collection started after 6 days to allow for circadian adaptation to the new time-zone.
Sleep quantity and sleep stages were assessed by means of wrist-actigraphy and one-channel EEG sensors, respectively. In addition, a sleep diary (Expanded Consensus Sleep Diary) was kept to facilitate analysis of the actigraphy data and to monitor background variables related to the athletes’ sleep hygiene (data reported elsewhere). Performance assessment included tests of (1) psychomotor performance, (2) fine motor performance and (3) gross motor performance. Psychomotor performance was assessed by means of a standardized 10-minute psychomotor vigilance task PVT. In consultation with the athletes’ coaches, fine and gross motor skill performance were assessed sport-specifically (Table 4.1). To allow for comparison across sports, test outcomes for fine and gross motor skill performance were transformed into norm scores (see ‘Data Processing’). In case of multiple performance tests, the test sequence was standardized. All performance measures were taken in the morning on uniform time points, following a standardized (sport-specific) warm-up. Performance tests were conducted between 6 AM and 10 AM, depending on sport and team, but at standardized times within individuals.

**Sleep Quantity**

Sleep quantity was assessed by means of an actigraph that was continuously worn around the non-dominant wrist and only detached during training or when being in contact with water (Actiwatch 2, Philips Respironics, Murrysville, USA). Motion was sampled at 32Hz, averaged and stored in 60 second bins. Parameters of interest were total sleep time (TST; h:min), sleep onset latency (SOL; min), wake after sleep onset (WASO; min), and sleep efficiency (SE; %).

**Sleep Stages**

Sleep stages were recorded by means of a wireless, self-logging headband sensor (Wireless System, WS; Zeo Inc., Newton, USA). WS was validated for sleep registration in healthy adults and performs automatic classification of sleep stages based on recordings of a single bi-polar channel, which was located at the forehead (EEG position approximately at Fp1-Fp2 with a ground at Fpz) and integrated into an elastic headband. Based on analysis of 30-second epochs the WS distinguishes between episodes of wakefulness, light sleep (comparable to S1/S2 or N1/N2), deep sleep (comparable to S3/S4 or N3) and Rapid Eye Movement (REM) sleep. 

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As reported by Shambroom, Fabregas, and Johnstone\(^9\), agreement between WS and Polysomnography (PSG) is 98.5% for scoring sleep / wakefulness and 83.6% for sleep stage classification. WS was attached just before lights-off and removed following lights-on. Parameters of interest were absolute time (h:min) spent in light sleep, deep sleep, and REM sleep.

**Performance Assessment**

Apart from assessing effects of sleep on psychomotor performance, the aim of the current study was to arrive at a broad but yet representative indication of the effects of sleep on fine and gross motor skill performance across different sports. For this reason, performance outcomes on sport-specific performance tests were standardized and pooled to reflect separate scores for fine and gross motor skill performance (see ‘Data Processing’).

**Psychomotor Performance.** Psychomotor performance was assessed by means of a custom made 10-minute PVT\(^{107}\). Using a standardized computer setup, participants were instructed to press a button as fast as possible upon appearance of a red target stimulus on an otherwise black screen. Stimulus appearance was randomized with inter-stimulus intervals ranging between 2 and 10 seconds. Reaction time delay (ms) was indicated by a scrolling counter and served as immediate feedback upon response. Reaction times below the anticipation criterion of ≤ 100 ms were excluded from further analysis. Reactions without a stimulus were considered as false alarms (errors of commission) and a lapse was operationalized as a reaction time ≥ 500 ms. The following outcome metrics were included: (a) mean reaction time, and (b) error rate (sum from the number of false alarms and the number of lapses)\(^{108}\). The PVT was usually assessed before the physical performance tests, except for handball- and volleyball players, who executed multiple performance tests. To arrive at a time efficient assessment protocol, those individual received a predefined testing sequence, that was standardized within individuals, but varied between individuals.

**Fine Motor Skill Performance.** Fine motor skills were operationalized as skills that incorporate intricate, precise movements, which use small muscle groups and generally involve high levels of hand-eye coordination\(^{22}\). Assessment of fine motor
Skills was sport-specific and, depending on the sport, comprised shooting accuracy, dribbling or a technical skills-track. A detailed description of all fine motor skill performance tests is provided in Appendix “Supplementary Material: Chapter 4”. Handball players and volleyball players performed a shooting accuracy test (e.g., 23, 109). In this test, participants had to throw (handball) or smash (volleyball) the ball in the direction of a target that was located in the top corners of the goal or in the outside corners of the back zone, respectively. Scores ranged from 1-4, depending on whether the balls hit the target closest to the side line (4; volleyball only), hit the target (3), hit the target border (2), or missed the target (1). The average score over 10 trials (5 aims towards the right side of the goal / court and 5 aims towards the left side of the goal / court) was taken as outcome measure. Soccer players performed a dribble test in which they had to dribble the ball as rapidly as possible through a slalom course that consisted of six cones set 1.5 m apart for a total of 10.5 m from start to finish (e.g., 110). The average time (in seconds) over two trials was taken as outcome measure. Similarly, mountain bikers performed a standardized technical skills-track, which they had to complete as fast as possible (e.g., 111). The average time (in seconds) over three trials was taken as outcome measure. In all time-dependent measures, speed was assessed using timing gates (Smart Speed, Fusion Sport, Queensland, Australia). Finally, given the nature of their sport (and in consultation with the coaches), road cyclists (n = 26) and triathletes (n = 8) did not perform a test of fine motor skill performance.

Gross Motor Skill Performance. Gross motor skills were operationalized as skills that involve large muscle movements, which are not very precise and include many fundamental movement skills (e.g., jumping, running, cycling)22. Assessment of gross motor skills was sport-specific and, depending on the sport, comprised vertical jumps, maximal sprints, or a constant power test. A detailed description of all gross motor skill performance tests is provided in Appendix “Supplementary Material: Chapter 4”. Handball- and volleyball players performed a vertical jump test in which they executed three trials of the counter movement jump (CMJ) and spike jump (SJ)112. The highest relative jump height (i.e., jump height minus standing reach height) was used as outcome measure. Jumps were conducted using a Vertec (Yardstick, Swift Performance Equipment, Lismore, Australia). In addition to the vertical jump test, handball players also performed a maximal 20-meter
sprint test (e.g., 113). The average time (in seconds) over two trials was taken as performance outcome. Road cyclists, mountain bikers and triathletes performed a constant power test (e.g., 114). The road cyclists and mountain bikers performed the constant power test by cycling for 10 minutes at a fixed (individualized) power of 4 watt/kg. Triathletes performed the constant power test by swimming over a 200-meter extent at constant (individually set) velocity. Lower heart rates indicate more efficient cycling / swimming and, thus, better performance. In all cases, average heart rate (bpm) over the entire test was taken as performance outcome. Finally, in consultation with the coaches, soccer players (n = 17) did not perform a test of gross motor skill performance.

**Data Processing**

Sleep and performance data were processed as described below. 

*Sleep Quantity:* Actigraphy data was analysed using Respironics Actiware 5 (Philips Respironics, Murrysville, USA), following the guidelines by the Society of Behavioural Sleep Medicine (SBSM) as delineated by Ancoli-Israel, Martin, Blackwell, et al. 115. Data was visually inspected and excluded when activity counts and light values indicated detachment of the sensor. In all other cases, rest intervals were manually set when (i) event markers identified bed- and rise time, or – in case of missing event markers – when (ii) light and activity was absent. If light and activity values were ambiguous, (iii) WS data and diary entries were used to set rest intervals.

The default setting (10-minutes immobility parameter) was used to identify sleep onset and sleep offset. Following Sargent, Lastella, Halson, and Roach15, episodes of sleep / wakefulness were identified using a high sleep-wake threshold (i.e., AW > 80; epochs are scored as wake if activity counts were above 80). TST was derived from the interval type “rest”. SOL, WASO and SE were derived from the interval type “sleep”.

*Sleep Stages:* Sleep stages were automatically classified by the WS. Consecutively, data was processed as follows: First, to determine lights-off and lights-on times, actigraphy and diary entries were taken as a reference. Second, in order to match time in bed (TIB) values with actigraphy and diary reports, missing epochs were manually added at the beginning and end of a night and classified as “undefined” when necessary. Third, nights with more than 15% “undefined” epochs were
excluded from further analysis, which was the case for 29.9% of the recordings (e.g., losing the headband, equipment malfunctioning). Consequently, from all 294 recordings / nights, 206 nights (70.1%) were maintained for statistical analysis. Little’s MCAR test revealed that data was missing at random ($\chi^2(9) = 16.666, p = .054$), indicating that available data (i.e., 206 of all 294 possible recordings) may be taken as representative. Fourth, sleep onset was operationalized as the first of three consecutive epochs of “light sleep”\textsuperscript{116}. Compared to polysomnography, the WS overestimates REM at the cost of “wake”\textsuperscript{90}. Therefore, all “undefined” or “REM” epochs that preceded sleep onset were manually scored as “wake”. Finally, based on the normative range of REM sleep onset (49.5-278.5 min) provided by Mitterling, Högl, Schoenwald, Hackner, Gabelia, Biermayr, and Frauscher\textsuperscript{92}, “REM” epochs within the first 30 minutes of the night and without succeeding “deep sleep” were also manually scored as “wake”.

Performance. Psychomotor performance (alertness) was assessed in standardized fashion across sports, using the PVT. Outcome measures were reaction time and error rate. Fine and gross motor skill-performance were assessed sport-specifically. To allow comparison across sports, performance outcomes were standardized by means of group-mean-centering, according to the following formula: $z = \frac{x - \text{mean}}{\text{std dev}}$. Standardized scores were then rescaled if needed such that high scores always reflected better performance. Whenever the assessment of fine or gross motor skill-performance consisted of more than one test (i.e., handball and volleyball players only), scores of different tests were averaged so as to express a single outcome measure for each type of performance.

Statistical Analysis
Descriptive statistics were performed for sleep quantity, sleep stages and performance outcomes. To investigate how natural variation in sleep affects subsequent performance, linear mixed-effects models were employed. Linear mixed-effects models are an extension to linear regression that take the nested structure of the data into account (i.e., repeated measurements within individuals). We used the `lmer` function of the `lme4` package (version 1.1-1) in R (R Core Team, 2015). All performance categories were analysed in separate models (psychomotor performance [mean reaction time and error rate], fine motor and gross motor skill-performance consisted of more than one test (i.e., handball and volleyball players only), scores of different tests were averaged so as to express a single outcome measure for each type of performance. To allow comparison across sports, performance outcomes were standardized by means of group-mean-centering, according to the following formula: $z = \frac{x - \text{mean}}{\text{std dev}}$. Standardized scores were then rescaled if needed such that high scores always reflected better performance. Whenever the assessment of fine or gross motor skill-performance consisted of more than one test (i.e., handball and volleyball players only), scores of different tests were averaged so as to express a single outcome measure for each type of performance.
performance). To optimize power, sleep quantity and sleep stage effects were tested in separate models, resulting in a total of 8 linear mixed-effects models. Each model included a fixed intercept and fixed effects for gender (with contrast set as 1 for male and -1 for female), age, time awake (time between awakening and performance assessment), and day. In the “sleep stage model” minutes spent in light sleep, deep sleep and REM sleep (all from the WS) were respectively included. In the “sleep quantity model”, TST, SOL, WASO and SE (all from the Actiwatch) were included. SOL was log10 transformed to correct for the non-normal distribution of SOLs. All variables were person-mean-centered, which means that for each variable we first took the mean value of all 3 measurements within each individual and then subtracted it from that individual’s respective day-values, resulting in 3 new person-mean-centered scores. The average of each individual’s person-mean centered scores equals 0. A maximal random-effects structure was used by including a per-participant random intercept as well as per-participant random slopes for time awake and the respective model’s corresponding sleep parameters. For convergence reasons, all possible random correlation terms among the random effects were excluded. P-values were determined using the function “mixed” from the package afex using type 3 tests and the parametric bootstrap method (with 10000 simulations), which in turn calls the function PBmodcomp from the package pbkrtest (version 0.4.6). Confidence intervals were calculated using parametric bootstrapping as implemented in lme4’s bootMer function, with 10000 simulations and by deriving 95% confidence intervals using the function boot.ci of the package boot (version 1.3.17).

RESULTS

Means and standard deviations for all sleep parameters and performance outcomes based on the three nights / days are displayed in Table 4.1 and Table 4.2. A more detailed 7-day sleep profile including sleep hygiene aspects of all participating athletes was previously published in. The three-day average total sleep time was 7:30 ± 1:05 hours. Across the three measurement days, within-individual day-to-day variation in total sleep time ranged from 4 minutes for the most consistent athlete to 149 minutes for the most variable athlete. Across all athletes, the average
variation was 57.14 ± 38.48 minutes. 36 out of 98 athletes had a variation in total sleep time of maximal ≥ 60 minutes across all three nights.

### Table 4.1. Sport-specific overview of performance assessment, including means and standard deviations.

<table>
<thead>
<tr>
<th>Observations</th>
<th>M</th>
<th>SD</th>
<th>Handball</th>
<th>Volleyball</th>
<th>Soccer</th>
<th>Road Cycling</th>
<th>Mountain Bike</th>
<th>Triathlon</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>13</td>
<td>30</td>
<td>17</td>
<td>26</td>
<td>4</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cognitive Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reaction Time (ms)</td>
<td>288</td>
<td>265.71</td>
<td>29.18</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Error Rate (#)</td>
<td>288</td>
<td>3.44</td>
<td>3.89</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Fine Motor Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shooting Accuracy (%)</td>
<td>123</td>
<td>33.40</td>
<td>17.52</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Dribble (sec)</td>
<td>31</td>
<td>9.53</td>
<td>0.61</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Skill-track (sec)</td>
<td>12</td>
<td>39.55</td>
<td>78.25</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Gross Motor Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprint (sec)</td>
<td>37</td>
<td>3.46</td>
<td>0.12</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Counter Movement Jump (cm)</td>
<td>114</td>
<td>47.42</td>
<td>10.70</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Spike Jump (cm)</td>
<td>114</td>
<td>55.54</td>
<td>13.32</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Constant Power Test (bpm)</td>
<td>92</td>
<td>158.05</td>
<td>10.75</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

**Note.** For statistical analyses, outcomes on sport-specific fine motor and gross motor performance tests were standardized by means of group-mean centering and aggregated such that each participant had one score (arbitrary unit) for fine motor performance and one score (arbitrary unit) for gross motor performance for each measurement occasion.

### Effect of Sleep Quantity and Sleep Stages on Psychomotor Performance

**Reaction Time**

With regard to the effect of sleep quantity on mean reaction time, linear mixed-effects models revealed a significant effect of total sleep time ($B = -0.070$, se = 0.04, 95% CI [−0.142, 0.001], $p = .04$), indicating an improvement in reaction time following nights in which an athlete slept longer than his/her own average ($TST = 0$, Figure...
4.1) The remaining sleep quantity parameters did not reach significance, with sleep onset latency ($B = -3.393, se = 3.19, 95\% CI [-9.758, 2.977], p = .29$), wake after sleep onset ($B = 0.100, se = 0.13, 95\% CI [-0.151, 0.356], p = .42$), and sleep efficiency ($B = 0.224, se = 0.42, 95\% CI [-0.610, 1.060], p = .60$).

Concerning the effect of sleep stages on reaction time, no significant associations were observed. That is, reaction time was not significantly affected by the time spent in light sleep ($B = -0.068, se = 0.05, 95\% CI [-0.166, 0.030], p = .15$), deep sleep ($B = -0.03, se = 0.10, 95\% CI [-0.244, 0.182], p = .77$), or REM sleep ($B = -0.090, se = 0.07, 95\% CI [-0.235, 0.055], p = .21$).

### Table 4.2. Descriptive Statistics of all sleep parameters of interest.

<table>
<thead>
<tr>
<th>Sleep Quantity</th>
<th>N</th>
<th>M</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Sleep Time (h:min)</td>
<td>282</td>
<td>7:30</td>
<td>1:05</td>
</tr>
<tr>
<td>Sleep Onset Latency (h:min)</td>
<td>282</td>
<td>0:14</td>
<td>0:17</td>
</tr>
<tr>
<td>Wake After Sleep Onset (h:min)</td>
<td>282</td>
<td>0:31</td>
<td>0:16</td>
</tr>
<tr>
<td>Sleep Efficiency (%)</td>
<td>282</td>
<td>88.73</td>
<td>5.55</td>
</tr>
<tr>
<td>Sleep Stages</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light (h:min)</td>
<td>206</td>
<td>3:54</td>
<td>0:50</td>
</tr>
<tr>
<td>Deep (h:min)</td>
<td>206</td>
<td>1:37</td>
<td>0:31</td>
</tr>
<tr>
<td>REM (h:min)</td>
<td>206</td>
<td>1:59</td>
<td>0:42</td>
</tr>
</tbody>
</table>

### Error Rate

With regard to the effect of sleep quantity on error rate, linear mixed-effects models revealed no significant association, with total sleep time ($B = -0.005, se = 0.01, 95\% CI [-0.020, 0.009], p = .44$), sleep onset latency ($B = -0.461, se = 0.60, 95\% CI [-1.666, 0.728], p = .45$), wake after sleep onset ($B = -0.011, se = 0.03, 95\% CI [-0.061, 0.039], p = .67$), and sleep efficiency ($B = 0.041, se = 0.07, 95\% CI [-0.104, 0.184], p = .59$).

Similar to sleep quantity, no significant associations could be established between sleep stages and error rate. That is, error rate was not significantly affected by variation in light sleep ($B = -0.000, se = 0.01, 95\% CI [-0.019, 0.018], p = .96$), deep sleep ($B = 0.25, se = 0.02, 95\% CI [-0.010, 0.060], p = .12$), or REM sleep ($B = -0.019, se = 0.01, 95\% CI [-0.041, 0.004], p = .09$).
Effect of total sleep time on reaction time.

Note. The graph shows that if an athlete has his/her own average total sleep time (TST = 0; i.e., not the groups’ average TST), his/her expected reaction time is 265ms. The model then predicts that for every additional hour of sleep, reaction time decreases by approximately 5 milliseconds.

Effect of Sleep Quantity and Sleep Stages on Fine Motor Skill Performance

Regarding the effect of sleep quantity on fine motor skill performance, linear mixed-effects models revealed no significant associations with total sleep time (B = 0.005, se = 0.00, 95% CI [-0.001, 0.010], p = .10), sleep onset latency (B = 0.185, se = 0.00, 95% CI [0.225, 0.593], p = .38), wake after sleep onset (B = -0.001, se = 0.01, 95% CI [-0.022, 0.020], p = .91), or sleep efficiency (B = -0.021 (se = 0.03), 95% CI [-0.089, 0.047], p = .52).

Similar to sleep quantity, no significant associations could be established between sleep stages and fine motor skill performance. That is, fine motor skills were not significantly affected by variation in light sleep (B = 0.001, se = 0.00, 95% CI [-0.008, 0.010], p = .74), deep sleep (B = .014, se = 0.01, 95% CI [-0.005, 0.033], p = .18), or REM sleep (B = 0.001, se = 0.01, 95% CI [-0.011, 0.013], p = .86).

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Effect of Sleep Quantity and Sleep Stages on Gross Motor Skill Performance

Regarding the effect of sleep quantity on gross motor skill performance linear mixed-effects models revealed a significant effect of sleep onset latency on gross motor skill performance ($B = -0.343$, $se = 0.16$, 95% CI [-0.670, -0.011], $p = .03$), suggesting shorter sleep onset latencies to be associated with improved gross motor skill performance. In addition, a small but significant effect of total sleep time on gross motor skill performance ($B = -0.005$, $se = 0.02$, 95% CI [-0.009, -0.001], $p = .008$) indicated that shorter total sleep time was associated with improved gross motor skill performance. Wake after sleep onset ($B = -0.009$, $se = 0.01$, 95% CI [-0.024, 0.005], $p = .18$) and sleep efficiency ($B = -0.030$, $se = 0.02$, 95% CI [-0.071, 0.012], $p = .14$) did not show significant associations with gross motor skill performance.

Concerning the effect of sleep stages on gross motor skills, a small but significant effect of light sleep on gross motor skill performance ($B = -0.007$, $se = 0.00$, 95% CI [-0.012, 0.001], $p = .01$) indicated that obtaining fewer minutes of light sleep was associated with improved gross motor performance. Deep sleep ($B = -0.005$, $se = 0.01$, 95% CI [-0.019, 0.008], $p = .41$), and REM sleep ($B = 0.005$, $se = 0.00$, 95% CI [-0.004, 0.014], $p = .28$) did not show significant associations with gross motor skill performance.

DISCUSSION

The current study investigated to which extent mild day-to-day variations in sleep are reflected in psychomotor and sport-specific performance of elite athletes. Objective measures of sleep quantity, sleep stages and subsequent (sport-specific) performances were taken on three non-consecutive occasions on uniform times among a large cohort of elite athletes. Our results show that small changes in sleep quantity (total sleep time) were reflected in small but significant changes in psychomotor performance (reaction time). In addition, small but inconsistent effects of sleep quantity and sleep staging on gross motor skill performance were observed. Fine motor skill performance remained insensitive to changes in sleep.

Effect of Sleep Quantity and Sleep Stages on Gross Motor Skill Performance

Regarding the effect of sleep quantity on gross motor skill performance linear mixed-effects models revealed a significant effect of sleep onset latency on gross motor skill performance ($B = -0.343$, $se = 0.16$, 95% CI [-0.670, -0.011], $p = .03$), suggesting shorter sleep onset latencies to be associated with improved gross motor skill performance. In addition, a small but significant effect of total sleep time on gross motor skill performance ($B = -0.005$, $se = 0.02$, 95% CI [-0.009, -0.001], $p = .008$) indicated that shorter total sleep time was associated with improved gross motor skill performance. Wake after sleep onset ($B = -0.009$, $se = 0.01$, 95% CI [-0.024, 0.005], $p = .18$) and sleep efficiency ($B = -0.030$, $se = 0.02$, 95% CI [-0.071, 0.012], $p = .14$) did not show significant associations with gross motor skill performance.

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Overall, athletes showed adequate though slightly fragmented sleep, with approximately 8 hours of total sleep time and a healthy distribution of sleep stages across the measurement period of 7-days (see: 117, for a more detailed report of sleep characteristics in the same population). With regard to psychomotor performance we found a significant negative association between total sleep time and reaction time, with longer sleep duration being related to faster responses on the psychomotor vigilance test. As appears from Figure 4.1, athletes’ mean reaction time increased or decreased with approximately 5ms when they slept about 60 minutes shorter or longer than their individual average, respectively. The fact that this effect is relatively small is in line with the literature16 and may be explained by the observation that within-subject variation in total sleep time across the three measurement occasions was also small (i.e., mean ∆ TST = 57.14 minutes). Still, in elite sports, small effects can be critical. Moreover, and in line with the dose–relationship between sleep duration and psychomotor vigilance, the current data suggests that when incidental sleep loss is more extreme (e.g., as might occur when approaching important competitions50), or continues over a number of days, effects may be expected to be substantially larger17. In this sense, the current study underlines that sleep loss negatively affects psychomotor vigilance but at the same time, highlights the potential benefits of sleep extension23.

With regard to our measures of sport-specific fine and gross motor skill, results indicated very few significant effects. While in part this confirms the idea that sleep has a stronger effect on psychomotor performance than on athletic performance, we had expected to substantiate this perspective by showing that performance on fine motor skills would be more strongly affected by sleep than performance on gross motor skills3. However, neither sleep quantity nor sleep staging appeared to have any effect on our measure of fine motor skill. Again, a likely explanation for the absence of significant effects is that within-subject variations in sleep across the three measurement occasions was simply too small to have a measureable impact on performance. At the same time, however, we did find a significant negative association between sleep onset latency and performance on gross motor skills (i.e., worse performance with longer sleep onset latencies), as well as improved gross motor skill performance as a function of less total sleep time and less light sleep. It should be noted, however, that the observed effects were generally small. Considering this, the general pattern of results appears to indicate that minor effects may be expected to be substantially larger17. In this sense, the current study underlines that sleep loss negatively affects psychomotor vigilance but at the same time, highlights the potential benefits of sleep extension23.

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variations in sleep quantity and sleep staging, as in the current study, are unlikely to have a strong influence on athletic performance. Future research, involving more extreme variations in sleep quantity and sleep staging is required to substantiate this finding and dissociate between effects on fine and gross motor skills.

Apart from the naturally restricted (day-to-day) variations in sleep, there are a number of potential limitations that need to be taken into account when interpreting the current findings. For one thing, the current field setting entailed that, to conveniently measure athletes’ sleep, we had to rely on wristwatch actigraphy (sleep quantity) and wireless one-channel EEG (sleep stages; see Methods). While both systems are often used in field research\(^\text{25, 117}\) and show adequate agreement with polysomnography (which is considered the gold standard)\(^\text{90, 118}\), absolute values may deviate and, for example, precise measurement of actigraphy-based sleep onset latency is prone to a systematic error\(^\text{119}\). The observed effect of sleep onset latency on gross motor skill performance should therefore be interpreted with caution. Also, in attempting to make a representative (sport-specific) distinction between effects of sleep on fine and gross motor skill performance across different sports, we chose to standardize and pool performance outcomes on different tests. While this was done according to a strictly formalized procedure, standardizing and pooling data across tests might have introduced noise and, hence, reduced measurement sensitivity. Similarly, arguments may be raised to suggest that the current performance categories may be overly broad and that pooling across more specific performance categories may be more useful. Future studies are therefore advised to incorporate more standardized tests of fine and gross motor skill performance, potentially also in a more homogeneous group of athletes. Moreover, it should be noted that in the current study, performance tests were always taken on standardized times in the morning. While this procedure effectively excluded potential time-of-day effects, literature suggests that effects of sleep loss on athletic performance may be slightly more pronounced when performance tests are conducted in the evening (i.e., with sustained wakefulness)\(^\text{73}\). Finally, sampling from a limited pool of elite athletes, age ranges may vary more than what is desired. In the current study, assessing within-subject effects and including age as a covariate in the analyses, strongly reduced the potential influence of age on sleep and performance. To fully exclude age effects, also in case of non-linear effects, future studies are advised to recruit athletes from a smaller age-range.

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All in all, the current study showed that even minor (day-to-day) variations in sleep can significantly impact on elite athletes’ psychomotor performance, with reduced total sleep time being associated with reduced psychomotor vigilance on the following morning. At the same time, fine motor skill performance and to a large extent also gross motor skill performance appeared largely irresponsive to mild variations in sleep. Taken together, results indicate that psychomotor performance is more strongly affected by sleep than athletic performance\(^3\) and highlight a dose-response relationship\(^{16}\). It is thereby suggested that one night of minor sleep loss (i.e., < 1 hour) may not be immediately problematic, but that more extreme sleep loss or accumulated sleep debt over time may prove to be detrimental for performance and recovery.

Footnote
- In specific cases, adjustments needed to be made in scheduling the performance tests to avoid interference with existing training schedules: female road cyclists \((n = 9)\): performance tests on day 1, 6, 7; soccer players \((n = 17)\): performance tests on day 1, 3, 6; volleyball players \((n = 30)\): performance tests on day 1, 5, 8).
- One might argue that, apart from these variables, sleep and performance analyses may also be controlled for alcohol intake, caffeine intake and the use of sleep aids. For reasons of model convergence, this was not done. During the study, substance use was monitored on a daily basis (data reported elsewhere\(^{89}\)), which generally indicated extremely low occurrence and no or minimal correlations with sleep. Hardly any alcohol was consumed in the evening (average occurrence: 2% of nights), standardized testing procedures prevented variation in caffeine intake in the morning, and only 1 out of 98 participants consistently took sleep medication (i.e., a low dose of melatonin, consistently taken throughout the measurement period). Based on these numbers, and considering that all analyses considered within-person effects, it is assumed that substance use had no impact on our results.

Footnote
- In specific cases, adjustments needed to be made in scheduling the performance tests to avoid interference with existing training schedules: female road cyclists \((n = 9)\): performance tests on day 1, 6, 7; soccer players \((n = 17)\): performance tests on day 1, 3, 6; volleyball players \((n = 30)\): performance tests on day 1, 5, 8).
- One might argue that, apart from these variables, sleep and performance analyses may also be controlled for alcohol intake, caffeine intake and the use of sleep aids. For reasons of model convergence, this was not done. During the study, substance use was monitored on a daily basis (data reported elsewhere\(^{89}\)), which generally indicated extremely low occurrence and no or minimal correlations with sleep. Hardly any alcohol was consumed in the evening (average occurrence: 2% of nights), standardized testing procedures prevented variation in caffeine intake in the morning, and only 1 out of 98 participants consistently took sleep medication (i.e., a low dose of melatonin, consistently taken throughout the measurement period). Based on these numbers, and considering that all analyses considered within-person effects, it is assumed that substance use had no impact on our results.
To indicate the extent to which very slow and/or very fast reaction times influenced the observed effect of TST on reaction time, a post-hoc analysis was performed using Basner, and Dinges' measure of 'response speed' (i.e., response speed = 1000/RT). As outlined by Basner, and Dinges, transforming reaction times to response speed reduces the influence of extreme values. As appeared from the analysis, TST did not significantly affect response speed (with, $B = 0.001$, $se = 0.001$, 95% CI [-0.001, 0.002], $p = .43$), thereby indicating that the observed effect of TST on reaction time was at least partly dependent on large variability in reaction times with increasing or decreasing TST.
CHAPTER 5

OPTIMIZING SLEEP IN ATHLETES: A SEARCH FOR EFFECTIVE INTERVENTIONS
INTRODUCTION

As revealed in previous chapters, athletes have relatively poor sleep estimates during periods of habitual training. To be more precise, 41% of athletes classify as poor sleepers, whereas 12% were classified as having a potential sleep disorder. Based on self-reports and actigraphy-based sleep estimates, athletes appear to have relatively long sleep onset latencies, slightly elevated wake after sleep onset and sleep fragmentation. Potentially as a consequence of relatively poor sleep, athletes felt only moderately refreshed and alert in the morning. For most athletes, sleep estimates remained within healthy ranges, however, results indicate that – even during training periods - sleep is under pressure. If athletes want to profit from a sleep-dependent performance benefit, sleep should be further optimized.

Predicated on the evidence accumulated in Chapter 2 and Chapter 3, non-pharmaceutical interventions are preferred that focus on shortening sleep onset latency and wake after sleep onset, which if combined, may result in improved sleep efficiency. More specifically, interventions are desired that target factors that potentially disrupt the sleep regulation processes. The two process model of sleep-wake regulation emphasizes a good alignment between the homeostatic process (process S) and the circadian process (process C) for sleep initiation and maintenance, as has been detailed in Chapter 1.

An accumulation of external and behavioral factors that may interfere with processes described in the two-process model is covered under the term “sleep hygiene”, which refers to “conditions and practices that promote continuous and effective sleep” (p. 347, American Academy of Sleep Medicine, 2001). Based on the association between sleep hygiene practices and sleep that has been established in the study depicted in Chapter 2, athletes may benefit from knowledge and guidelines with regard to their daytime behavior in order to improve their sleep. Chapter 5a provides an evidenced based overview of sleep hygiene strategies specifically for athletes, alongside a smartphone application that enables athletes to monitor their sleep and sleep hygiene habits throughout periods of training and competition.

Two additional (environmental) factors that are involved in how sleep is regulated are light and body temperature. Both mechanisms will be introduced shortly, and more detailed in the Chapters 5b and 5c.
Close to sleep onset, skin temperature increases which causes vasodilatation and a drop in core body temperature. More specifically, research has shown that increasing the distal to proximal gradient in skin temperature (DPG) before bedtime predicts sleep onset latency under strict experimental conditions\textsuperscript{121, 125, 126}. After comparing different methods to increase skin temperature in the laboratory, increasing foot temperature by approximately 6 °C prior or during sleep onset has been proven to be the most effective method to increase DPG and to accelerate sleep initiation\textsuperscript{127}.

Chapter 5b provides the results of a pilot study that was conducted among sub-elite athletes to examine the effectiveness of distal skin warming by means of heated bed socks on DPG and consequently sleep initiation in the field.

Exposure to light in the evening, and especially to short wavelength light (e.g., emitted by electronic screens) delays circadian phase by suppressing melatonin secretion by the pineal gland\textsuperscript{33}. In humans, melatonin indicates the biological night and is crucial for sleep initiation and maintenance\textsuperscript{128}. In line with this observation, prior studies have shown that a blocking short-wavelength light in the evening can preserve melatonin secretion and potentially improve sleep\textsuperscript{129, 130}. In Chapter 5c, a pilot study is described in which the effectiveness of blocking short-wavelength light in the evening on sleep under natural conditions was assessed among a group of recreational athletes\textsuperscript{131}.

In Chapter 5d, a general discussion of these pilot interventions is provided.
SLEEP HYGIENE STRATEGIES FOR ELITE ATHLETES
INTRODUCTION

“Sleep is like a dove which has landed near one’s hand and stays there as long as one does not pay any attention to it.”

by Viktor E. Frankl

Sleep is easiest initiated when we pay the least attention to it, but there are certain "conditions and practices that promote continuous and effective sleep" (p. 347, American Academy of Sleep Medicine, 2001). These daytime behaviors and environmental conditions are referred to as "sleep hygiene practices". Empirical data reveals that poor sleep hygiene causes worsened sleep in normal sleepers and in insomniacs, but inadequate sleep hygiene is not considered the primary cause of insomnia, neither sufficient for its treatment. A negative association between sleep hygiene practices and sleep quality has also been established among a large cohort of elite athletes (Figure 5.1), while implementing selective sleep hygiene strategies has proven to improve athletes’ sleep. Given the potential benefits of sleep hygiene practices on sleep and the observation of poor sleep characteristics among elite athletes, in this chapter, sleep regulating mechanisms are explained, and a selection of sleep-permissive and wake-promoting conditions and behaviors that bears specific relevance to athletes, is provided.

Figure 5.1. Association between sleep hygiene practices and sleep (based on).

Note. PSQI = Pittsburgh Sleep Quality Index (left); HSDQ = Holland Sleep Disorder Questionnaire (right). Higher scores on the sleep questionnaires indicate poorer sleep, and higher scores on the sleep hygiene index point at poorer sleep hygiene practices.
Sleep timing and consolidation is regulated by two main processes - a homeostatic drive for sleep ‘process S’ and an endogenous circadian oscillation in arousal ‘process C’. Process S describes a steady increase in sleep propensity throughout sustained wakefulness, which decreases once sleep is initiated. The metaphor of an hourglass is regularly used to depict this process. Process C, in turn, represents a sleep-independent circadian oscillation in arousal during approximately 24 hours, which is crucial for the timing and consolidation of sleep. Sleep is initiated and maintained when both processes align, that is, when sleep pressure is highest and the circadian arousal is lowest. A mismatch between the processes, as for example in shiftwork and (social-) jet lag (i.e., irregular sleep-wake patterns), frequently results in sleep problems. Additional and often more subtle external factors, such as light, temperature, stress, daytime naps, and stimulants can further interfere with the components of the dual-process model and disrupt sleep.

Fortunately, most of the factors mentioned above can be optimized to promote continuous and effective sleep. Guidelines for optimal sleep hygiene behavior are diverse, but include as a minimum regularity of bed- and rise times, restriction of alcoholic and caffeinated beverages, regular exercise, nutrition, and environmental factors that enhance restful sleep. Unfortunately, for elite athletes who may greatly benefit from adequate sleep, it can be particularly challenging to comply with such guidelines, both during training and competition. During training periods, athletes have been shown to struggle with regular bed- and rise times, are frequently exposed to artificial light in the evening, consume heavy meals late in the evening, experience psychological strain and have problems refraining from stimulating substances such as caffeine. During competition periods, these aspects are often complemented by further delayed bedtimes (e.g., due to late completion times and travel), rumination, anticipatory stress and anxiety.

To facilitate compliance to adequate sleep hygiene practices in athletes, this chapter provides (1) general knowledge on sleep promoting and disturbing factors, followed by (2) tailored sleep hygiene guidelines that are complemented where possible with (3) information on new technologies that may facilitate good sleep hygiene practices. For means of better understanding, in the remainder of this chapter, sleep hygiene guidelines are organized into five sub-categories, which are regularity, stimulants and substances, and competition.
psychological strain, active (pre-) sleep behavior and environment. A comprehensive overview of each sub-category and accompanying sport-specific guidelines are depicted in Table 5.1.

Table 5.1. Sleep hygiene strategies that may facilitate sleep in elite athletes.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>COMPONENT</th>
<th>ADVICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>REGULARITY</td>
<td>Sleep Timing</td>
<td>• Regular bed- and rise times</td>
</tr>
<tr>
<td></td>
<td>Naps</td>
<td>• Daytime naps &lt; 20 minutes, before 4 PM</td>
</tr>
<tr>
<td></td>
<td>Limit TIB</td>
<td>• Limit time in bed to what is necessary</td>
</tr>
<tr>
<td>STIMULANTS AND SUBSTANCES</td>
<td>Caffeine</td>
<td>• Limit caffeine consumption (e.g., coffee, energy drinks, sport drinks, tea, chocolate milk) to less than 6 beverages a day, and none after 6 PM</td>
</tr>
<tr>
<td></td>
<td>Alcohol</td>
<td>• Moderate alcohol consumption to a maximum of two consumptions per day with a maximum of 5 per week, preferably not within the last hours before bedtime</td>
</tr>
<tr>
<td></td>
<td>Nicotine</td>
<td>• Nicotine should be avoided in general, and especially prior to bedtime</td>
</tr>
<tr>
<td></td>
<td>Nutrition</td>
<td>• Avoid eating a large meal within the last three hours before bedtime</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• In the early evening, choose for a high-glycemic meal (e.g., white rice, pasta, potatoes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• A light snack before bedtime should be rich in tryptophan (e.g., dairy products, pumpkin seeds, turkey)</td>
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<tr>
<td></td>
<td></td>
<td>• Avoid drinking large amounts of water in the evening, distribute fluid-intake throughout the day, and opt for sodium richer drinks in the late evening</td>
</tr>
<tr>
<td></td>
<td>Melatonin and Sleep Medication</td>
<td>• Melatonin should only be used to limit symptoms of phase shift, such as jet lag post inter-meridian travel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Sleep medication should be avoided where possible, and if necessary only administered for short-term use</td>
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Table 5.1. Continued.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>COMPONENT</th>
<th>ADVICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSYCHOLOGICAL</td>
<td>Manage Stress</td>
<td>• Avoid bed time stress and worry (e.g., use relaxation strategies, stretching)</td>
</tr>
<tr>
<td>STRAIN</td>
<td></td>
<td>• Stop to think and plan while in bed (opt for e.g., a to-do-list in the early evening)</td>
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<tr>
<td></td>
<td></td>
<td>• Avoid important work before bedtime (e.g., studying)</td>
</tr>
<tr>
<td>ACTIVE PRE-SLEEP</td>
<td>Activity</td>
<td>• Finalize your last intense training three hours before bedtime, but do engage in daily moderate exercise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Avoid physiologically activating activities before bedtime (e.g., playing videogames, cleaning)</td>
</tr>
<tr>
<td>ENVIRONMENT</td>
<td>Bedroom</td>
<td>• Use your bedroom for sleep and intimacy only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Avoid clutter in your bedroom</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Make sure you sleep in a comfortable bed, with a comfortable pillow and mattress</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>• Opt for a cool ambient temperature in your bedroom (16-19 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Promote heat loss by mild skin-warming (e.g., footbath, bed-socks, hot shower)</td>
</tr>
<tr>
<td></td>
<td>Light</td>
<td>• Keep the bedroom as dark as possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Expose yourself to bright light in the morning and during the day (sunlight suffices), and reduce evening light exposure, especially by electronic screens</td>
</tr>
<tr>
<td></td>
<td>Noise</td>
<td>• Eliminate noise in your sleep environment as far as possible or mask environmental noise if unavoidable</td>
</tr>
</tbody>
</table>

FIVE SLEEP HYGIENE SUB-CATEGORIES

Regularity

Regular bed- and rise times. The circadian system (process C) promotes sleepiness in the evening and triggers the secretion of essential hormones in the morning that initiate the process of waking up. By going to bed and waking up at the same time of day, every day, the sleep period can be adequately aligned with the circadian system.
facilitating continuous sleep during the night, and waking up in the morning, even without an alarm clock. In contrast, irregular bed- and wake time can disturb sleep. Going to bed much earlier, for example, can increase sleep onset latency, while sleeping longer than usual in the morning (sleeping in) can increase wake time in the last third of the night, because the circadian system has initiated the secretion of wake promoting hormones. Sleeping in affects the sleep-wake regulatory process in two more ways – first, sleeping in dissipates sleep pressure (decreases wake time) and can complicate subsequent sleep initiation (process S). Second, sleeping in prevents exposure to bright morning light which is crucial for synchronizing the circadian system to the 24 hour day (process C). It is therefore suggested to maintain a regular sleep-wake schedule, also during the weekends and free days, with a maximal deviation of preferably less than one hour to prevent the negative effects of a larger ‘social jet lag’.

Maintaining regularity in sleep and wake times may be the key element of sleep hygiene, but is often incompatible with training and competition timing. Athletes and coaches may want to reconsider the timing of training, such to at least allow for regular wake-times, and hence standardized morning-light exposure. During off-days, athletes should strive to keep their regular sleep-wake schedule. Sleep duration may be supplemented by daytime naps.

**Daytime Naps.** Daytime naps (brief sleeps) can counteract sleepiness and supplement nocturnal sleep. However, napping does decrease sleep pressure (process S). In order to prevent deteriorated nighttime sleep, naps should preferably be kept to a duration of 20 minutes and not occur after 4 PM\(^{28}\). Athletes with a sleep deficit (debt) or an elevated recovery need, as a consequence of multiple training sessions a day, may want to catch up on all sleep stages by napping for 60-90 minutes. In case of an extended nap, 6-8 hours of subsequent wake time are preferred to reduce adverse effects on nocturnal sleep.

The performance benefits vary depending on the duration of the nap. A brief nap of approximately 20 minutes can benefit alertness and cognitive performance immediately and for a duration of 1-3 hours. A longer nap of > 30 minutes, may induce sleep inertia – a feeling of grogginess post awakening, but cognitive benefits last much longer\(^{132}\). The optimal duration of a nap and its timing with regard to performance without disturbing nocturnal sleep warrants additional research.

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Stimulants and Substances

Caffeine. The alerting effect of caffeine is supposed to work by blocking adenosine receptors in the central nervous system. Adenosine appears to be a mediator of the sleep-inducing effects of wakefulness. The half-life time of caffeine is 3-7 hours, and caffeine concentration may accumulate throughout the day. Athletes frequently use caffeine in order to promote wakefulness, alertness and even performance. However, general recommendations with regard to sleep (not overall health) suggest no more than 6 caffeinated beverages a day (<400-500 mg/day), and none after 6 PM, or within the last 6 hours prior to bedtime. While some people may not encounter problems with sleep initiation or sleep disruption following a cup of coffee after dinner, research has shown that sleep is lighter and less refreshing. Caffeinated beverages concern coffee et cetera (e.g., coffee 80-180 mg caffeine), but also most energy drinks (80 mg caffeine), soft drinks (e.g., cola: 18 mg caffeine), some sport drinks, and most tea-sorts (30 mg caffeine). For those who are sensitive to caffeine, it is suggested to also avoid chocolate (15 mg caffeine) and chocolate milk (4 mg caffeine).

Alcohol and Nicotine. Alcohol is often used to self-medicate ‘nightcap’ and can indeed shorten sleep onset latency due to its sedative effects. However, following a moderate dose of ethanol (0.55 g/kg of body weight) ingested 6 hours before bedtime, subsequent sleep is more superficial, fragmented, shows reduction in REM sleep, and increased time awake in the second half of the night. To minimize the sleep disturbing effects of alcohol, consumption should be moderated and finalized four hours prior to sleep.

Nicotine promotes arousal and wakefulness, thereby disrupting sleep. Although seldom used among elite athletes, nicotine should be avoided, especially in the evening.

Nutrition. Consuming a large meal within the last hour before bedtime is associated with increased metabolic effort, and an increased gastric volume which may lead to physical discomfort. Having a large meal within the last 1-3 hours before bedtime is therefore discouraged. However, although current evidence is weak, some nutrients may have a favorable, yet small, effect on sleep. Ingesting a high glycemic meal (e.g., white rice, pasta, potatoes), as long as four hours before bedtime, or a light milk (4 mg caffeine).

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snack rich in tryptophan (e.g., dairy-products, pumpkin seeds, turkey) are suggested to facilitate sleep onset. A detailed review of the effects of various nutrients and herbal sleep aids can be found here. Finally, as athletes tend to show rather large fluid intakes post training or competition, also in the evening, a potential sleep disturbing factor in athletes is the need to use the bathroom at night. Distributing hydration equally throughout the waking day and replacing low-sodium drinks (Na, e.g., water), with drinks higher in sodium (e.g., milk), may reduce the need to urinate at night.

Melatonin and Sleep Medication. Melatonin and sleep medication are rather supplements than ‘stimulants and substances’, but will be discussed here as their use is associated with sleep regulation. Melatonin is a hormone of the circadian system, rather than a sleep aid. Its’ secretion by the pineal gland is regulated by the suprachiasmatic nuclei (SCN), the circadian master clock, which uses environmental light for synchronizing the internal time to the geographical day. As a circadian hormone, exogenous administration of melatonin may improve sleep problems associated with a disturbed circadian clock (e.g., delayed sleep phase disorder), potentially by stabilizing circadian phase and thus increasing sleep density. However, melatonin is a chronobiotic, it’s efficaciousness as a sleep aid is very weak, which is why the European Guidelines for the Diagnosis and Treatment of Insomnia formulated a strong recommendation against the use of melatonin for insomnia treatment (i.e., sleep problems). A further complication of the use of melatonin is its correct administration in terms of circadian timing and dosage. In contrast to what is instructed on the over-the-counter melatonin prescription, exogenous melatonin is administered approximately 3 hours before dim light melatonin onset (DLMO), with the intention to advance circadian phase and sleep timing, rather than immediately before bedtime. DLMO is considered the gold standard for assessing the phase of the circadian clock, and indicates the beginning of the biological night, which can vary tremendously across individuals. Melatonin dosages administered for treatment vary substantially (0.2 mg – 3 mg), but a well and individually adjusted dosage is crucial for its effectiveness. Too low doses may be ineffective, while too high doses may not only be ineffective, but also detrimental to sleep.

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External administration of melatonin should be avoided entirely or limited to alleviating symptoms of phase shifts, that is following jet lag post inter-meridian travel\(^{45}\). Importantly for elite athletes, next morning cognitive performance and alertness can decrease following evening ingestion of 5 mg of melatonin\(^{41}\), whereas physical performance is less likely to be affected the following day\(^{46}\).

Sleep medication, such as benzodiazepines (BZ, e.g., temazepam) and benzodiazepine receptor agonists (BZRAs, e.g., zolpidem), does not contravene with 2018 World-Anti Doping Agency rules and athletes may be inclined to use hypnotics to counteract anticipatory stress the night prior to competition or after a late-night match in order to fall asleep easier and to artificially extend sleep duration. However, sleep medication adversely affects sleep architecture, as for example reflected in reduced amounts of deep sleep (slow wave sleep)\(^{47}\). Moreover, athletes can experience hangover effects and altered hand-eye coordination the following morning\(^{48}\). Against this background and due to the high possibility for tolerance and dependence\(^{42}\), the benefits of using sleep medication may not outweigh its detrimental effects. Sleep medication is not recommended for the longer-term treatment of insomnia (symptoms)\(^{42}\).

**Psychological Strain**

*Bedtime stress and worry.* Psychosocial stress, sometimes also referred to as rumination, bedtime stress or worry, is known to adversely affect subsequent sleep, as is featured in shortened sleep, sleep fragmentation and potentially a reduction in deep sleep (stage 3 and 4 sleep)\(^{49}\). In athletes, sleep is often disturbed prior to important competitions\(^{58}\), with the most frequent report of problems initiating sleep (~81%)\(^{52, 53}\). Thoughts about the competition and nervousness ‘anticipatory stress’ seem to be the most relevant contributors to problems with falling asleep\(^{52, 53}\). Given the negative effects of stress on sleep, it is important to avoid (complicated) thinking or planning while in bed. In order to minimize the sleep disturbing effect of bedtime stress and worry, strategies such as expressive writing (writing about emotions and stress), keeping a worry-journal, a to-do list, or a gratefulness-journal in the early evening, may help. Other techniques that may help to promote sleep in times of high stress entail strategies to enhance relaxation\(^{50}\), such as meditation, imagery training, and controlled breathing (e.g., using apps like calm, meditation, imagery training, and controlled breathing (e.g., using apps like calm, ...
headspace)\textsuperscript{151}, autogenic training, progressive muscle relaxation\textsuperscript{152}, or brainwave entrainment\textsuperscript{64}.

No important work before bedtime. Stress and worry may be further reduced by eliminating important work (i.e., paying bills, planning, working or studying) before bedtime. Furthermore, in some cases being on social media, watching exciting movies or disturbing news can cause frustration, anger and cognitive arousal. Sometimes, it is out of the recipients control whether the media content is disturbing (social media) rather than soothing, which is why these media should be avoided shortly before bedtime\textsuperscript{153}.

Active (pre-sleep) Behavior

Exercise. Regular exercise exhausts the body (increases sleep pressure, process S) and is associated with shorter sleep onset latencies, fewer occurrences of wake after sleep onset, longer sleep durations, fewer sleep stage changes and more regular REM to non-REM transitions\textsuperscript{59}. However, under specific conditions, such as high training load or extreme intensities, exercise may jeopardize sleep quantity and quality\textsuperscript{48, 49, 56}. Exercising shortly before bedtime may further disturb sleep via elevated core body temperature\textsuperscript{35}, physiological and psychological arousal\textsuperscript{36}, and increased metabolism\textsuperscript{96}. In contrast, Hague, Gilbert, Burgess, Ferguson, and Dawson\textsuperscript{59} reported, that in trained athletes a sedentary day may reduce the depth of subsequent sleep. To this end, moderate (restorative) exercise that is finalized three hours before bedtime is recommended, even during tapering for competition. High intensity training sessions, of those with longer durations should be scheduled earlier in the day. To further prevent adverse effects of exercise on sleep (e.g., muscle soreness), athletes are recommended to regularly participate in adequate recovery strategies. Some examples are given here\textsuperscript{62}, alongside a review of their effectiveness which can be found here\textsuperscript{54}.

Activating activities. Further activating pre-sleep activities that should be avoided are, for example, playing video games that require physical activity, or cleaning. Keeping a bedtime routine entailing relaxing activities can further signal the body that it is about time to sleep, and help the body to wind down. However, in case of late-evening competition, psychological and physiological pre-sleep arousal is

headspace)\textsuperscript{151}, autogenic training, progressive muscle relaxation\textsuperscript{152}, or brainwave entrainment\textsuperscript{64}.

No important work before bedtime. Stress and worry may be further reduced by eliminating important work (i.e., paying bills, planning, working or studying) before bedtime. Furthermore, in some cases being on social media, watching exciting movies or disturbing news can cause frustration, anger and cognitive arousal. Sometimes, it is out of the recipients control whether the media content is disturbing (social media) rather than soothing, which is why these media should be avoided shortly before bedtime\textsuperscript{153}.

Active (pre-sleep) Behavior

Exercise. Regular exercise exhausts the body (increases sleep pressure, process S) and is associated with shorter sleep onset latencies, fewer occurrences of wake after sleep onset, longer sleep durations, fewer sleep stage changes and more regular REM to non-REM transitions\textsuperscript{59}. However, under specific conditions, such as high training load or extreme intensities, exercise may jeopardize sleep quantity and quality\textsuperscript{48, 49, 56}. Exercising shortly before bedtime may further disturb sleep via elevated core body temperature\textsuperscript{35}, physiological and psychological arousal\textsuperscript{36}, and increased metabolism\textsuperscript{96}. In contrast, Hague, Gilbert, Burgess, Ferguson, and Dawson\textsuperscript{59} reported, that in trained athletes a sedentary day may reduce the depth of subsequent sleep. To this end, moderate (restorative) exercise that is finalized three hours before bedtime is recommended, even during tapering for competition. High intensity training sessions, of those with longer durations should be scheduled earlier in the day. To further prevent adverse effects of exercise on sleep (e.g., muscle soreness), athletes are recommended to regularly participate in adequate recovery strategies. Some examples are given here\textsuperscript{62}, alongside a review of their effectiveness which can be found here\textsuperscript{54}.

Activating activities. Further activating pre-sleep activities that should be avoided are, for example, playing video games that require physical activity, or cleaning. Keeping a bedtime routine entailing relaxing activities can further signal the body that it is about time to sleep, and help the body to wind down. However, in case of late-evening competition, psychological and physiological pre-sleep arousal is
inevitable. In order to maximally preserve quality sleep, relaxation techniques as described above can be employed alongside set bedtimes, as can elimination of stimulants and light-emitting technologies before bedtime.51.

Environment

Bedroom. According to the stimulus control model proposed by Bootzin, the bedroom should be associated with sleep, comfort and relaxation, rather than with stress, work, worry, arousal and insecurity. Extending time in bed, that is staying in bed longer than necessary is discouraged. In addition, when having problems to fall asleep, it is better to leave the bedroom and to engage in a relaxing activity under dim-light until feeling sleepy again. The bedroom should be dedicated to sleep and intimacy, rather than to work and screen-time. Furthermore, a bedroom should be free of clutter, the bed should have a comfortable mattress, blanket and pillow that suit the bodies’ ergonomic needs and preferred sleep position. Accommodation at training camps may be less comfortable and less accustomed, which is why bringing an own pillow, blanket or even matress may be considered.

Temperature. Extreme ambient temperatures can disturb sleep. For optimal sleep, ambient temperature should be rather low, around 16-19 °C. The reason for rather cool ambient temperatures is that the core body temperature needs to drop in order for sleep to be initiated. A cool, rather than a warm ambient temperature, facilitates the body in transferring heat to the cooler environment. By means of heat exposure during a hot shower, bath or sauna session 2-3 hours before bed time, vasodilatation of the warmed skin can accelerate heat loss and potentially shorten sleep onset latency (see also Chapter 5b). Mild-skin warming by means of a thermos-suit, or simply heated bed socks may have the same beneficial effect on sleep.

Light. Light has a profound impact on sleep timing, as periodic light-dark exposure is the most prominent ‘Zeitgeber’ for aligning the circadian rhythm to the geographical day. Supporting natural lighting by increasing morning and daytime bright light exposure, and evening light restriction, for example, by wearing amber-lens glasses can further benefit sleep (see also Chapter 5c and Chapter 6). Additionally, it is recommended to limit evening exposure to short-wavelength light.
emitted by electronic screens. A simple, yet not fully sufficient, way is to use blue-light filters (e.g., night shift (iOS), twilight (Android) and f.lux (laptops)), alternatively one may want to fully restrain from electronic devices during the last hour before bedtime to further eliminate the potentially stimulating effect of media content. During the night, the bedroom should preferably be kept dark. While traveling or staying in a non-habitual sleep environment, sleep masks can help to create artificial darkness.

Noise. Sleep can be disturbed by (environmental) noise. Therefore, noise should be eliminated where possible. During travel, earplugs can be used as can applications that provide white noise to mask more stimulating or unanticipated environmental sounds. During flights, noise cancelling headphones or earplugs are recommended.

MORE PERSISTENT AND SEVERE SLEEP PROBLEMS

While sleep hygiene is a necessary first step towards better sleep, self-initiated attempts to improve sleep may not suffice in case of more persistent or severe sleep problems. In case of severe sleep problems, athletes are advised to contact a (sleep-) physician. In the European Guidelines for the Diagnosis and Treatment of Insomnia, Cognitive Behavioral Treatment for Insomnia (CBT-I) is suggested as first-line treatment, rather than sleep medication. CBT-I treatment is not yet easily available, but due to the advent of new technologies, this has slowly started to change. Online versions of CBT-I (eCBT-I) have been proven about equally effective as group therapies. One well-validated web-based application of CBT-I is, for example, SLEEPIO. CBT-I curtails all aspects of sleep hygiene (psycho-education, relaxation techniques), and in addition to that, sleep restriction therapy, stimulus control therapy, and cognitive therapy. However, caution is warranted with regard to the sleep restriction component of CBT-I. While effective in treating insomnia, sleep restriction therapy is associated with reduced objective sleep time, increased daytime somnolence and impaired vigilance. Therefore, athletes should only apply sleep restriction with great caution and under supervision, while opting for a milder variant (e.g., a more liberal sleep window, i.e., Time in Bed).

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CLOSING REMARK

In case of good, undisturbed and refreshing sleep of appropriate duration and quality\textsuperscript{12}, additional attention to sleep related daytime behaviors may do more harm than good. Excessive monitoring of sleep and sleep-related daytime behaviors, worrying about not getting the highest possible sleep score on a wearable (a score that may not be attainable), or dysfunctional beliefs about the daytime consequences of poor sleep quality can induce or further maintain sleep problems. Instead, it is advised to listen to the body, turn around the bedside-clock, relax and remember that one night of poor sleep won’t jeopardize athletic performance\textsuperscript{166}.

Staying on track – Sleep hygiene monitoring app for athletes

The above-mentioned sleep hygiene strategies offer a good starting point for optimizing sleep. Creating awareness about sleep behaviors by keeping a sleep diary and a checklist of the respective achievements may motivate to prioritizing sleep and to restrain from other behaviors that are more rewarding on the short term (e.g., delaying bedtime by watching series). Multiple applications are designed for coaching individuals to become better sleepers, provide the necessary knowledge and motivation to stay on track (e.g., personal sleep coach “Shleep”). Especially elite athletes may benefit from being aware of their sleep habits and how they may differ during training and competition. Therefore, a smartphone application, that can be found behind the QR-code that will be added to this theses, has been developed specifically for elite athletes. Based on an individual self-reported sleep pattern and sleep hygiene practices, the app provides individualized sleep hygiene advice, depending on the athletes’ respective situation, as for example while training at home or during competition abroad.
INCREASING DISTAL SKIN TEMPERATURE TO OPTIMIZE SLEEP IN ATHLETES

Published as:
ABSTRACT — Athletes’ recovery and performance capacity may benefit from adequate sleep. Paradoxically, athletes experience difficulties initiating and maintaining sleep and overall report mediocre sleep quality. One of many factors involved in sleep initiation and maintenance is thermoregulation. Specifically, increases in distal skin temperature and a larger distal to proximal skin temperature gradient (DPG) have been reported to shorten sleep onset in the laboratory. The present study assessed the effectiveness of increased DPG on sleep (onset latency) in a field setting.

Nineteen sub-elite athletes, ages 17-32 years (13 female) participated in a two week within-subject cross-over protocol. Within each week, sleep was monitored for 5 nights (of which 2 nights of habituation) using actigraphy, a one-channel EEG-sensor and self-report measures of sleep quality. During the experimental condition, athletes wore heatable socks 30 minutes prior to lights-off (vs. conventional socks in the control condition). Ambient and skin temperature was measured using iButton temperature loggers. The effect of increased DPG on sleep estimates was assessed using repeated measure ANCOVA’s.

Results showed that wearing heatable socks 30 minutes before bedtime was effective in increasing DPG, as compared to the control condition. However, increased DPG did not significantly shorten sleep onset latency, nor did it improve any of the remaining sleep estimates (all p’s > .493).

To conclude, the current study indicated that wearing heatable socks can increase DPG in a field setting, but that it was ineffective in optimizing sleep. Future research is warranted that involves larger sample sizes and more sensitive measurement devices.
INTRODUCTION
The recovery and performance benefits athletes may gain from adequate sleep are striking\(^{81}\). However, despite the potential benefits, athletes experience difficulties initiating and maintaining sleep, and have been shown to report mediocre subjective sleep quality\(^{89, 117}\).

One of the many mechanisms that regulates sleep and alert wakefulness is body temperature\(^{121}\). Around sleep onset, skin temperature increases, which causes vasodilatation and facilitates a drop in core body temperature. Previous work has indicated a functional link between mild skin warming and the initiation of sleep, showing that increasing the distal-proximal skin temperature gradient (DPG) before lights-off is the best physiological predictor of sleep onset under strictly controlled experimental conditions\(^{121, 126}\). Based on this initial observation, various protocols to manipulate skin temperature have been tested. According to Raymann, Swaab, and Van Someren\(^{127}\), the most effective method to increase DPG and accelerate the initiation of sleep, is to increase (distal) foot temperature by approximately 6°C during or prior to sleep onset\(^{127}\).

The current study aimed to conduct a field test of the method introduced by Raymann, Swaab, and Van Someren\(^{127}\), and examined whether increasing DPG by means of distal skin warming before bedtime can accelerate sleep onset among a cohort of Dutch athletes. Secondary outcome measures included wake after sleep onset, sleep efficiency and subjective markers of sleep quality and morning state. We hypothesized that increasing distal skin temperature (DST) will increase the distal to proximal skin temperature gradient (DPG) and facilitate sleep onset in athletes.

METHODS
Participants
Nineteen athletes (field hockey players), aged 17-32 years (\(M \pm SD: 22.21 \pm 3.8\) yrs; 13 female), all without (severe) subjective sleep complaints (mean PSQI = 3.68 ± 1.7, cut-off > 5; mean HSDQ = 1.47 ± 0.3, cut-off > 2.02), participated after informed consent. Athletes were recruited from the first (female and male) team of a regional hockey club and competed in the second national division. They had four (female

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team) or three (male team) practice sessions a week, with an additional match on Sundays. Practice sessions were scheduled between 5.00 and 9.30 PM.

Procedure
The study followed a within-subject crossover design, and had a duration of two weeks. Within each week, athletes’ sleep was monitored during two nights of habituation and three experimental-nights by means of actigraphy and a wireless one-channel EEG sensor. During the experimental-nights, athletes were either instructed to wear heatable socks (intervention condition) or neutral socks (control condition) during 30 minutes prior to lights-off. The order of conditions was counterbalanced between subjects and weekdays were matched across conditions. To maintain similar circumstances between conditions, athletes were instructed to follow a sleep hygiene protocol. Protocol adherence was monitored daily, by means of the Sleep Hygiene Index\textsuperscript{76}.

Temperature Manipulation and Assessment
Skin Temperature. Distal skin temperature (DST) was manipulated by means of heatable socks (Hot Feet, Gizzys), which contained a grain filling that could be heated using a microwave (2.30 min, 900 W). Temperature was measured using iButton Temperature Loggers (type: DS1922L #F50)[5], with 3-minutes intervals and a resolution of .0625ºC. In order to measure DST, two iButtons were taped onto the instep of each foot between the first and second web space. Proximal skin temperature (PST) was measured by an iButton taped 2 cm below the right clavicle and on the abdomen (2cm above the navel). Ambient temperature (AT) was assessed by means of an iButton that was placed on the nightstand next to the bed. Athletes were instructed to attach the iButtons 60 minutes before lights-off (T1), hence 30 minutes before wearing the socks. Multiple measurements obtained from the same body-position (e.g., DST vs. PST) were averaged. Distal to proximal skin temperature gradient (DPG) was calculated using the following formula: DPG = DST – PST. For statistical analysis, values for DST, PST, DPG and AT were determined at three different time points: T1 (35 minutes before lights-off), T2 (5 minutes before lights-off) and T3 (sleep onset) and averaged across the three days within each condition.
Sleep Estimates. Sleep data were collected by means of an actigraph (Actiwatch 2, Philips Respironics, Murrysville, USA) and a wireless one-channel EEG-sensor (Zeo Inc., Newton, USA). The actigraph was attached to the wrist of the non-dominant hand one hour before lights-off. Motion and photopic light was sampled at 32Hz, averaged and stored in 60 second bins. Since actigraphy-based SOL is prone to errors, we also employed the ZEO-sleep manager, a wireless system validated for measuring sleep in healthy adults\(^\text{90}\). It has an overall agreement with PSG of 93.6\%.\(^\text{90}\) Athletes were instructed to attach the headband shortly before lights-off. Sleep onset was operationalized as the first of three consecutive epochs of ‘light sleep’ (comparable to S1/S2 or N1/N2). For both measurement devices, variables of interest were sleep onset latency (SOL; min.), wake after sleep onset (WASO; min.) and sleep efficiency (SE; %). Subjective sleep quality was evaluated following lights-on, using a one-item question (scores: 1-10, with 10 indicating high sleep quality), the Groningen Sleep Quality Scale (GSQS)\(^\text{72}\), the Global Vigor and Affect Scale (GVA)\(^\text{74}\), the Karolinska Sleepiness Scale (KSS)\(^\text{75}\), and an additional item on feeling of fitness (scale 1-10). Scores were analyzed as described in the respective validation papers and averaged within each condition. Comfort of the heatable socks was assessed by a single-item question, with scores ranging between 1 to 7, with 7 indicating the highest possible comfort.

**Statistical Analysis**

Habitation nights were omitted from the analysis. Actigraphy and EEG-based SOL and WASO followed a non-normal distribution and were lg10-transformed. Protocol adherence (sleep hygiene) was tested using a paired t-test, temperature (DST, PST, DPG and AT) was tested using 2 x 3 (condition x time) repeated measure ANCOVA's, and sleep estimates were tested using one-way (condition) repeated measure ANCOVA's. All ANCOVA's included group (female team vs. male team) as a covariate and significance was set at \(\alpha = .05\).

**RESULTS AND DISCUSSION**

Analyses for protocol adherence (sleep hygiene) and ambient temperature (AT) indicated no significant differences between conditions (all \(p > .19\)), indicating that the intervention and control condition were performed under similar circumstances.

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Athletes rated the heatable socks as fairly comfortable with an average score of 5 ± 1.7 (7-point scale).

As depicted in Figure 5.2, the heatable socks effectively increased DST by approximately 5°C from T1 to T2. PST showed no significant differences across conditions (Table 5.2). Consequently, DPG was significantly larger in the intervention condition compared to the control condition. Table 5.2 displays the means, standard deviations and results of the 2 x 3 repeated measures ANCOVA’s.

Due to loss of data (e.g., equipment malfunctioning, not wearing or losing the EEG-headband) the analyses of sleep estimates was based on 14 and 9 participants for the Actigraphy and ZEO-based measurements, respectively (see Table 5.3). Sleep onset latencies appeared to be slightly shorter in the intervention condition, but and despite the effective increase in DST and DPG, effects did not reach statistical significance (see Table 5.3). In addition, wake after sleep onset, sleep efficiency and the self-report estimates of sleep quality and morning state (i.e., sleep quality, GSQS, global vigor & affect, KSS) were not significantly different between conditions (all p’s > .493; Table 5.3).

In the current study, wearing heatable socks during the last 30 minutes before bedtime, effectively increased DPG but was ineffective in significantly accelerating sleep onset (cf., 121, 127). Mean values for SOL, however, were in the expected direction. Given that the current study was conducted in a field setting, uncontrolled factors such as circadian and homeostatic components, stress, and other environmental (wake-promoting) circumstances, may have masked a potential effect of increased DPG on SOL. In addition, low power of the current study (especially in relation to our assessment of sleep onset) might have prevented finding statistically significant effects.

CONCLUSION

To conclude, the current study indicates that in a field setting, mild skin warming by means of wearing heatable socks close before bedtime, does not significantly accelerate sleep onset. Because positive effects of skin warming on sleep onset may naturally be expected to be small126, especially in healthy athletes, a critical field test involving a larger sample size and more sensitive measurement devices is warranted.

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Table 5.2. Mean distal skin temperatures (DST), proximal skin temperatures (PST) and distal to proximal skin temperature gradient (DPG) at T1, T2 and T3.

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Control</th>
<th>Results of Statistical Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>T2</td>
<td>T3</td>
</tr>
<tr>
<td>DST (°C)</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Int.</td>
<td>30.42</td>
<td>1.76</td>
</tr>
<tr>
<td>Cnt.</td>
<td>31.90</td>
<td>2.43</td>
</tr>
<tr>
<td>Effect</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>DF2</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>20.81</td>
<td></td>
</tr>
<tr>
<td>p</td>
<td>&lt;.001</td>
<td></td>
</tr>
<tr>
<td>η²p</td>
<td>.565</td>
<td></td>
</tr>
<tr>
<td>PST (°C)</td>
<td>33.74</td>
<td>0.87</td>
</tr>
<tr>
<td>Int.</td>
<td>33.30</td>
<td>0.98</td>
</tr>
<tr>
<td>Cnt.</td>
<td>33.02</td>
<td>0.94</td>
</tr>
<tr>
<td>Effect</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>DF2</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>3.27</td>
<td></td>
</tr>
<tr>
<td>p</td>
<td>.079</td>
<td></td>
</tr>
<tr>
<td>η²p</td>
<td>.017</td>
<td></td>
</tr>
<tr>
<td>DPG (°C)</td>
<td>-3.24</td>
<td>1.84</td>
</tr>
<tr>
<td>Int.</td>
<td>-.33</td>
<td>0.98</td>
</tr>
<tr>
<td>Cnt.</td>
<td>-.30</td>
<td>0.96</td>
</tr>
<tr>
<td>Effect</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>DF2</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>4.97</td>
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</tr>
<tr>
<td>p</td>
<td>.043</td>
<td></td>
</tr>
<tr>
<td>η²p</td>
<td>.262</td>
<td></td>
</tr>
</tbody>
</table>

Note: T1 = 35 min before lights-off, T2 = 5 min before lights-off, T3 = sleep onset. Paired-sample t-tests on the interaction-effect revealed that DST_{Int} > T1<T2<T3 at p < .001, while the increase in DST_{Cnt} was only significant for T2<T3 (p < .001), DST_{Int} > DST_{Cnt} at T2 (p < .001), and T3 (p < .004), but not at T1 (p = .130). Paired-sample t-test on the interaction-effect revealed that DPG_{Int} > T1<T2>T3 at p < .001, while there were no significant differences between T1, T2 and T3 for DPG_{Cnt} (all p's > .075). DPG_{Int} > DPG_{Cnt} at T2 and T3 (p < .006). At T1 DPG_{Int} > DPG_{Cnt} at p = .048.
Figure 5.2. Average DST and PST for the intervention (int) and control condition (cont) from 60 minutes before sleep onset (0) until 90 minutes thereafter. The manikin on the right displays the iButton-placement.

Table 5.3. Descriptive statistics and ANCOVA’s results of all sleep measures of interest.

<table>
<thead>
<tr>
<th></th>
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<th>Results of Statistical Analysis</th>
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<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Objective Estimates</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOL&lt;sub&gt;ACT&lt;/sub&gt; (min)</td>
<td>9.56</td>
<td>6.99</td>
<td>11.10</td>
<td>7.97</td>
</tr>
<tr>
<td>SOL&lt;sub&gt;ZEO&lt;/sub&gt; (min)</td>
<td>11.46</td>
<td>3.81</td>
<td>14.69</td>
<td>3.32</td>
</tr>
<tr>
<td>WASO&lt;sub&gt;ACT&lt;/sub&gt; (min)</td>
<td>50.36</td>
<td>19.04</td>
<td>49.89</td>
<td>18.29</td>
</tr>
<tr>
<td>WASO&lt;sub&gt;ZEO&lt;/sub&gt; (min)</td>
<td>4.22</td>
<td>3.47</td>
<td>2.74</td>
<td>2.31</td>
</tr>
<tr>
<td>SE&lt;sub&gt;ACT&lt;/sub&gt; (%)</td>
<td>85.23</td>
<td>5.24</td>
<td>84.75</td>
<td>5.21</td>
</tr>
<tr>
<td>SE&lt;sub&gt;ZEO&lt;/sub&gt; (%)</td>
<td>94.79</td>
<td>0.72</td>
<td>95.03</td>
<td>0.60</td>
</tr>
<tr>
<td>Subjective Estimates</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep Quality (1-10)</td>
<td>7.15</td>
<td>.90</td>
<td>7.00</td>
<td>1.02</td>
</tr>
<tr>
<td>GSQS (0-14)</td>
<td>1.84</td>
<td>2.07</td>
<td>2.33</td>
<td>2.51</td>
</tr>
<tr>
<td>Global Vigor (0-100)</td>
<td>74.57</td>
<td>1.57</td>
<td>74.73</td>
<td>1.84</td>
</tr>
<tr>
<td>Global Affect (0-100)</td>
<td>52.77</td>
<td>1.51</td>
<td>52.84</td>
<td>1.37</td>
</tr>
<tr>
<td>Fitness (1-10)</td>
<td>6.46</td>
<td>1.73</td>
<td>6.74</td>
<td>1.90</td>
</tr>
<tr>
<td>KSS (1-9)</td>
<td>3.74</td>
<td>1.30</td>
<td>3.77</td>
<td>1.33</td>
</tr>
</tbody>
</table>

Note: SOL = sleep onset latency, WASO = wake after sleep onset, SE = sleep efficiency, ACT = Actigraphy-based, ZEO = ZEO-based, GSQS = Groningen Sleep Quality Scale, KSS = Karolinska Sleepiness Scale; a higher score indicates higher sleepiness.
RESTRICTING SHORT-WAVELENGTH LIGHT IN THE EVENING TO IMPROVE SLEEP IN RECREATIONAL ATHLETES – A PILOT STUDY

Based on:
ABSTRACT — Sleep is crucial for recovery and skill acquisition in athletes. Paradoxically, athletes often encounter difficulties initiating and maintaining sleep, while having sufficient sleep opportunity. Blue (short-wavelength) light as emitted by electronic screens is considered a potential sleep thief, as it suppresses habitual melatonin secretion. The current study sought to investigate whether blocking short-wavelength light in the evening can improve sleep onset latency and potentially other sleep parameters among recreational athletes.

The study had a within-subject crossover design. Fifteen recreational athletes, aged between 18 and 32 years (12 females, 3 male), were randomly assigned to start the intervention period with either the light restriction condition (LR; amber-lens glasses), or the no-light restriction condition (nLR; transparent glasses). Sleep hygiene practices, actigraphy- and diary-based sleep estimates were monitored during four consecutive nights within each condition.

Sleep hygiene practices did not significantly differ between conditions. Results indicate that blocking short-wavelength light in the evening, as compared to habitual light exposure, significantly shortened subjective sleep onset latency (Δ = 8 minutes), improved sleep quality (Δ = 0.6; scale 1-10), and increased alertness the following morning. Actigraphy-based sleep estimates showed no significant differences between conditions.

Blocking short-wavelength light in the evening by means of amber-lens glasses is a cost-efficient and promising means to improve subjective sleep estimates among healthy recreational athletes in their habitual home environment. The relatively small effects of the current study may be strengthened by additionally increasing morning- and daytime light exposure and, potentially, by reducing the alerting effects of media use before bedtime.
INTRODUCTION

Sleep is considered indispensable for recovery and skill acquisition in athletes\textsuperscript{1–3}. Paradoxically, athletes show markers of poor sleep quality and sleep efficacy despite having sufficient opportunity to sleep (i.e., based on an approximation of 8.30 hours of time spent in bed (TIB))\textsuperscript{25, 117}. Modern-technologies, such as smartphones and laptops, are often blamed for high-jacking sleep, particularly in adolescents and athletes who are susceptible to the ‘fear of missing out’\textsuperscript{68}. The effect is twofold; The psychological sleep threatening components concern the stimulating effect of media content associated with higher bedtime arousal and delayed bedtimes\textsuperscript{153}. Another, physiological component which will be focused on in this study, concerns evening exposure to artificial light, especially short wavelength light, which is thought to delay circadian phase by suppressing habitual melatonin synthesis\textsuperscript{23}. Melatonin is crucial for sleep initiation and maintenance in humans\textsuperscript{128}. Given the significance of sleep as a means for recovery and skill acquisition in athletes\textsuperscript{167}, the current study sought to determine whether reducing evening exposure to short-wavelength light can improve sleep among recreational athletes.

Sleep and wakefulness are regulated by two distinct process: a homeostatic process (Process S) that depicts increasing sleep pressure following sustained wakefulness, and a circadian process (Process C)\textsuperscript{30}, which is regulated by the circadian system and requires periodic light-dark exposure for stable entrainment to the geographical day\textsuperscript{140, 158}. Specifically, information on environmental light is received by photoreceptors in the retina and, via non-image forming intrinsically photoreceptive retinal ganglion cells (ipRGC)\textsuperscript{128, 168}, directly transmitted to the suprachiasmatic nucleus (SCN), the site of the circadian ‘master clock’. The SCN, in turn sends information on circadian time to, for example, the pineal gland where melatonin is secreted in the evening, or suppressed in case of evening-light exposure\textsuperscript{128}. Hence, the timing of light exposure is crucial: daytime light exposure facilitates the process of waking up and staying alert during the early day, while in the evening, the absence of light facilitates sleepiness.

Due to artificial lighting and the advent of light-emitting hand-held screens, however, evening light is often abundant, tricking our circadian system to think it is daytime\textsuperscript{122}. Part of the environmental lighting and almost all electronic screens are rich in short-wavelength light (~460 nm), which lies in the visual spectrum of blue-
green. Importantly, a specific type of photoreceptive cells is particularly sensitive to light of this (short) wavelength (446–477 nm) and modulates activation of the suprachiasmatic nucleus (SCN) such that melatonin secretion becomes actively suppressed. A full suppression or delay in melatonin secretion is associated with reduced sleepiness, increased alertness, delayed sleep onset and reduced sleep efficiency. Accordingly, exposure to especially short-wavelength light in the evening may delay circadian phase and disrupt sleep in athletes.

In line with the hypothesis that evening light exposure may negatively affect sleep, previous studies have shown that light-restriction in the evening can help to maintain an habitual melatonin secretion. While these results are certainly promising, it should be noted that subsequent effects on sleep have not often been assessed, that many studies have been conducted among shift-workers or problematic sleepers, and that studies have often lacked a (sufficiently neutral) control condition, or reported differences at baseline in a between subject design.

Considering these limitations and gaps in the current literature, the present study investigated the effectiveness of blocking short-wavelength light in the evening on sleep under natural conditions in a healthy and physically active population. Using a within-subject crossover design, recreational athletes were instructed to wear amber-lens glasses before bedtime in the experimental condition, which were substituted by non-vision adjusting transparent glasses in the control condition. In both conditions, sleep was monitored using wrist-worn actigraphy and daily sleep diaries for a period of nine nights. Considering the recent literature and the effects of short-wavelength light on the melatonin synthesis, it was hypothesized that using blue-light blocking amber-lens glasses in the evening will improve actigraphy- and diary-based sleep onset latency, and potentially secondary measures such as total sleep time, sleep efficiency, and subjectively rated sleep quality.

### METHODS

Fifteen recreational athletes, aged between 18 and 32 years ($M \pm SD; 23.27 \pm 3.63$ yrs) of whom 12 were females (3 male), participated with written informed consent. Inclusion criteria were (1) exercising one or more hours a week (endurance and/ or weight training), (2) moderate to good subjective sleep quality based on the Pittsburgh Sleep Quality Index (PSQI: all $< 7$; $M \pm SD; 3.87 \pm 1.55$), (3) no severe

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subjective sleep complaints based on the Holland Sleep Disorder Questionnaire\textsuperscript{70} (HSDQ: all < 2.06; M ± SD; 1.57 ± 0.26), (4) being free of sleep medication, (5) consuming < 500 mg caffeine a day (∼ 5 espressos) and < 5 standard units alcohol, (6) no current use of psychoactive medication, (7) absence of psychiatric and mood disorders, (8) no serious or unstable medical illness, (9) no diagnosed sleep disorders, (10) no time-zone crossing travel during the assessment period, (11) no pregnancy, and (12) no shift work. Participants were recruited among active members of the University Sports Centre. The study was approved by the faculty’s ethical committee [ECSW2016-1403-376], and participation was financially reimbursed. Data was collected in April 2016.

**Design and Procedure**

The study had a within-subject crossover design. Participants were randomly assigned to start the intervention period with either the light restriction condition (LR), or the no-light restriction condition (nLR). Each condition started with two days of habituation, followed by seven days of intervention, that were scheduled four days apart to allow all participants to always start on the same weekday (Monday). The order of conditions was counterbalanced between participants. In the light-restriction condition, participants were instructed to wear amber-lens glasses three hours before bedtime (Eye shield soft red Safety Glasses, Königswinter, Germany), which were substituted by non-vision adjusting transparent glasses in the no-light restriction condition (clear non-prescription lenses black, by Oramics). To prevent explicit outcome expectancies from influencing our findings, participants were informed that the study was designed to assess effects of light regulation on mood and alertness. Across both conditions, sleep was monitored for nine consecutive nights by means of wrist-worn actigraphy and paper-based morning- and evening diaries. To allow for a fair comparison between the experimental conditions, participants were instructed to follow a set of behavioral guidelines throughout both conditions (see below).

**Light Restriction**

In the light-restriction condition (LR), participants were instructed to wear amber-lens glasses (Eye shield soft red Safety Glasses, Königswinter, Germany) during the last three hours before bedtime and at the latest at 9.00 PM\textsuperscript{30}. The amber-
lens glasses filter 100% of wavelength up to 400 nm, and 89-99.9% of wavelength between 400 and 500 nm. The effectiveness of these glasses in preserving normal evening melatonin production during bright-light exposure has been reported elsewhere\textsuperscript{130}. Therefore, most of the blue (wavelength of 490-450 nm), and parts of the green light (560 – 520 nm) was effectively restricted.

To standardize the experimental protocol across conditions, in the no-light regulation condition (nLR), participants were instructed to wear non-vision adjusting transparent glasses (clear non-prescription lenses, by Oramics). Hence, short-wavelength light was not restricted in the evening.

**Sleep Estimates**

Sleep data was collected by means of wrist-actigraphy and paper-based sleep diaries, which are less sensitive to detecting small changes in sleep onset than the gold-standard polysomnography\textsuperscript{82,170}, but generally well accepted in any field-based measurement of sleep\textsuperscript{25,117}.

Objective sleep estimates were collected using an actigraph (Actiwatch 2, Philips Respironics, Murrysville, USA), that was continuously worn around the non-dominant wrist and only detached during training or when being in contact with water. Activity and photonic light was sampled in 60 second bins. Primary measure of interest was sleep onset latency (SOL; min), and secondary measures were wake after sleep onset (WASO; min), fragmentation index (%), total sleep time (TST; h:min), and sleep efficiency (SE; %). Actigraphy data were analyzed using Respironics Actiware 5 (Philips Respironics, Murrysville, USA) and processed in accordance with the guidelines formulated by the Society of Behavioural Sleep Medicine (SBSM)\textsuperscript{115}. Data were visually inspected and excluded when activity counts and light values indicated detachment of the sensor. In all other cases, rest intervals were manually set when (i) event markers identified bed- and rise time, or – in case event markers were missing – when (ii) light and activity was absent. If light and activity values were ambiguous, (iii) diary entries were used to set rest intervals. The default setting (10-minutes immobility parameter) was used to identify sleep onset and sleep offset. Epochs were scored as wake if activity counts were above 40 (medium sleep-wake threshold).

Subjective sleep estimates were assessed using the Consensus Sleep Diary-E\textsuperscript{71}. In the morning, the sleep diary was filled in immediately following awakening, and lens glasses filter 100% of wavelength up to 400 nm, and 89-99.9% of wavelength between 400 and 500 nm. The effectiveness of these glasses in preserving normal evening melatonin production during bright-light exposure has been reported elsewhere\textsuperscript{130}. Therefore, most of the blue (wavelength of 490-450 nm), and parts of the green light (560 – 520 nm) was effectively restricted.

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Subjective sleep estimates were assessed using the Consensus Sleep Diary-E\textsuperscript{71}. In the morning, the sleep diary was filled in immediately following awakening, and
in the evening shortly before switching the lights off. Primary measures of interest was sleep onset latency (SOL; min), and secondary measures were wake after sleep onset (WASO; min), number of awakenings (#), total sleep time (TST; h:min), sleep quality (scale 1-10), and the feeling of being refreshed (scale 1-10). Lastly, alertness/sleepiness was assessed upon awakening and before bedtime using the Karolinska Sleepiness Scale (KSS)\(^7\). Scores ranging from 1-9, with higher scores indicating higher sleepiness.

### Behavioural Guidelines and Evaluation of the Glasses

To allow for a fair comparison between conditions, participants were instructed to follow a list of behavioural guidelines, including: (1) a regular sleep-wake pattern that was standardized within individuals, but could differ between individuals; (2) restricted alcohol and caffeine consumption to 300 mg caffeine and a maximum of two alcohol consumptions a day, with a weekly maximum of five alcohol containing beverages being tolerated.

During both conditions, sleep hygiene practices and compliance with the behavioural guidelines were monitored on a daily basis, by means of the evening section of the Consensus Sleep Diary-E\(^7\), and an adapted version of the Sleep Hygiene Index\(^6\) (SHI; yes/no answer format). The SHI asks participants to report the presence of several environmental characteristics and engagement in broad categories of physiologically and psychologically activating evening behavior that may potentially disturb sleep. Sleep hygiene items on staying in bed longer (item #5) and on sleep environment (item #10, 11) were removed, while items on sleep location (home/away), and on having a bed- or room partner (yes/no) were added.

In order to evaluate the convenience of the glasses, each evening, participants had to rate the usability and comfort of the respective evening glasses on a scale from 1 to 10, on which 10 indicates high usability / comfort.

### Data Processing and Statistical Analysis

The first two habituation nights and, due to technical issues\(^9\), the first three nights of each condition were omitted from analysis, leaving four nights per individual and per condition. Actigraphy- and diary-based sleep estimates, sleep hygiene scores, and ratings on usability / comfort were averaged across participants and conditions. Actigraphy and diary-based sleep onset latencies followed a non-normal

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distribution and were log10-transformed. Compliance to the behavioural guidelines and to sleep hygiene practices was compared between conditions using a paired t-test. The effectiveness of light-restriction as a means to improve sleep estimates was assessed using one-way repeated measure ANOVA’s. Based on our within-subject design, intervention effects directly follow from comparing the LR and nLR conditions (main effect of condition).

RESULTS

Sleep Hygiene Practices and Protocol Compliance

Preliminary analysis showed no significant differences between conditions for the respective sleep hygiene items (p’s > .068, Table 5.4), indicating that the light-restriction and the no-light-restriction conditions were performed under similar environmental and behavioural circumstances. Table 5.4 also displays the frequency of various sleep hygiene practices across all measurement days within each condition (i.e., showing the percentage of days on which specific practices occurred). Compliance with regular sleep-wake patterns was fair, as displayed by the lights-off and lights-on time shown in Table 5.5. For both actigraphy- and diary-based estimates, lights-off and lights-on times did not differ across conditions, with all p’s > .560.

Evaluation of the comfort of the glasses revealed that the amber-lens glasses (light-restriction condition; M ± SD; 6.72 ± 1.22) were rated about equally comfortable as the transparent glasses (no-light restriction condition; M ± SD; 6.96 ± 1.11). Also in terms of usability, the glasses were rated equally, with M ± SD; 7.33 ± 1.13 for the transparent glasses and M ± SD; 7.07 ± 1.32 for the amber-lens glasses. Taken together, these data indicate that the participants did wear the glasses and that it is unlikely that the comfort and usability of the different types of glasses impacted the current results.

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### Table 5.4. Sleep hygiene practices.

<table>
<thead>
<tr>
<th>No-light Restriction</th>
<th>Light Restriction</th>
<th>Results of Statistical Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Daytime naps lasting two or more hours, or past 3 PM</td>
<td>.07</td>
<td>.21</td>
</tr>
<tr>
<td>Went to bed 30 minutes earlier or later than yesterday</td>
<td>.33</td>
<td>.35</td>
</tr>
<tr>
<td>Got-up 30 minutes earlier or later than yesterday</td>
<td>.25</td>
<td>.35</td>
</tr>
<tr>
<td>Exercised within the last hour before bedtime</td>
<td>.12</td>
<td>.28</td>
</tr>
<tr>
<td>Used alcohol, tobacco, caffeine within the last four hours before bedtime</td>
<td>.28</td>
<td>.34</td>
</tr>
<tr>
<td>Did something that may wake me up before bedtime</td>
<td>.66</td>
<td>.26</td>
</tr>
<tr>
<td>Went to bed feeling stressed, angry, upset, or nervous</td>
<td>.10</td>
<td>.21</td>
</tr>
<tr>
<td>Use my bed for things other than sleeping or sex</td>
<td>.41</td>
<td>.41</td>
</tr>
<tr>
<td>I did important work before bedtime</td>
<td>.18</td>
<td>.29</td>
</tr>
<tr>
<td>I thought, planned, or worried when I was in bed</td>
<td>.02</td>
<td>.06</td>
</tr>
<tr>
<td>Slept at home</td>
<td>.98</td>
<td>.15</td>
</tr>
<tr>
<td>Had a bed or room partner</td>
<td>.04</td>
<td>.10</td>
</tr>
</tbody>
</table>

Note: The answer format of all questions was Yes (1) or No (0). Statistics are based on mean values rather than percentages. The percentages indicate how often a behavior occurred across all nights within each condition.
Table 5.5. Descriptive statistics and results of the statistical testing for actigraphy-based and diary-based sleep estimates.

<table>
<thead>
<tr>
<th></th>
<th>No-light Restriction</th>
<th>Light Restriction</th>
<th>Results of Statistical Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td>Actigraphy-based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lights-off</td>
<td>0.03</td>
<td>0.02</td>
<td>23.57</td>
</tr>
<tr>
<td>Lights-on</td>
<td>0.11</td>
<td>0.37</td>
<td>8.12</td>
</tr>
<tr>
<td>SOL (h:min)</td>
<td>10.90</td>
<td>11.95</td>
<td>5.98</td>
</tr>
<tr>
<td>WASO (h:min)</td>
<td>45.09</td>
<td>18.42</td>
<td>46.6</td>
</tr>
<tr>
<td>Fragmentation (%)</td>
<td>27.89</td>
<td>9.21</td>
<td>28.65</td>
</tr>
<tr>
<td>TST (h:min)</td>
<td>07:10</td>
<td>01:02</td>
<td>07:17</td>
</tr>
<tr>
<td>SE (%)</td>
<td>85.58</td>
<td>5.76</td>
<td>85.57</td>
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<tr>
<td>Diary-based</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Lights-off</td>
<td>23.55</td>
<td>00:55</td>
<td>23.46</td>
</tr>
<tr>
<td>Lights-on</td>
<td>08.09</td>
<td>00:32</td>
<td>08.14</td>
</tr>
<tr>
<td>SOL (h:min)</td>
<td>19.42</td>
<td>11.21</td>
<td>11.55</td>
</tr>
<tr>
<td>WASO (h:min)</td>
<td>13.15</td>
<td>9.04</td>
<td>10.60</td>
</tr>
<tr>
<td>Awakenings (#)</td>
<td>1.74</td>
<td>0.67</td>
<td>1.23</td>
</tr>
<tr>
<td>TST (h:min)</td>
<td>7.30</td>
<td>0.36</td>
<td>7.49</td>
</tr>
<tr>
<td>Sleep Quality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep Quality (1-10)</td>
<td>6.91</td>
<td>1.02</td>
<td>7.48</td>
</tr>
<tr>
<td>Refreshed (1-10)</td>
<td>6.43</td>
<td>1.25</td>
<td>6.94</td>
</tr>
<tr>
<td>KSS evening (1-9)</td>
<td>6.40</td>
<td>1.03</td>
<td>5.95</td>
</tr>
<tr>
<td>KSS morning (1-9)</td>
<td>4.23</td>
<td>1.32</td>
<td>3.62</td>
</tr>
</tbody>
</table>

Sleep Estimates

A full overview of sleep estimates (means, standard deviations and test outcomes) is displayed in Table 5.5. None of the actigraphy-based sleep estimates differed between the conditions (all $p’s > .310$). Diary-based sleep estimates, however, revealed shorter subjective sleep onset latencies and better subjective sleep quality in the light-restriction condition. Specifically, subjectively reported sleep onset...
latency was 8 minutes shorter in the light-restriction condition, with $F(1,12) = 11.607$, $p = .005$, $\eta^2_p = .492$. In addition, self-reported sleep quality was 0.6 points higher in the light-restriction condition compared to the no-light restriction condition, with $F(1,14) = 6.106$, $p = .027$, $\eta^2_p = .304$. Lastly, participants felt more alert in the morning following evenings on which the amber-lens glasses were worn, as compared to the transparent glasses (KSS; $\Delta = 0.61$, with $F(1,14) = 4.634$, $p = .049$, $\eta^2_p = .249$. In the evening, ratings of sleepiness showed no significant difference between conditions (KSS; $p = .112$). None of the remaining sleep estimates differed significantly between conditions (all $p's > .053$, Table 5.5).

**DISCUSSION**

The current pilot-study set out to investigate the effect of blocking short-wavelength light in the evening on improving sleep among recreational athletes. In line with the hypothesis, blocking short-wavelength light resulted in shorter subjective sleep onset latencies, better sleep quality and higher alertness in the morning, as compared to habitual evening light exposure (no light-restriction).

In line with previous studies suggesting that habitual melatonin secretion may be preserved by means of evening light restriction, blocking short-wavelength light was mainly effective in shortening subjective sleep onset latency but did not impact on secondary sleep estimates, such as total sleep time or wake after sleep onset. The observation that the sleep permissive effects of light-restriction were limited to subjective estimates is probably not surprising given the low wake-detection capacity of actigraphy, and usually small correlations between subjective and objective measures of sleep. Although future studies are thus required to examine effects on objective sleep estimates in more detail (preferably using polysomnography), the current results are in line with findings of several studies which show that exposure to short-wavelength light in the evening (e.g., through the use of electronic devices) is not always reflected in objective measures of sleep.

Importantly, the observed decrease in subjective sleep onset latency was accompanied with an increase in subjective sleep quality and morning alertness (see Table 5.5). Subjective sleep quality and alertness in the morning are considered primary outcomes in evaluating insomnia complaints, and improvements bear
relevance for athletes, as good subjective sleep quality and morning alertness can increase motivation and decrease perception of effort²⁵.

From a practical perspective, the current results indicate that selective evening short-wavelength light restriction may prove to be a cost-efficient and accessible way to improve subjective markers of sleep in athletes, requiring only small behavioural adjustments and no prior training. The high ease of use of amber-lens glasses facilitates high ‘therapist compliance’, especially when their design allows to wear them in public without attracting much attention. Given the promising results and the potential high ‘therapy compliance’, future research should further investigate and attempt to increase the effectiveness of short-wavelength light-restriction for optimizing sleep in healthy individuals. The current effects may be strengthened by additionally increasing morning- and daytime light exposure, which has already been shown to facilitate circadian entrainment and improve sleep estimates among populations with circadian rhythm- and neurological disorders¹⁵⁹, ¹⁷⁷, ¹⁷⁸. Moreover, because many devices that contribute to evening light exposure (e.g. smartphone, tablets) are associated with increased anxiety, stress, arousal and delayed bedtimes⁶⁸, ¹²³, results may be further strengthened if the stimulating effect of media use can be limited by ‘unplugging’ within the last hour before bedtime, and by keeping technologies out of the bedroom (e.g., ³³, ¹⁵³).

Limitations encountered in the current study should be addressed in future research. Monitoring the duration during which the glasses were worn before bedtime (protocol compliance), obtaining a more detailed measure of daytime light exposure (e.g., electronic device use), and utilizing markers of circadian phase, such as melatonin or core body temperature, may prove useful in determining the optimal duration and timing of light restriction. Furthermore, in line with previous studies, effects of light manipulation were visible in subjective but not in actigraphy-based measures of sleep (see also ¹⁷², ¹⁷³, ¹⁷⁴, ¹⁷⁵). Although participant instructions were designed to prevent outcome expectancies from influencing our findings, it is important that the current findings be replicated and extended with objective measurements. Especially since effects are likely to concentrate around sleep onset, employing sensitive objective measures of sleep, such as the gold standard Polysomnography, is highly recommended. Finally, future studies may attempt to extend the current findings to an elite athlete population (among whom evening exposure to short-wavelength light has been found to be particularly prevalent;
and examine whether positive effects on sleep also bear implications for recovery and performance.

CONCLUSION

In addition to current approaches aiming to improving sleep in athletes (see: for a recent review), the current pilot-study suggests that restriction of short-wavelength light in the evening can be an effective means to improve subjective sleep onset latency, sleep quality and alertness in the morning among healthy, recreational athletes in their habitual home-environment.

Footnote

During the first days of the protocol, participants pilot-tested a prototype of a light-emitting morning goggle to be used in later (follow-up) studies. Due to technical issues in the manufacturing of the morning goggles, this part of the study was aborted after night 2. To prevent any potential effect on our results – and before processing or analyzing the data – we conservatively excluded night 1-3 in both conditions for all participants.
CHAPTER 5D

INTERIM DISCUSSION AND CONCLUSION

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**INTERIM DISCUSSION**

The previous chapters (Chapter 5a, 5b, and 5c) provided an evidence-based sleep hygiene protocol for athletes, a pilot study assessing the effects of increased distal skin temperature on sleep, and a pilot study assessing the effects of restricting short-wavelength light in the evening on sleep, respectively.

While sleep hygiene strategies as provided in Chapter 5a are a good starting point in an attempt to optimize sleep, their sole effectiveness in treating insomnia symptoms is often debated. Whether athletes can follow specific sleep hygiene guidelines for an extended time period, and whether sleep can be optimized on the long term warrants empirical testing of such a protocol. Monitoring sleep and sleep hygiene practices during extended time periods, or during very specific occasions such as training camps and competitions, can help to identify patterns in sleep and sleep hygiene practices. The smartphone application that has been developed as an extension of the sleep hygiene protocol, provides an accessible means for this aim (Chapter 5a).

The pilot study depicted in Chapter 5b reveals that wearing heatable socks during the last 30 minutes before lights-off, was effective in increasing DPG but not in shortening sleep onset latency significantly or in improving the remaining (actigraphy-/one-channel EEG-based) sleep estimates among sub-elite athletes. These results are not in line with previous studies that were conducted in the laboratory. While the positive effects of mild skin warming on sleep onset latency can naturally be expected to be subtle, uncontrolled factors such as further circadian or homeostatic components, stress and additional wake promoting behaviors may have masked a potentially positive effect of the increase DPG on sleep onset latency. Future research is warranted to assess this mechanism in the field, while ensuring larger sample sizes and utilizing more sensitive measurement devices.

The pilot study assessing the effect of restricting evening-exposure to short-wavelength light on sleep revealed more promising results as outlined in Chapter 5c. More specifically, and in line with the study hypothesis, wearing amber-lens glasses to block short-wavelength light in the evening was effective in reducing self-reported sleep onset latency, improving sleep quality and alertness the following morning, as compared to habitual evening light exposure.

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Based on these promising results, a follow up study is warranted that overcomes some of the limitations of the presented study, such as a relatively small assessment period (i.e., four nights), a relatively small sample size, and lack of process evaluation and detailed protocol compliance. Furthermore, and in order to extend the effect of light regulation on sleep beyond self-reported sleep onset latency, quality and morning alertness, the potential additive effect of morning light exposure should be investigated. Prior studies have underlined the importance of morning and daytime light exposure for circadian entrainment and overall sleep consolidation\textsuperscript{159}. Yet, studies in the field that focused on sleep rather than circadian phase markers and on healthy individuals rather than individuals with disordered sleep\textsuperscript{160, 178-181}, are scarce.

CONCLUSION

It follows from the above that light restriction, as compared to mild distal skin warming, is a promising strategy for optimizing sleep among athletes in the habitual sleep environment. Integrating adequate sleep hygiene practices into athletes’ daily routines may further improve their sleep. The smartphone application that has been introduced in Chapter 5a provides an accessible platform that aids athletes to gain insight into their sleep, and sleep hygiene behaviors. Nevertheless, future research is warranted that addresses the limitations encountered in the pilot studies and the potential effect of these sleep optimization interventions on relevant performance indices.

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DIM LIGHT, SLEEP TIGHT, AND WAKE UP BRIGHT – SLEEP OPTIMIZATION IN ATHLETES BY MEANS OF LIGHT REGULATION

Based on:
ABSTRACT — Despite sufficient opportunity to sleep, athletes reveal relatively low sleep efficiency and quality. The timing and consolidation of sleep is driven by the circadian system, which requires periodic light-dark exposure for stable entrainment to the 24-hour day. Insufficient morning light exposure and evening light pollution may cause sleep problems. This study sought to determine whether combining fixed sleep-wake schedules with morning light exposure and short-wavelength light restriction in the evening (light regulation), as compared to a fixed sleep-wake schedule only (no light regulation), could optimize sleep in recreational athletes.

The study had a within-subject crossover design. Twenty-six athletes (mean age 24.64 years ± 3.43 (SD), 14 female, 12 male) were randomly assigned to start the intervention with either the light-regulation-week or the no light-regulation-week. Sleep was monitored by means of sleep diaries and actigraphy.

Data indicated low protocol adherence regarding the fixed sleep-wake schedules, therefore two datasets were constructed; one including athletes who managed to keep a strict sleep-wake schedule (n = 8), and one that also included athletes who had a more lenient sleep-wake schedule (n = 25). Light regulation improved self-reported sleep onset latency (Δ SOL = 8 minutes; lenient sleep-wake schedule) as compared to no light regulation. This effect was stronger (Δ SOL = 17 minutes) and complemented by enhanced subjective sleep quality in case of a strict sleep-wake schedule. None of the actigraphy-based estimates differed significantly between conditions. Light regulation may be considered an effective sleep optimization strategy for athletes, but less obtrusive methods should be explored to increase protocol compliance.
INTRODUCTION

The timing and consolidation of sleep is predominantly driven by the circadian system, which requires periodic light-dark exposure for stable entrainment to the 24-hour day. Timing of exposure to (sun-)light is often disturbed in athletes due to unfavorable and variable training and competition schedules, social and media obligations, electronic-device use, as well as spending time (training) indoors. In addition to irregular sleep-wake schedules, disturbed exposure to the light-dark cycle may be a contributing factor to the frequently reported problems of initiating and maintaining sleep and low sleep quality among (elite) athletes, in spite of sufficient sleep opportunity. Assuming that adequate sleep is an essential resource for recovery and performance capacity in athletes, the current study aimed to investigate whether imposing fixed sleep-wake schedules and mimicking a more natural light-dark cycle (i.e., bright morning-light exposure and evening light restriction), improves sleep.

The 24-hour light-dark cycle is the most potent ‘Zeitgeber’ for re-aligning the circadian rhythm to the geographical day. Information on environmental light is received by the classical photoreceptors in the retina and, via non-image forming intrinsically photoreceptive retinal ganglion cells (ipRGC), directly transmitted to the suprachiasmatic nucleus (SCN), the circadian ‘master clock’. The SCN sends information on circadian time to, for example, the pineal gland, where melatonin is secreted, thereby signaling optimal sleep timing. Morning light exposure synchronizes circadian phase and facilitates the process of waking up, while the absence of light facilitates melatonin secretion, which is a signal for optimal sleep timing in humans.

For circadian entrainment, light exposure needs to be of sufficient intensity, of a particular wavelength, and occur at a suitable circadian time (phase response curve). However, nowadays, day-time light exposure is often reduced as a consequence of time spent surrounded by low and static indoor lighting, which is most likely of insufficient intensity to entrain the circadian system. Whereas day-time light exposure tends to be insufficient, light pollution in the evening is often high. The spectral composition of artificial light is different from sunlight, and especially screen-light (e.g., emitted by TV, laptop, tablet and smartphone) has large proportions of short wavelength light (in the visual spectrum 440–450 nm) and is received by the classical photoreceptors in the retina and, via non-image forming ipRGC, directly transmitted to the SCN, the circadian ‘master clock’. The SCN sends information on circadian time to, for example, the pineal gland, where melatonin is secreted, thereby signaling optimal sleep timing. Morning light exposure synchronizes circadian phase and facilitates the process of waking up, while the absence of light facilitates melatonin secretion, which is a signal for optimal sleep timing in humans.

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of blue-/green light) that may suppress melatonin secretion by the pineal gland. In addition to the suppression of melatonin, light exposure in the evening is associated with reduced sleepiness, increased alertness, delayed sleep onset and reduced sleep efficiency. To counteract these effects, several studies have attempted to improve circadian rhythms- and sleep timing by increasing daytime light exposure and reducing evening light exposure. Studies focusing on shifting circadian phase indicate that short pulses of bright-light that are given at standardized times in the circadian night or circadian day, can effectively phase advance or delay circadian rhythms and sleep timing, with the aim to better align with a desired sleep-wake schedule. Thereby, and provided that the timing of light exposure is standardized across several consecutive days, these studies demonstrate the ability of the circadian system to entrain to light regardless of the timing of sleep. In line with this effect, daytime bright light exposure has been shown to result in improved sleep continuity, supposedly by increasing the SCN amplitude. Further sleep improvements included shorter sleep onset latency, advanced sleep onset time, increased sleep duration, improved daytime functioning and lower daytime sleepiness. Studies that focused on restricting light exposure in the evening indicate that this may also be an effective means to facilitate sleep. Specifically, a reduction of evening exposure to short-wavelength light has been shown to secure individuals’ habitual melatonin secretion, and supposedly circadian phase.

While both morning light exposure and evening light restriction may thus promote sleep, to date, their combined effect has only rarely been evaluated. The majority of studies evaluated the effectiveness of light in shifting or stabilizing circadian phase, using circadian phase markers rather than sleep estimates as outcome measure. In those cases that sleep was used as outcome measure, most studies concerned clinical populations that suffered from pathology-related sleep problems (e.g., Alzheimer’s disease, age-related optical changes in the eye, delayed/advanced sleep phase disorder, sleep onset insomnia). As such, the extent to which light regulation may benefit sleep in a young and healthy population of athletes remains unknown.

In search of a non-pharmaceutical sleep optimization strategy that may effectively improve athletes’ sleep in their home environment, the current study...
aimed to assess whether combining fixed sleep schedules with light regulation would lead to more consolidated sleep. It was hypothesized that compared to a fixed sleep schedule only, carefully timed morning-light exposure and blue-light blocking in the evening, would improve (1) objective, actigraphy-based measures of sleep onset latency, wake after sleep onset, sleep fragmentation, sleep efficiency and total sleep time; (2) subjective measures of sleep onset latency, wake after sleep onset, sleep efficiency and total sleep time, and (3) self-reported sleep quality, the feeling of being refreshed and sleepiness in the morning.

### METHODS

#### Pre-registration

Research question, hypotheses, in- and exclusion criteria, methods, materials, and statistical analyses were all pre-registered on the Open Science Framework and can be accessed online (osf.io/h2gu4). The study was approved by the faculty’s ethical committee [ECSW2016-1403-376]. After finalizing the study, participants were granted insight into their own sleep patterns, were provided with sleep education, and were financially reimbursed.

#### Participants

Thirty-one recreational athletes subscribed for the study with informed consent, of which 26 completed the protocol. Participants (14 female, 12 male) were aged between 19 and 32 years ($M \pm SD; 24.64 \pm 3.43$ yrs), and had an average body mass index of $21.83 \pm 2.27$ kg/m$^2$. All participants were physically active, exercising on average $8.90 \pm 4.56$ hours a week (Gymnastics, Martial Arts, Road Cycling, Rowing, Running, Strength Training, Tennis, Track and Field, Triathlon). On average, participants had somewhat poor sleep quality (Pittsburgh Sleep Quality Scale$^{69}; 5.19 \pm 3.07; M \pm SD; \text{cutoff } = 5$), but were without severe subjective sleep complaints (Holland Sleep Disorder Questionnaire$^{50}; 1.46 \pm .51; M \pm SD; \text{cutoff } \geq 2.02$). Participants were free of sleep medication and, based on the Munich ChronoType Questionnaire$^{187}$, showed no extreme chronotypes (midpoint of sleep on free days, corrected for ‘oversleep’ on free days: $\text{MSF}_{sc} = 4:07 \pm 0:28 \text{ h: min}$, range $3:06 - 5:00 \text{ h: min}$). Data was collected between February and May 2017, except for the week following the switch to daylight saving time (26th of March clocks advanced one hour).

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The measurement periods were planned such that for individual participants, the entire protocol was either completed before switching to daylight saving time, or started at least one week after the time adjustment.

**Design and Procedure**

The study had a within-subject crossover design. Three baseline nights were followed by two experimental weeks (intervention vs. control) that were scheduled one week apart to allow for residual effects to dissipate ("wear-off period"). The order of conditions was counterbalanced between participants. Participants were randomly assigned to start with either the light regulation week (LR; intervention), or the no light regulation week (nLR, control). In both conditions, sleep was monitored every night, by means of sleep diaries and wrist-worn actigraphy.

**Behavioral Guidelines**

To facilitate circadian entrainment and to allow for a fair comparison between conditions (LR versus nLR), in both conditions, participants were instructed to follow a set of behavioral guidelines, including: (1) a regular sleep-wake pattern, in which a maximal deviation in bed and rise times of 30 minutes was tolerated. Bed- and rise times were standardized within individuals to match personal preferences, but varied between individuals; (2) a maximum of 6 caffeinated beverages a day, none after 5:00 PM, and no more than two alcoholic consumptions a day. Lastly (3), the experimental weeks were individually scheduled such that they matched in terms of environmental and daily stressors (e.g. exams, training intensity, and competitions). Adherence to behavioral guidelines was not required during the 3-day baseline and the wear-off period in-between both conditions.

**Light Regulation**

In the light regulation condition (LR), portable, light-emitting goggles were worn each morning, for a period of 30 minutes upon final awakening (morning light exposure)\(^{182}\), whereas in the evening, blue-light blocking amber-lens glasses were worn during the last three hours before bedtime (evening light restriction)\(^{130}\). The light-emitting goggles administered light directly into the visual field via four light emitting diodes mounted on the lower frame of the goggles (Re-Timer\(^{TM}\), Bedford Park, SA, Australia). The device emitted blue-green light (500 nm) at an intensity
of 506 lm/m² and 230 μW/cm² (i.e., ‘high intensity’ setting), and has been shown to effectively shift circadian phase. The amber-lens glasses (Eye shield soft red Safety Glasses, Königswinter, Germany) filtered 100% of light with a wavelength up to 400 nm, and 89-99.9% of light with a wavelength between 400 and 500 nm, thereby restricting exposure to most of the blue and parts of the green light. The effectiveness of the amber-lens glasses in preserving normal evening melatonin production during bright-light exposure has been demonstrated elsewhere. In the no-light regulation condition (nLR), no morning goggles were worn and the amber-lens glasses were replaced by non-vision adjusting, transparent glasses (clear non-prescription lenses, Oramics). Thus, participants were not exposed to bright-light in the morning, nor was short-wavelength light restricted in the evening.

Protocol Adherence
To facilitate compliance, an instant messaging service (Esendex, UK) was installed to remind participants of morning- and evening goggle use and the behavioral guidelines, twice daily (morning and evening). Treatment compliance was assessed by means of a daily diary question assessing whether, and for how long, athletes wore the respective goggles. Compliance to the behavioral guidelines and potential differences in sleep hygiene were assessed daily, using items adapted from the Sleep Hygiene Index (SHI). Items on competition, sleep environment, and physical training load were added. Training load was measured on a scale from 1-10, with 10 indicating the highest possible training load, while all other items were assessed using a yes/no answer format. Compliance to a regular sleep-wake pattern was assessed by means of actigraphy.

Sleep Estimates
Objective sleep estimates were assessed by means of an actigraph (Actiwatch 2, Philips Respironics, Murrysville, USA). The actigraph was continuously worn around the non-dominant wrist and was only detached during training or when being in contact with water. Activity and photopic light were sampled in 60 second bins. Parameters of interest were sleep onset latency (SOL; min), wake after sleep onset (WASO; min), fragmentation index (%), total sleep time (TST; h:min), and sleep efficiency (SE; %). Actigraphy data were analyzed using Respironics Actiware 5 (Philips Respironics, Murrysville, USA) and processed in accordance with the
guidelines formulated by the Society of Behavioural Sleep Medicine (SBSM), as delineated by Ancoli-Israel, Martin, Blackwell, Buenaver, Liu, Meltzer, Sadeh, Spira, and Taylor115. Data were visually inspected and excluded when activity counts and light values indicated detachment of the sensor. In all other cases, rest intervals were manually set when (i) event markers identified bed- and rise time, or – in case event markers were missing – when (ii) light and activity were absent. If light and activity values were ambiguous, (iii) diary entries were used to set rest intervals. The default setting (10-minutes immobility parameter) was used to identify sleep onset and sleep offset. Epochs were scored as wake if activity counts were above 40 (medium sleep-wake threshold).

Subjective sleep estimates were assessed using the morning section of the Consensus Sleep Diary (CSD-M)71. Variables of interest were sleep onset latency (h:min), wake after sleep onset (h:min), total sleep time (h:min), and sleep efficiency (%; TST/TIB*100 = SE). For comparison of the experimental conditions, data on bedtime (h:min), lights-off time (h:min), rise-time (h:min), daytime naps (#, min.), caffeine and alcohol consumption, and sleep medication was also assessed. Finally, additional questions on the presence of a bed- or room-partner (yes/no), and the sleep location were added.

Subjective sleep quality was assessed using the corresponding item on sleep quality and feeling of being refreshed from the CSD-M71, with scores ranging from 1-10, with 10 indicating high sleep quality/refreshment. Alertness/sleepiness upon awakening was assessed using the Karolinska Sleepiness Scale (KSS)75, with scores ranging from 1-9, with higher scores indicating higher sleepiness.

**Process Evaluation**

Wearing of the glasses (yes/no) and the duration of use (h:min) were assessed on a daily basis, by means of self-report. Furthermore, after finalizing either condition, comfort and ease of use of the respective goggles were also assessed. Following Saunders, Evans, and Joshi189, the intervention process was evaluated after finalizing the whole study. This was done using an online survey. The survey first assessed participants’ self-perceived need for a sleep intervention (scale 1-10), with higher scores indicating a higher need for a sleep optimization strategy. Additionally, each goggle was evaluated on a set of symptoms adapted from the Light Effect Questionnaire by Lovato, and Lack188. Additional yes/no-items on whether the...
goggles interfered with daily activities, the ability to read, and the ability to see in the distance were added, as well as an item rating the appearance / looks of the goggles (scale 1-10), with higher scores indicating better looks.

Data Processing and Statistical Analysis

In line with the preregistration protocol, habituation nights and the wear-off week were omitted from the analysis. In addition, one participant was excluded due to structural napping shortly before bedtime. Nights on which the sleep environment was substantially different (e.g., sleeping mat during training-camp, 16 out of 350 nights), or on which participants did not comply with the protocol (i.e., wore the morning goggles for less than 20 minutes (3 out of 350 nights) or the evening goggles for less than 90 minutes (24 nights out of 350 nights)), were also excluded. To assess compliance with the instructed regular sleep-wake pattern (± 30 min.), actigraphy-based bed- and rise times were compared to an individual’s weekly average of the corresponding condition. Unfortunately, only one out of 25 individuals met the preregistered criterion for 100% of the experimental nights. Consequently, to allow for statistical analysis to proceed, we broadened the criterion such that all individuals who adhered to the instructed sleep-wake schedule for at least three nights in both conditions, were included (i.e., maximal deviation in bed and rise times ≤ 30 min; SW30, n = 8). At the individual level, only nights on which participants met this criterion were included. To further preserve statistical power and to assess the robustness of the intervention effect to larger variation in bed- and rise times, we generated a second data set in which we also included nights with a more irregular sleep-wake pattern (i.e., maximal deviation in bed and rise times ≤ 120 minutes; SW120, n = 25).

For each respective dataset (SW30 and SW120), actigraphy- and diary-based sleep estimates, including sleep hygiene items were averaged within participants and conditions. In each dataset, actigraphy- and diary-based sleep onset latency, as well as diary-based wake after sleep onset violated the assumption of normality and were log10 transformed. To assess the effectiveness of the intervention (LR vs. nLR) in both datasets, group means were tested against each other using separate one-way within subject repeated measure ANOVAs for each dependent variable. In all analyses, ‘order’ (starting with the LR condition vs. starting with the nLR condition) was initially added as covariate, but was only retained in case of

data only if significant. As such, data were treated as non-parametric with multiple one-way within subject repeated measure ANOVAs. To assess the effectiveness of the intervention (LR vs. nLR) in both datasets, group means were tested against each other using separate one-way within subject repeated measure ANOVAs for each dependent variable. In all analyses, ‘order’ (starting with the LR condition vs. starting with the nLR condition) was initially added as covariate, but was only retained in case of

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statistical significance (see footnote Table 6.1). Partial eta squared is provided as measure of effect size.

RESULTS

Behavioral Guidelines and Protocol Adherence

Preliminary analysis showed no significant differences between conditions for any of the sleep hygiene variables (all \( p's > .05 \), indicating that the LR and nLR conditions were performed under similar (environmental and behavioral) circumstances. Consequently, sleep hygiene items were not included as covariates in the main analysis. Results can be obtained upon request from the first author.

Overall, in the lenient dataset (SW120), sleep phase turned out to be slightly delayed in the LR condition, as was reflected in later actigraphy-based lights-off times (\( \Delta = 27 \) minutes, \( t(21) = -3.535, p = .002 \), and lights-on times (\( \Delta = 23 \) minutes, \( t(21) = -3.363, p = .003 \)), compared to the nLR condition. No differences (delayed sleep phase) were found for subjective sleep estimates, or in the strict sleep-wake dataset (SW30) (all \( p's > .399 \)).

Sleep Estimates

Across both conditions, sleep quality was fairly poor, as was reflected in actigraphy-based sleep efficiencies falling below the threshold of 85% (range 80.99% - 83.90%). On average, participants slept around 7 to 8 hours per night (see Tables 6.1 and 6.2).

Results of the statistical testing are displayed in Table 6.1 (strict; SW30) and Table 6.2 (lenient; SW120). None of the actigraphy-based sleep estimates differed significantly between conditions (all \( p's > .07 \)). Subjective reports, however, revealed faster sleep onset latencies in the LR condition for both datasets. In the strict dataset (SW30), subjective sleep onset latency was 17 minutes shorter in the LR condition compared to the nLR condition (\( F(1,22) = 14.641, p = .006, \eta^2 p = .677 \)). In the lenient dataset (SW120), this effect was smaller (\( \Delta \) SOL = 8 minutes, \( F(1,22) = 5.984, p = .023, \eta^2 p = .214 \)). No other sleep quantity estimates differed significantly between conditions (all \( p's > .07 \)).

Finally, in the strict dataset, the faster sleep onset latencies in the LR condition were accompanied by significantly better sleep quality (\( \Delta = 0.42 \), scale 1-10), with \( F(1,7) = 11.882, p = .011, \eta^2 p = .629 \). In the lenient dataset, faster sleep onset latencies in the LR condition were accompanied by significantly better sleep quality (\( \Delta = 0.42 \), scale 1-10), with \( F(1,7) = 11.882, p = .011, \eta^2 p = .629 \). In the lenient dataset,
this effect did not reach significance, $F(1,22)=1.103, p = .305, \eta^2_p = .048$. Across both datasets, none of the remaining sleep quality estimates differed significantly between conditions (all $p’s > .09$).

Table 6.1. Results obtained from the dataset including nights with regular sleep-wake patterns (SW30).

<table>
<thead>
<tr>
<th>30 minutes SW</th>
<th>No-light Regulation</th>
<th>Light Regulation</th>
<th>Results of Statistical Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M ± SD</td>
<td>M ± SD</td>
<td>$\eta^2_p$</td>
</tr>
<tr>
<td>Actigraphy-based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOL (h:min)</td>
<td>0.12 ± 0.11</td>
<td>0.16 ± 0.23</td>
<td>7.005 .944 .001</td>
</tr>
<tr>
<td>WASO (h:min)</td>
<td>1.02 ± 0.25</td>
<td>1.02 ± 0.27</td>
<td>7.000 .995 .000</td>
</tr>
<tr>
<td>Fragmentation (%)</td>
<td>32.0 ± 10.77</td>
<td>35.6 ± 11.29</td>
<td>6.000 .175 .690 .028</td>
</tr>
<tr>
<td>TST (h:min)</td>
<td>7.24 ± 0.51</td>
<td>7.10 ± 0.44</td>
<td>6.000 .314 .126 .344</td>
</tr>
<tr>
<td>SE (%)</td>
<td>83.53 ± 5.96</td>
<td>81.27 ± 6.71</td>
<td>6.000 .960 .365 .138</td>
</tr>
<tr>
<td>Diary-based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOL (h:min)</td>
<td>0.34 ± 0.27</td>
<td>0.17 ± 0.10</td>
<td>7.146 .006 .677</td>
</tr>
<tr>
<td>WASO (h:min)</td>
<td>0.25 ± 0.22</td>
<td>0.24 ± 0.21</td>
<td>7.003 .885 .003</td>
</tr>
<tr>
<td>TST (h:min)</td>
<td>7.41 ± 0.40</td>
<td>7.52 ± 0.39</td>
<td>7.153 .256 .180</td>
</tr>
<tr>
<td>SE (%)</td>
<td>89.19 ± 8.18</td>
<td>91.25 ± 7.96</td>
<td>7.150 .259 .177</td>
</tr>
<tr>
<td>Sleep Quality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep Quality (1-10)</td>
<td>6.63 ± 0.88</td>
<td>7.05 ± 0.67</td>
<td>7.118 .011 .629</td>
</tr>
<tr>
<td>Refreshed (1-10)</td>
<td>6.20 ± 1.15</td>
<td>6.38 ± 1.32</td>
<td>7.393 .088 .360</td>
</tr>
<tr>
<td>KSS (1-9)</td>
<td>5.51 ± 1.42</td>
<td>5.16 ± 1.28</td>
<td>7.138 .289 .158</td>
</tr>
</tbody>
</table>

Note. *The covariate ‘order’ was significant and remained in the statistical model. SOL = sleep onset latency, WASO = wake after sleep onset, TST = total sleep time, SE = sleep efficiency, KSS = Karolinska Sleepiness Scale.

Process Evaluation

Across both datasets (n = 25), the light-emitting goggles were rated as rather uncomfortable (M ± SD; 4.88 ± 1.87, scale 1-10), but relatively easy to use (M ± SD; 6.59 ± 1.66, scale 1-10). The amber-lens glasses (LR) were rated more comfortable than the transparent glasses (nLR), with M ± SD; 6.31 ± 1.78 and 6.00 ± 1.46, respectively.
respectively, but without reaching statistical significance ($t(15) = -0.573, p = 0.575$). With regard to ease of use, there was no difference in ratings between both glasses ($t(15) = 0.000, p = 1.00$), with 6.81 ± .39 for the transparent glasses and 6.81 ± .61 for the amber-lens glasses.

Upon finalizing the experiment, a majority of participants indicated that they felt in need of a sleep optimization strategy ($M ± SD: 6.79 ± 2.36$; scale 1-10), with 18 participants scoring > 6 and six participants scoring ≤ 6. Two participants had missing data on this item. Table 6.3 displays a set of symptoms related to wearing the different goggles. Overall, the light-emitting goggles received the poorest ratings on appearance and symptoms, followed by the amber-lens glasses and the transparent glasses.

Table 6.2. Results obtained from the dataset including irregular sleep-wake pattern (SW120).

<table>
<thead>
<tr>
<th>120 minutes SW</th>
<th>No-light Regulation</th>
<th>Light Regulation</th>
<th>Results of Statistical Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M ± SD</td>
<td>M ± SD</td>
<td>F</td>
</tr>
<tr>
<td>Actigraphy-based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOL (min)</td>
<td>0.16 ± 0.20</td>
<td>0.11 ± 0.13</td>
<td>21</td>
</tr>
<tr>
<td>WASO (min)</td>
<td>0.58 ± 0.23</td>
<td>1.03 ± 0.33</td>
<td>21</td>
</tr>
<tr>
<td>Fragmentation (%)</td>
<td>34.90 ± 15.10</td>
<td>36.71 ± 14.62</td>
<td>21</td>
</tr>
<tr>
<td>TST (h:min)</td>
<td>7.04 ± 0.49</td>
<td>6.55 ± 0.59</td>
<td>21</td>
</tr>
<tr>
<td>SE (%)</td>
<td>82.37 ± 9.81</td>
<td>80.99 ± 11.15</td>
<td>21</td>
</tr>
<tr>
<td>Diary-based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOL (min)</td>
<td>0.21 ± 0.20</td>
<td>0.20 ± 0.21</td>
<td>22</td>
</tr>
<tr>
<td>WASO (min)</td>
<td>7.40 ± 0.45</td>
<td>7.42 ± 0.53</td>
<td>22</td>
</tr>
<tr>
<td>TST (h:min)</td>
<td>92.10 ± 6.42</td>
<td>92.45 ± 6.74</td>
<td>22</td>
</tr>
<tr>
<td>SE (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep Quality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep Quality (1-10)</td>
<td>6.81 ± 0.83</td>
<td>6.95 ± 0.94</td>
<td>22</td>
</tr>
<tr>
<td>Refreshed (1-10)</td>
<td>6.37 ± 1.01</td>
<td>6.43 ± 1.06</td>
<td>22</td>
</tr>
<tr>
<td>KSS (1-9)</td>
<td>4.90 ± 1.38</td>
<td>4.75 ± 1.11</td>
<td>22</td>
</tr>
</tbody>
</table>

Note: SOL = sleep onset latency, WASO = wake after sleep onset, TST = total sleep time, SE = sleep efficiency, KSS = Karolinska Sleepiness Scale.

Table 6.2. Results obtained from the dataset including irregular sleep-wake pattern (SW120).

<table>
<thead>
<tr>
<th>120 minutes SW</th>
<th>No-light Regulation</th>
<th>Light Regulation</th>
<th>Results of Statistical Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M ± SD</td>
<td>M ± SD</td>
<td>F</td>
</tr>
<tr>
<td>Actigraphy-based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOL (min)</td>
<td>0.16 ± 0.20</td>
<td>0.11 ± 0.13</td>
<td>21</td>
</tr>
<tr>
<td>WASO (min)</td>
<td>0.58 ± 0.23</td>
<td>1.03 ± 0.33</td>
<td>21</td>
</tr>
<tr>
<td>Fragmentation (%)</td>
<td>34.90 ± 15.10</td>
<td>36.71 ± 14.62</td>
<td>21</td>
</tr>
<tr>
<td>TST (h:min)</td>
<td>7.04 ± 0.49</td>
<td>6.55 ± 0.59</td>
<td>21</td>
</tr>
<tr>
<td>SE (%)</td>
<td>82.37 ± 9.81</td>
<td>80.99 ± 11.15</td>
<td>21</td>
</tr>
<tr>
<td>Diary-based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOL (min)</td>
<td>0.21 ± 0.20</td>
<td>0.20 ± 0.21</td>
<td>22</td>
</tr>
<tr>
<td>WASO (min)</td>
<td>7.40 ± 0.45</td>
<td>7.42 ± 0.53</td>
<td>22</td>
</tr>
<tr>
<td>TST (h:min)</td>
<td>92.10 ± 6.42</td>
<td>92.45 ± 6.74</td>
<td>22</td>
</tr>
<tr>
<td>SE (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep Quality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep Quality (1-10)</td>
<td>6.81 ± 0.83</td>
<td>6.95 ± 0.94</td>
<td>22</td>
</tr>
<tr>
<td>Refreshed (1-10)</td>
<td>6.37 ± 1.01</td>
<td>6.43 ± 1.06</td>
<td>22</td>
</tr>
<tr>
<td>KSS (1-9)</td>
<td>4.90 ± 1.38</td>
<td>4.75 ± 1.11</td>
<td>22</td>
</tr>
</tbody>
</table>

Note: SOL = sleep onset latency, WASO = wake after sleep onset, TST = total sleep time, SE = sleep efficiency, KSS = Karolinska Sleepiness Scale.
Table 6.3. Process evaluation outcome and list of identified symptoms.

<table>
<thead>
<tr>
<th></th>
<th>Light goggles</th>
<th>Amber glasses</th>
<th>Transparent glasses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headache</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dizziness</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nausea</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Eye irritation</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Eye redness</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Blurred vision</td>
<td>9</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Light bothersome to eyes</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Restlessness</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Excessive energy</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Irritability</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Other:</td>
<td>6</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

`Looking down, showering, eating, moving, social activities, getting dressed, walking the stairs in the dark, seeing dots/stars, orientating in the dark, no depth vision` | `Dry eyes, showering, intimacy, reflections of light-sources in the dark, no sharp vision, eye lashes touched the glasses, tired eyes, reduced vision in dark places, getting tired more easily` | `Dry eyes, showering, intimacy` |

<table>
<thead>
<tr>
<th></th>
<th>Light goggles</th>
<th>Amber glasses</th>
<th>Transparent glasses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance (1-10)</td>
<td>3.92 ± 2.17</td>
<td>4.12 ± 2.21</td>
<td>6.23 ± 1.66</td>
</tr>
<tr>
<td>Inconvenience during other activities (yes)</td>
<td>17</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>Reading (yes)</td>
<td>24</td>
<td>25</td>
<td>26</td>
</tr>
<tr>
<td>Distance vision (yes)</td>
<td>23</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>
DISCUSSION

The current study sought to determine whether combining fixed sleep schedules with light regulation (LR), as compared to a fixed sleep schedule only (nLR), can improve sleep in recreational athletes. Overall, results indicated the effectiveness of light regulation (light exposure in the morning and light restriction in the evening) in shortening self-reported sleep onset latency, compared to no light regulation. This effect was stronger and complemented by improved subjective sleep quality when athletes kept a strict sleep-wake schedule. No significant differences between conditions were observed for the remaining subjective sleep parameters or for actigraphy-based estimates.

Using objective as well as subjective measures to evaluate sleep is common and crucial in both clinical and research settings. Krystal and Edinger explain that individuals may report poor sleep quality despite of objective markers indicating good quality sleep, and vice versa. Because of the low wake-detection capacity in actigraphy, it is not surprising that effects were found for subjective, but not for objective markers of sleep. Individuals’ subjective perception of sleep onset latency and sleep quality is fundamental to the evaluation of restorative sleep and considered a primary outcome in evaluating insomnia complaints. Hence, a shortening of 17 minutes in sleep onset latency and an improved rating of sleep quality, as demonstrated in the strict light regulation condition of this study, can be considered as highly relevant improvement (cf. 20 minutes post full CBT-I treatment). One last curiosity that deserved mentioning is the slight delay in actigraphy-based sleep phase on nights on which the amber-lens glasses were worn. Based on the combination of morning light exposure and evening light restriction, a phase advance would be expected rather than a phase delay. Given that subjective sleep estimates did not show a delayed sleep phase, and knowing that field studies feature greater variation in sleep timing, this observation may be considered incidental.

The observation that subjective sleep estimates improved with light regulation despite deviations from the (strict) sleep-wake protocol, warrants discussion of responsible mechanisms. In order to facilitate optimal alignment between sleep phase and the circadian system, morning light exposure needs to be carefully timed across standardized times of day (or with regard to ones’ mid-sleep), and for several conditions were observed for the remaining subjective sleep parameters or for actigraphy-based estimates.

Using objective as well as subjective measures to evaluate sleep is common and crucial in both clinical and research settings. Krystal and Edinger explain that individuals may report poor sleep quality despite of objective markers indicating good quality sleep, and vice versa. Because of the low wake-detection capacity in actigraphy, it is not surprising that effects were found for subjective, but not for objective markers of sleep. Individuals’ subjective perception of sleep onset latency and sleep quality is fundamental to the evaluation of restorative sleep and considered a primary outcome in evaluating insomnia complaints. Hence, a shortening of 17 minutes in sleep onset latency and an improved rating of sleep quality, as demonstrated in the strict light regulation condition of this study, can be considered as highly relevant improvement (cf. 20 minutes post full CBT-I treatment). One last curiosity that deserved mentioning is the slight delay in actigraphy-based sleep phase on nights on which the amber-lens glasses were worn. Based on the combination of morning light exposure and evening light restriction, a phase advance would be expected rather than a phase delay. Given that subjective sleep estimates did not show a delayed sleep phase, and knowing that field studies feature greater variation in sleep timing, this observation may be considered incidental.

The observation that subjective sleep estimates improved with light regulation despite deviations from the (strict) sleep-wake protocol, warrants discussion of responsible mechanisms. In order to facilitate optimal alignment between sleep phase and the circadian system, morning light exposure needs to be carefully timed across standardized times of day (or with regard to ones’ mid-sleep), and for several...
consecutive days\textsuperscript{140, 158}. In our study, however, light exposure was effectively established for only a limited number of days, not always consecutive (e.g., due to difficulty with protocol adherence) and, at least in the lenient dataset (SW120), not strictly timed across set times of day. Although more rapid effects of light exposure cannot be omitted (see\textsuperscript{193}), it is thus doubtful that alignment of the circadian system to the sleep phase was sufficient to improve sleep consolidation. Effects of evening light restriction, on the other hand, are more robust to variation in bed- and rise times and, therefore, more likely to have contributed to the observed improvement in subjective sleep estimates. In both the strict and more lenient dataset (SW30 and SW120), reduced exposure to short-wavelength light in the evening may have counteracted the alerting effects of light and allowed for habitual melatonin onset\textsuperscript{123, 124}. This, in turn, may have facilitated sleepiness and sleep onset. In the strict dataset (SW30), more consistent timing of morning light exposure may have strengthened this effect and improved self-reported sleep quality, as morning light exposure provided a stronger ‘Zeitgeber’\textsuperscript{178, 180}.

While light regulation appears to be a promising intervention to facilitate sleep, process evaluation and protocol adherence highlighted that practical implementation of the intervention is problematic. Process evaluation revealed that whilst wearing the morning goggles was unproblematic (only 3 out of 350 nights were excluded), the goggles were rated as being rather uncomfortable. Furthermore, athletes had difficulties wearing the evening glasses for the prescribed duration of three hours prior to bedtime (amber-lens glasses and transparent glasses, 16 out of 350 nights excluded). Active participation in traffic, social interaction and evening-trainings were frequently reported activities that interfered with wearing of the glasses, leading athletes to engage in alternative activities (e.g., stay inside as opposed to going out) or wearing the glasses for shorter periods of time. Based on these results, and to further enhance user-friendliness of the intervention, future work may therefore consider alternative, less obtrusive ways of light regulation that are feasible indoors, outdoors and without attracting much attention in public. Furthermore, given the difficulty that most participants showed to adhere to a strict sleep-wake schedule, future work might explicitly test differences in intervention effectiveness depending on variability in bed- and rise times.

It is important to acknowledge that the current study was performed in an ambulatory setting. While on the one hand this introduced variability in the study,
especially with respect to protocol compliance, it also provided a realistic field-test; exposing potential difficulties in terms of practical implementation of the intervention. In addition, it should be acknowledged that the current choice to consider combined effects of morning light exposure and evening light restriction (i.e., with the aim to maximize potential effects on sleep), makes it impossible to draw conclusions regarding independent intervention components. Hence, to disentangle the individual contribution of morning light exposure and evening light restriction, future work is required. Finally, the protocol may be further strengthened by including an objective manipulation check of (daytime) light exposure and a marker of circadian phase (e.g., melatonin, core body temperature or cortisol).

CONCLUSION

In sum, the current study shows that carefully timed exposure to bright-light in the morning combined with restriction of short-wavelength light in the evening is effective in shortening self-reported sleep onset latencies in recreational athletes. This effect was stronger and accompanied by improved sleep quality, if athletes kept a strict sleep-wake schedule. Although user-friendliness of the intervention may be further improved, the observed magnitude of effects (i.e., average Δ SOL between 8 and 17 minutes) suggests that light regulation may be considered a meaningful sleep optimization strategy for athletes.
CHAPTER 7

GENERAL DISCUSSION
Athletes need sufficient opportunity to recover from previous exercise and to perform at the peak of their capabilities. Considering that sleep is the recovery strategy par excellence and indispensable for overall health and performance capacity, the current thesis aimed to: (1) characterize sleep of elite athletes, (2) identify factors that adversely affect sleep, (3) investigate the effects of sleep on performance and, (4) explore promising interventions to optimize sleep in athletes.

Structured along the lines of these main aims, this final chapter provides a general discussion of the results. Subsequently, strengths and limitations, future research prospects, and practical implications are addressed, and a general conclusion is formulated.

### DISCUSSION OF MAIN FINDINGS

#### Aim 1: Characterizing sleep of elite athletes

Upon commencing the current research, available evidence suggested inferior sleep among elite athletes as compared to gender and age-matched, non-athletic controls. The observation of poor sleep among athletes appeared to be relatively coherent across sports and contexts, but was predominantly based on actigraphy-based estimates. To extend knowledge, the current thesis provided insight into subjective sleep estimates (i.e., questionnaires, diaries). Moreover, a refined actigraphy sleep-wake sensitivity threshold was employed to improve measurement accuracy and, for the first time, EEG-based analyses of sleep stage distributions were conducted at a large scale. All estimates were collected among a large and representative cohort of 98 elite athletes during a week of habitual training (Chapters 2 and 3).

In general, elite athletes were found to be healthy sleepers. However, based on sub-clinical questionnaires, it was shown that a vast minority of 41% did classify as poor sleeper (PSQI cutoff poor sleeper ≥ 5) and that 12% was identified as having a potential sleep disorder (HSDQ cutoff ≥ 2.02). Restless leg symptom / periodic limb movement disorder (RLS/PLMD) was the most frequently reported sleep disturbance. Daily self-reports revealed an average sleep duration of 8 hours.
well within the recommended range of 7-9 hours\textsuperscript{12, 13}. Yet, self-reported sleep onset latency (20 minutes) and wake after sleep onset (13 minutes) revealed areas for improvement. Finally, self-reports of sleep quality revealed that, with the given amount of sleep, athletes felt only moderately refreshed, alert, and vigorous in the morning\textsuperscript{89}.

Actigraphy-based sleep estimates depicted a similar pattern. As may be expected, absolute values did differ from subjective measures\textsuperscript{83, 170, 171}. The seven-day average sleep duration was close to 8 hours. Wake after sleep onset was elevated (33 minutes) and sleep efficiency (88%) was lower than the average for this age group (i.e., 92%)\textsuperscript{94}. The latter finding indicates relatively fragmented sleep. During 22% of the nights, sleep efficiency scores were below 85%, a threshold that is considered the upper limit for poor sleep\textsuperscript{95}.

Analysis of the EEG-based sleep stage distributions revealed typical values for the amount of light and REM sleep\textsuperscript{5, 94} (Chapter 3). However, in line with the high activity level of elite athletes\textsuperscript{56}, the amount of deep sleep was at the higher end of the optimum (21%)\textsuperscript{117}. According to the recovery hypothesis of sleep, deep sleep adapts to the body’s current need for recovery. That is, the amount of deep sleep typically increases with sustained wakefulness or following strenuous exercise\textsuperscript{10}. As such, the relatively high proportion of deep sleep may reflect an elevated recovery need in athletes.

Professional athletes are starting to acknowledge the importance of sleep for optimal recovery and performance capacity, as is reflected in anecdotes of sleep durations between 8 and 16 hours\textsuperscript{192}. The results of Chapters 2 and 3, however, revealed that such sleep durations are still the exception rather than the rule. With an average sleep duration of 8 hours per night, objective sleep estimates remained within healthy ranges and were slightly more favorable compared to previous reports\textsuperscript{25, 26}. This may be due to the more liberal actigraphy setting that was employed in the current study (i.e., \( AW > 80 \) instead of \( AW > 40 \))\textsuperscript{55}. Nevertheless, sleep deficiencies were in line with previous reports\textsuperscript{25, 26}, as was featured by relatively long sleep onset latencies and elevated wake after sleep onset\textsuperscript{94}. Self-reports of sleep revealed a similar picture. For some athletes (41% PSQI; 12% HSDQ) sleep is relatively poor or below clinically relevant thresholds. Furthermore, despite sufficient opportunity to sleep (~8:30 hours of time in bed based on actigraphy), sleep diaries revealed that athletes did not feel well-rested in the morning\textsuperscript{89, 117}.
This may be a consequence of the observed elevations in sleep onset latency and fragmented sleep. The current results are in line with Gupta, Morgan, and Gilchrist\textsuperscript{27}, who observed that insomnia symptomatology, defined as longer sleep onset latencies, sleep fragmentation, non-restorative sleep, and excessive daytime fatigue, are high among elite athletes. According to these authors, elite athletes’ sleep is particularly vulnerable during competitive events, high-intensity training, and long-haul travel\textsuperscript{27}. The results depicted in the current thesis suggest that, in some individuals and during some nights, sleep is also under pressure during periods of habitual training.

**Box I. Conclusion Aim 1: Characterizing sleep of elite athletes (Chapters 2 and 3).**

- Athletes’ sleep generally remained within healthy ranges.
- Despite sleep durations of approximately 8 hours per night, ratings of feeling refreshed and alert in the morning were meagre, potentially indicating insufficient recovery.
- A substantial minority of athletes (41\%) reported poor sleep quality.
- Actigraphy-based estimates revealed relatively long sleep onset latencies, elevated wake after sleep onset and sleep fragmentation.
- Overall, results suggest a need for more continuous and effective sleep in athletes.

**Aim 2: Identifying sleep jeopardizing factors**

Elite athletes frequently encounter circumstances that may interfere with adequate sleep – wake regulation\textsuperscript{30, 31}. In the literature, several sleep compromising factors have been identified among elite athletes, including psychological and physiological pre-sleep arousal\textsuperscript{15, 52, 63} , jet lag\textsuperscript{44} , and training and competition schedules\textsuperscript{15, 46, 50, 51}. To counteract the detrimental effects of these factors on sleep, sleep education and optimization of sleep hygiene strategies are often recommended\textsuperscript{14}. At the start of the current research, however, a detailed quantification of sleep hygiene practices among elite athletes was lacking. To this end, the current thesis assessed a broad range of sleep hygiene practices during habitual training periods of elite athletes. Also, the extent to which sleep hygiene practices were associated with self-reported estimates of sleep was calculated (Chapter 2).

Overall, sleep hygiene practices were adequate. Yet, results revealed that athletes have difficulties to keep regular sleep-wake patterns, experience psychological strain and fragmentation of sleep. The current results are in line with Gupta, Morgan, and Gilchrist\textsuperscript{27}, who observed that insomnia symptomatology, defined as longer sleep onset latencies, sleep fragmentation, non-restorative sleep, and excessive daytime fatigue, are high among elite athletes. According to these authors, elite athletes’ sleep is particularly vulnerable during competitive events, high-intensity training, and long-haul travel\textsuperscript{27}. The results depicted in the current thesis suggest that, in some individuals and during some nights, sleep is also under pressure during periods of habitual training.

**Box I. Conclusion Aim 2: Identifying sleep jeopardizing factors**

- Athletes’ sleep generally remained within healthy ranges.
- Despite sleep durations of approximately 8 hours per night, ratings of feeling refreshed and alert in the morning were meagre, potentially indicating insufficient recovery.
- A substantial minority of athletes (41\%) reported poor sleep quality.
- Actigraphy-based estimates revealed relatively long sleep onset latencies, elevated wake after sleep onset and sleep fragmentation.
- Overall, results suggest a need for more continuous and effective sleep in athletes.
in the evening, and engage in activating pre-sleep activities\textsuperscript{89}. These questionnaire results were complemented by a seven-day diary assessment of sleep hygiene practices. Again, only a few behaviors appeared to be suboptimal. These suboptimal behaviors included late-evening consumptions of heavy meals and caffeinated beverages, as well as engagement in sedentary activities that involved artificial light exposure in the evening (75\% of nights). A notable observation was that athletes infrequently engaged in daytime sleep (naps; 18\% of days).

Correlation analyses indicated that adequate sleep hygiene is indeed associated with better sleep quality and less disordered sleep among athletes. This is in line with reports among non-athletes\textsuperscript{76}. The association between sleep hygiene and sleep was relatively strong for questionnaire results, but weaker and less consistent for the daily monitored sleep hygiene behaviors\textsuperscript{89}. In light of these results, improving sleep hygiene practices may further facilitate sleep in athletes. Standardizing bed- and wake times, reducing psychological strain and avoiding activating pre-sleep activities seem to be promising paths to go.

Given the prominent role of training in athletes’ daily routines, special attention was paid to identifying the effects of (variation in) training load on sleep. To this end, variations in athletes’ self-reported training load were monitored over a seven-day training period and associations with actigraphy- and EEG-based sleep estimates were calculated (Chapter 3). Results revealed moderate training load (mean = 5.4, scale 1-10) across all seven-days of assessment. Large intra-individual differences were observed that low, medium and sometimes high levels of training load were covered\textsuperscript{117}. Despite relatively large variation within individuals, day-to-day differences in self-reported training load were not reflected in actigraphy-based sleep measures (e.g., sleep duration, sleep efficiency), nor in EEG-based sleep stage distributions\textsuperscript{117}.

The observation that sleep was irresponsive to variation in training load contradicts prior studies\textsuperscript{48, 49}, and requires discussion of alternative explanations. The observed null-findings can be attributed to three main causes related to training intensity, timing and environmental circumstances. First, in the current study, extremely high values of training load (i.e., perceived training load ≥ 9) were underrepresented, training demands and rest were more carefully balanced across the week (i.e., alterations in low, medium and high training load), and generally less intense compared to previous studies that showed compromised sleep following
extended periods of intensified training load\textsuperscript{48, 49}. Second, in the current study, training was ended at least within three hours before bedtime, which may have reduced adverse effects of elevated core body temperature\textsuperscript{25}, high (physiological) arousal\textsuperscript{35}, or increased metabolism\textsuperscript{96} on sleep. Third, given that the current study was conducted in a field setting, the effects of training load on sleep may have been masked or outweighed by a multitude of (environmental) factors that actively influence sleep. Thus, small changes in one particular factor may not necessarily have a significant impact on sleep.

### Box II. Conclusion Aim 2: Identifying sleep jeopardizing factors (Chapters 2 and 3).

- Sleep hygiene was adequate, but might benefit from the following actions:
  - Regularity in bed- and rise times
  - Reducing psychological strain
  - Reducing activating pre-sleep activities
  - Avoiding large meals and caffeine before bedtime
  - Avoiding (blue) light in the evening.
- Sleep hygiene is generally associated with better sleep quality.
- Day-to-day variation in self-reported training load did not significantly impact sleep.
- Improving critical sleep hygiene aspects may facilitate continuous and effective sleep.

### Aim 3: Establishing the effects of sleep on athletic performance

While still in its infancy, prior research suggests a deterioration of cognitive and athletic performances following (partial) sleep deprivation\textsuperscript{3}, while performance appears to improve following sleep extension\textsuperscript{23, 24}. Importantly, in their daily life, athletes usually encounter subtle day-to-day changes in sleep that are smaller than the changes employed in experimental studies (e.g., ± 4 hours). Given the lack of research, the extent to which such small changes in sleep may be reflected in (sport-specific) performance as yet remains unclear. Against this background, the study reported in Chapter 4 is the first in the literature to shed light on the extent to which rather mild, naturally occurring day-to-day variations in sleep quantity and sleep stages are reflected in the cognitive and sport-specific performance of elite athletes.

In Chapter 4, actigraphy-based sleep estimates and one-channel EEG-based sleep stage durations, as well as psychomotor vigilance and sport-specific

extended periods of intensified training load\textsuperscript{48, 49}. Second, in the current study, training was ended at least within three hours before bedtime, which may have reduced adverse effects of elevated core body temperature\textsuperscript{25}, high (physiological) arousal\textsuperscript{35}, or increased metabolism\textsuperscript{96} on sleep. Third, given that the current study was conducted in a field setting, the effects of training load on sleep may have been masked or outweighed by a multitude of (environmental) factors that actively influence sleep. Thus, small changes in one particular factor may not necessarily have a significant impact on sleep.

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In Chapter 4, actigraphy-based sleep estimates and one-channel EEG-based sleep stage durations, as well as psychomotor vigilance and sport-specific
performance of fine and gross motor skills were repeatedly assessed among a large cohort of elite athletes. Results revealed that small changes in total sleep time were immediately reflected in small but significant changes in psychomotor vigilance (i.e., reaction time) the following day. Additionally, small and inconsistent effects of sleep quantity and sleep stages on gross motor skill performance were observed, but no effects were established for fine motor skill performances\textsuperscript{166}.

In line with previous research\textsuperscript{16}, a dose-response relationship between sleep duration and psychomotor vigilance was found. Accordingly, results indicate larger performance decrements following more substantial sleep loss while, at the same time, suggesting that sleep extension may result in significant performance benefits\textsuperscript{23, 24}. Due to a heavier reliance on cognitive functions, it was hypothesized that fine motor skill performance would be more compromised by changes in sleep than gross motor skill performance. However, in the current study the opposite was the case. Fine motor skills remained insensitive to changes in sleep, while some weak and contradictory effects were observed for gross motor skill performance.

In explaining why sleep only had limited effects on performance, three potential causes may be mentioned. First, natural variations in sleep were rather small, and this may explain why effects on performance were also small. Second, inconsistent findings concerning sleep and athletic performance may (in part) be attributed to the somewhat smaller number of observations that could be obtained for the sport-specific tests of fine and gross motor skill (see Table 4.1 in Chapter 4). Third, aggregating (pooling) data from different performance tests may have further reduced the sensitivity of the performance outcomes (see ‘Methods – Data processing’ in Chapter 4). Future research that involves larger variation in sleep estimates and larger sample sizes in testing effects on performance is warranted to indicate the thresholds for changes in sleep to be reflected in different types of athletic performance.

**Box III.** Conclusion Aim 3: Establishing the effects of sleep on athletic performance (Chapter 4).

- Day-to-day variation in sleep duration immediately impacts psychomotor vigilance (reaction time) the following morning.
- The impact of sleep duration on psychomotor vigilance showed a dose-response relationship.
- Athletic performance was not or only inconsistently affected by small changes in sleep.
Aim 4: Optimizing sleep in athletes
In order to improve the sleep deficiencies identified in Chapters 2 and 3, and potentially optimize performance (Chapter 4), the current thesis aimed to examine the effectiveness of specific sleep interventions. Despite the health and performance benefits of adequate sleep, the number of interventions tested among a healthy population such as elite athletes, as yet is limited. Based on the observed associations between sleep hygiene and sleep quality (Chapter 2), Chapter 5a provided an evidenced-based sleep hygiene protocol and presented a smartphone application that athletes can use to self-monitor their sleep hygiene and sleep quality during training and competition periods. Next, specific interventions were examined that aimed at reducing the noted deficiencies in sleep onset latency and wake after sleep onset, including sleep fragmentation (Chapter 2 and 3). In Chapters 5b and 5c, two studies were reported that evaluated the merit of temperature and light interventions (i.e., chronobiological interventions). The results outlined in Chapter 5b revealed that wearing heatable socks (vs. conventional socks) during the last 30 minutes before bedtime effectively increased distal to proximal skin temperature gradient (DPG) in sub-elite athletes. However, against expectations, the augmented DPG did not result in shorter sleep onset latency or improvement of the remaining actigraphy- and one-channel EEG-based sleep estimates.

In Chapter 5c, a pilot study was described in which short-wavelength light exposure was restricted in the evening in order to facilitate sleep among a small sample of recreational athletes. Results showed that wearing amber-lens (short wavelength blocking) glasses during three hours before bedtime had no effect on actigraphy-based sleep estimates. However, subjective estimates revealed shorter sleep onset latencies, improved sleep quality and alertness in the morning, as compared to habitual evening light exposure. Proceeding from the promising evidence provided in Chapter 5c, Chapter 6 reported the results of an intervention study in which evening light restriction was combined with bright light exposure in the morning. Effects of the intervention were compared to a condition that involved no light regulation. Although athletes had difficulties to keep strict bed- and wake times, which was a requirement in both conditions, results of the intervention were promising. Results indicated a significant effect of light regulation on sleep onset latency ($\Delta$ SOL = 8 minutes). When athletes kept a stricter sleep-wake schedule during both conditions, self-reported sleep
onset latency was even shorter (Δ SOL = 17 minutes), and accompanied by a significant improvement in self-rated sleep quality.

The results from Chapter 6 indicate that light regulation is a promising means to optimize sleep in athletes. The observed decrease in sleep onset latency (17 minutes) is comparable to the effect that has been demonstrated following Cognitive Behavioural Therapy for Insomnia (CBT-I, i.e., 20 minutes shorter sleep onset latency)\(^\text{190}\). CBT-I is currently the recommended first line treatment for insomnia\(^\text{142}\). This result is quite remarkable when taking into account that insomnia patients typically report much longer sleep onset latencies (>30 minutes\(^\text{95, 176}\)) than healthy sleepers such as athletes (i.e., patients have more room for improvement). Finally, it is important to note that the current results were obtained in a field setting, where limited control over environmental factors may interfere with the effect of the intervention. Unlike the temperature intervention reported in Chapter 5b, light regulation (Chapters 5c and 6) appeared to be robust against such interference, which underlines the essential role of light in the regulation of sleep (see also:\(^\text{159}\)).

Despite the promising results, several practical aspects of the reported light intervention require further attention. For example, difficulty with protocol adherence (strict bedtimes) and self-reported inconvenience in wearing the (light-emitting) goggles indicated that user-friendliness of the intervention should be improved. New ways of light manipulation that are less invasive to daytime functioning are thus warranted.

Box IV. Conclusion Aim 4: Optimizing sleep (Chapters 5a, 5b, 5c and 6).

- Improving sleep hygiene practices may facilitate sleep.
- Wearing heatable bed socks before bedtime does not significantly accelerate sleep onset.
- Light regulation can improve self-reported sleep onset latency and sleep quality in athletes.
STRENGTHS AND LIMITATIONS

The current thesis provides an extensive and detailed characterization of elite athletes’ sleep and – based on an analysis of deficiencies – points towards promising interventions that allow further improvement. To guide the interpretation of the above-mentioned findings, a series of strengths and limitations is listed below.

Strengths

The main strengths of the current thesis relate to sample characteristics and a variety of methodological and design choices.

The studies outlined in Chapters 2, 3 and 4 are based on a large and representative sample of elite (youth) athletes (i.e., 98) that compete at the highest (inter-)national level. Involving such a large sample of elite athletes carries three particular strengths. First, the size and representativeness of the sample add to the ecological validity of the obtained sleep estimates (Chapters 2 and 3). Second, in elite athletes, performance margins are small due to the relatively low variation in fitness level and high skill proficiency. This positively contributed to the validity of performance test outcomes in Chapter 4. Third, due to the large sample size, specific skills-types could be differentiated (fine vs. gross motor skill performance), which substantiated the effects of sleep on more specific types of athletic performance.

In addition to the sample characteristics, three additional methodological strengths can be mentioned. The first is the utilization of a wide array of mixed-methods to measure athletes’ sleep. Sleep was characterized using subjective (questionnaire, diary) and objective (actigraphy, one-channel EEG) sleep measures (especially Chapters 2 and 3). Integrating information obtained from all modalities added to the current understanding of sleep in elite athletes that, until now, was predominantly based on actigraphy-based sleep estimates. The study reported in Chapter 3 was the first to assess sleep stages among a large cohort of elite athletes during an entire week of habitual training. This provided unique insight in sleep architecture and - to some extent- recovery demands of athletes.

Second, employing within-subject designs is a shared strength of most of our empirical studies. Within-individual repeated measure designs have the advantage of reducing between-individual variability (i.e., extraneous variables such as gender...
Second, within-subject designs increased the statistical power of the studies by reducing inter-individual differences. These designs however, also have some disadvantages. For example, the increased load of taking part in an experiment may have caused withdrawal during the course of the intervention (Chapter 6). Individuals may also become tired and bored which may reduce their commitment and age). In such designs individuals can serve as their own controls. Within-subject designs were employed in monitoring elite athletes’ sleep and performance in the field (Chapters 3 and 4), as well as in the intervention studies that aimed to improve athletes’ sleep (Chapters 5c, 5d and 6). The same holds for the use of linear mixed-effects models. In these models, within-subject variability in training load or habitual sleep could be taken into account (Chapters 3 and 4).

Third, monitoring sleep in the field provides more representative findings as compared to a laboratory setting (Chapters 2 and 3). Similarly, employing sport-specific tests of fine- and gross motor skill enhanced the ecological validity of the performance results reported in Chapter 4. By using unobtrusive measurements, such as wrist-actigraphy and wireless one-channel EEG-sensors, sleep could be monitored in the habitual environment of the athletes while interference with daily activities was kept to a minimum. Moreover, using unobtrusive measurements, sleep could be monitored for several consecutive days. Multiple days of assessment are recommended in field studies due to the large intra-individual variation in sleep. Meeting this recommendation, a variety of rest and training days were covered. This substantially added to the quality of the results.

Limitations

In line with the above, the main limitations of this thesis also relate to sample characteristics and methodological and design choices.

First, to minimize load on the elite athlete population, the intervention studies reported in Chapters 5b, 5c and 6 were conducted with convenience samples of recreational and sub-elite athletes. This choice was justified, presuming that the underlying mechanisms (sleep-regulation by means of temperature and light regulation) apply similarly to elite athletes as to recreational or sub-elite athletes. Thus, while the targeted mechanisms (temperature and light regulation) are independent of elite-status, results of the intervention studies may be less representative for and generalizable to elite athletes.

Second, within-subject designs increased the statistical power of the studies by reducing inter-individual differences. These designs however, also have some disadvantages. For example, the increased load of taking part in an experiment may have caused withdrawal during the course of the intervention (Chapter 6). Individuals may also become tired and bored which may reduce their commitment and age). In such designs individuals can serve as their own controls. Within-subject designs were employed in monitoring elite athletes’ sleep and performance in the field (Chapters 3 and 4), as well as in the intervention studies that aimed to improve athletes’ sleep (Chapters 5c, 5d and 6). The same holds for the use of linear mixed-effects models. In these models, within-subject variability in training load or habitual sleep could be taken into account (Chapters 3 and 4).

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and willingness to perform. Lastly, participants may improve when being assessed repeatedly (e.g., Chapter 4). While these are all plausible shortcomings, the current thesis minimized their occurrence and impact by counterbalancing test sequences, monitoring levels of motivation, and by installing reminders (e.g., SMS-services) to facilitate compliance and commitment.

Third, in field studies, ambulatory measurement devices, such as actigraphy, are frequently used to capture sleep in the habitual environment. Both the one-channel EEG and actigraphy devices that were employed in the current thesis show adequate agreement with polysomnography (PSG). The latter is considered the gold standard in the laboratory. However, their measurement sensitivity is compromised and absolute values may slightly deviate from the gold standard. As such, while the chosen measurement instruments were adequate for the aims of this thesis, caution is warranted in drawing clinical conclusions or in comparing the absolute values reported here to (laboratory-based) PSG estimates reported elsewhere.

Fourth, while conducting intervention studies in the field carried the advantage of "capturing life as it is lived", a lack of control over environmental factors potentially added noise to the results. As a consequence, results that proved significant in the laboratory happen to be weaker or even disappear in field-based replication studies (e.g., Chapter 5b). Using larger sample sizes and within-subject designs can minimize, but not fully account for noise induced by uncontrolled external factors. Field studies are thus less controlled and more prone to environmental interferences. While this reduces power to obtain significant effects, it also indicates how viable a laboratory-based intervention is in daily life, that is, under natural circumstances.

Lastly, the deliberate choice to solely monitor instead of manipulate sleep and training load allowed for ecologically relevant conclusions. It also carries disadvantages. For example, naturally occurring variations in training load (Chapter 3) and sleep (Chapter 4) are often much smaller than manipulations utilized in experimental protocols. Furthermore, estimates are also more likely to be unbalanced, as could be seen in Chapter 3, where reports of extremely high training load were rare. Because of less extreme values in training load and smaller day-to-day variation in sleep, effects on outcome variables are likely to be smaller as well.
FUTURE RESEARCH PERSPECTIVES

Based on the results reported in the current thesis, several suggestions for future research may be given.

First, the current thesis identified sleep hygiene as a relevant component in understanding sleep disturbances and in improving sleep in athletes (Chapter 2). Moving from association to causation, future studies may further examine the impact of changes in selected sleep hygiene practices on athletes’ sleep. For example, the current assessment indicated relatively high psychological strain among athletes during training periods. Knowing that pre-sleep arousal and anticipatory stress are even more prevalent prior to important events and can mediate insomnia symptoms, future interventions may focus on testing the effectiveness of stress-reduction and coping strategies. In addition to selective sleep hygiene strategies, the effectiveness of broader sleep hygiene protocols should be evaluated across several occasions, including training, competition and travel.

Second, Chapter 3 indicated that training load does not necessarily degrade sleep among elite athletes, other studies that studied more intense training regimes found opposing results. Due to the conflicting results and because there is reason to believe that exercise can both jeopardize and benefit sleep, more thorough research into this relation is required. In the present study, single-item measures of training load were employed. These measures have high face validity, are an efficient means to capture multiple aspects of training (i.e., multiple sessions a day, individual differences), and show fair correlations with objective measures (e.g., heart rate). However, to arrive at a thorough understanding of the effects of training load on sleep, future research is needed that also distinguishes between different training activities (e.g., strength, endurance, high intensity (interval) training). Additionally, effects of training duration and frequency should also be assessed.

Third, Chapter 4 showed that minor day-to-day changes in sleep immediately affect psychomotor vigilance, but that such fairly small changes are unlikely to have large effects on sport-specific performance of fine- and gross motor skills. The observed dose-response relationship between total sleep time and psychomotor vigilance highlights the importance of sleep duration. Anecdotal evidence showed...
performance benefits following prolonged sleep extension\(^{23}\), but still much remains to be learned in the field of sleep extension in sports. For example, future research is needed to assess whether daytime naps are an equally effective means to enhance performance as compared to extended nocturnal sleep. In addition, future research should examine the extent to which sleep history (sleep debt vs. sleep banking) moderates the effects of acute sleep loss on performance. Insight from these studies would teach us, whether sleep banking has the potential to mitigate the negative effects of one night (acute) sleep loss on recovery and performance.

Lastly, evidence suggests a prominent role of daytime light exposure on sleep\(^{31, 159, 161}\) (Chapters 5c and 6). Results of laboratory-based interventions and field-studies reveal promising results\(^{31, 161}\), but protocols are still interfering with the social life of participants. Future research should investigate more subtle methods of light optimization during the waking day and the respective effects on sleep among athletes.

**PRACTICAL IMPLICATIONS FOR ATHLETES AND SPORT PROFESSIONALS**

Based on the results from the current thesis, several practical implications for athletes and sport professionals can be formulated. These are described below and summarized in Box V.

First, Chapter 2 revealed that adequate sleep hygiene practices bear relevance for sleep in athletes. Athletes’ should thus be properly educated about the relevance of specific daytime behaviors and environmental circumstances for optimal sleep. The guidelines provided in Chapter 5a can aid in this endeavor. Following from Chapter 2, special attention should be devoted to reducing psychosocial stress in the evening as this is an often reported factor that interferes with athletes’ night time sleep\(^{52}\). For optimally consolidated and refreshing sleep, regular and standardized timing of sleep- and wake periods is essential\(^{20, 31}\). Coaches and staff should investigate possibilities to reschedule training and competition timing to minimize interference with the preferred sleep period. A schedule is preferred that allows for standardized rise times during training as well as free-days.

Second, the analysis of subjective sleep estimates in Chapter 2 revealed that a substantial minority of elite athletes rates their sleep as being ‘poor’ and feels
insufficiently recovered in the morning. Although Chapter 3 indicated that day-to-day changes in self-reported training load were not reflected in objective assessments of sleep quantity and sleep stages, poor sleep quality during intensified training periods can be a sign of overreaching [96]. For this reason, it is recommended to add information on sleep to daily training logs. Logging data as simple as sleep duration, timing, and the feeling of being refreshed, can reveal patterns and provide valuable insight on recovery responses to intensified training programs. Logging these variables can further help to determine optimal sleep timing and duration.

Chapter 4 revealed that small naturally occurring variations in sleep have a stronger effect on basic psychomotor vigilance than on sport-specific measures of fine and gross motor skill. Following from these results, it may be assumed that sleep deficiencies have a stronger effect on performance in sports that heavily rely on cognitive aspects such as alertness and vigilance than in sports that depend less on such aspects. Previous studies have reported athletes to experience performance decrements as a result of dysfunctional thoughts, that is fear of underperformance as a consequence of a poor night of sleep [27]. The current study shows that this concern may be ill-founded, given that small variations in sleep are unlikely to have a large impact on (athletic) performance. In addition, the observed dose-response relationship between sleep duration and psychomotor vigilance suggests that banking sleep (e.g., by means of power napping or extended nocturnal sleep) may help to counteract adverse effects of a single night of compromised sleep.

Finally, the regulation of morning and evening light exposure revealed promising improvements in sleep (Chapters 5c and 6). Based on these findings, athletes are recommended to increase (natural) light exposure in the morning and during the day and to reduce exposure to light, and especially to short-wavelength (blue) light, in the evening.
Box V. Practical implications for athletes and sport professionals

- Inform and educate athletes about recommended sleep hygiene practices.
- Reduce psychological strain in the evening.
- Schedule training and competition to allow for standardized bed- and rise times that can be kept during free days as well.
- Add information on sleep duration, timing and the feeling of being refreshed to training logs.
- Small day-to-day variation in sleep is unlikely to result in large performance effects.
- To optimize sleep: ensure exposure to bright light in the morning and during the day, and reduce exposure to (short-wavelength) light in the evening.

GENERAL CONCLUSION

While elite athletes appear to sleep an average of almost eight hours per night, their sleep tends to be fragmented and ratings of feeling refreshed and alert were modest at best. To optimize sleep and improve performance capacity, good sleep hygiene practices and light regulation are promising avenues to pursue.
Fine Motor Skill Performance

Shooting accuracy. Handball- and Volleyball players performed a shooting accuracy test. Standardized set-ups were given by the coach. Handball players ($n = 13$) performed jump shots in the direction of a target that was located in the top left and right corner of the goal. The target was a metal frame (50 x 50 cm), with a 5 cm wide framework and an opening of 40 x 40 cm. Shots were taken from the 9 meter line. Players took a regular 3-step run-up before executing the jump shot. To mimic actual performance situations, two air-bodies were placed in the center of the 7 meter line. Scores ranged from 1-3, depending on whether the ball was thrown through the target opening (3 points), hit its framework (2 points), or missed the target (1 point). The average score over 10 trials (5 aims towards the right side of the goal and 5 aims towards the left side of the goal) was taken as outcome measure.

Volleyball players ($n = 30$) performed smashes in the direction of a target area that was located in the right and left outside corners of the opponents back zone, in one meter distance from the attack-line (3-meter line). The target area (180 x 180 cm) was divided into three rectangular parts of the same size (180 cm long x 60 cm wide). Smashes were taken from the position of the ‘middle blocker’, just behind the net. Scores ranged from 1-4, depending on whether the volleyball hit the target closest to the side line (4 points), hit the central-part of the target (3 points), hit the most inside part of the target (2 points), or missed the target (1 point). The average score over 10 trials (5 aims towards the right side of the court and 5 aims towards the left side of the court) was taken as outcome measure.

Dribbling. Soccer players ($n = 17$) performed a dribble test in which they had to dribble the ball as rapidly as possible through a slalom course that consisted of six cones set 1.5 m apart for a total of 10.5 m from start to finish. Start and end of the slalom course were indicated by timing gates (Smart Speed, Fusion Sport, Queensland, Australia). Each trial was started from a position 50 cm in front of the start gate. The average time (in seconds) over two trials was taken as outcome measure.
Technical skills-track. Mountain bikers (n = 4) performed a standardized indoor technical skills-track, which they had to complete as fast as possible. The track entailed a pumptrack (2.5 rounds), ramps, sharp turns, jumps, trunk overpasses and balancing. The task was timed using timing gates (Smart Speed, Fusion Sport, Queensland, Australia). The average time (in seconds) over three trials was taken as outcome measure.

Gross Motor Skill Performance

Vertical Jumps. Handball players (n = 13) and volleyball players (n = 30) performed a vertical jump test in which they executed three trials of the counter movement jump (CMJ) and spike jump (SJ)\textsuperscript{12}. The highest relative jump height (i.e., jump height minus standing reach height) was used as outcome measure. Jump height and standing reach height were measured using Vertec (Yardstick, Swift Performance Equipment, Lismore, Australia).

Maximal Sprints. Handball players (n = 13) performed a maximal 20-meter sprint test. Start and end of the sprint were indicated by timing gates (Smart Speed, Fusion Sport, Queensland, Australia). Each trial was started from a position 50 cm in front of the start gate. The average time (in seconds) over two trials was taken as outcome measure.

Constant Power tests. Road cyclists (n = 26), mountain bikers (n = 4) and triathletes (n = 8) performed a constant power test. Road cyclists and mountain bikers performed the constant power test by cycling for 10 minutes at a fixed (individualized) power of 4 watt/kg. After a standardized warm-up, the 10-minutes started as soon as athletes arrived at their pre-defined power output. The athletes were instructed (and followed by car) to cycle the same route on an individually set power, and at a self-preferred cadence. The average cadence at which participants cycled was 83 rpm, with a within-subject variation of 3.86 rpm (i.e., 3.24 %), indicating that across tests participants adopted a constant pace. Average heart rate during the constant power test was obtained with the Garmin (or other) chest-worn heart rate sensors. Triathletes performed the constant power test by swimming over a 200-meter extent at constant (individually set) velocity. Velocity was monitored every 25 m and communicated by the coach, a method the athletes were familiar with. Heart rate
was assessed using waterproof chest-sensors (version T31) by Polar (version v800) that had a transmitter integrated in a back pocket of a small vest. The transmitter send the heart rate data to a laptop located next to the pool were the test intervals were manually indicated by event markers (Hosand GT aqua system).
INTRODUCTION

Elite athletes have high activity profiles and thus depend rather heavily on the recovery and performance benefits that can be attained from good quality sleep. Considering that sleep is the recovery strategy par excellence and indispensable for overall health and performance capacity, the aim of this thesis was to (1) shed light on sleep quantity and quality in elite athletes, (2) identify factors that adversely affect their sleep, (3) extend knowledge on the effects of sleep on performance, and (4) investigate promising interventions to optimize sleep.

Aim 1: Characterizing sleep of elite athletes

Initial evidence of objective estimates of actigraphy-based sleep quantity and sleep quality indicated that athletes’ sleep is inferior to that of non-athlete controls and potentially insufficient for adequate recovery and optimal performance\(^\text{25}\). In order to provide a more complete picture of sleep in elite athletes, the current thesis sought to extend this information by (1) also assessing subjective estimates of sleep quantity and quality (questionnaire and diary-based), (2) using an actigraphy threshold with higher sensitivity to sleep in assessing objective sleep quantity, and (3) providing preliminary insight in (EEG-based) sleep stage distributions. Sleep was monitored among a large cohort of 98 elite athletes during seven consecutive days of habitual training using daily morning- and evening diaries, wrist-worn actigraphy and a wireless one-channel EEG headband sensor.

In general, elite athletes were found to be healthy sleepers. However, based on sub-clinical questionnaires, the study reported in Chapter 2 showed that a vast minority of 41% did classify as poor sleeper (PSQI cutoff poor sleeper ≥ 5\(^\text{69}\)) and that 12% was identified as having a potential sleep disorder (HSDQ cutoff ≥ 2.02\(^\text{70}\)). Restless leg symptom / periodic limb movement disorder (RLS/PLMD) was the most frequently reported sleep disturbance. Daily self-reports revealed an average sleep duration of 8 hours, well within the recommended range of 7-9 hours\(^\text{12, 13}\). Yet, self-reported sleep onset latency (20 minutes) and wake after sleep onset (13 minutes) revealed areas for improvement. Finally, diary studies revealed that, with the given amount of sleep, athletes felt only moderately refreshed, alert, and vigorous in the morning\(^\text{89}\).
The actigraphy-based sleep estimates reported in Chapter 3 depicted a similar pattern. As may be expected, absolute values did differ from subjective measures\(^{170, 171}\). The seven-day average sleep duration was close to 8 hours. Wake after sleep onset can be improved (33 minutes) and sleep efficiency (88%) was lower than the average for this age group (i.e., 92%)\(^{94}\). The latter finding indicates relatively fragmented sleep. During 22% of the nights, sleep efficiency scores were below 85%, a threshold that is considered the upper limit for poor sleep\(^{95}\). Analysis of the EEG-based sleep stage distributions revealed typical values for the amount of light and REM sleep\(^{5, 94}\) (Chapter 3). However, in line with the high activity level of elite athletes\(^{55}\), the amount of deep sleep was relatively high (21%). According to the recovery hypothesis of sleep, deep sleep adapts to the body’s current need for recovery. That is, the amount of deep sleep typically increases with sustained wakefulness or following strenuous exercise\(^{10}\). As such, the relatively high proportion of deep sleep may reflect an elevated recovery need in elite athletes.

**Aim 2: Identifying sleep jeopardizing factors**

In the literature, individual and environmental factors such as jet lag\(^{44}\), psychological and physiological pre-sleep arousal\(^{15, 52, 53}\), training and competition schedules\(^{15, 46, 50, 51}\), have all been related to compromised sleep quantity and quality in athletes. However, a broad assessment of elite athletes’ general sleep hygiene practices (i.e., daytime behaviors and environmental conditions that facilitate good quality sleep) is lacking. Quantifying the presence (or absence) of such practices – and calculating their association with sleep quality – can aid in the development of tailored sleep hygiene guidelines for elite athletes. Therefore, Chapter 2 reported self-reported estimates of sleep hygiene and sleep in 98 elite athletes during seven consecutive days of training.

Results of a general questionnaire showed that athletes’ sleep hygiene practices were generally adequate. Still, athletes reported difficulties to keep a regular sleep-wake pattern, experienced psychological strain in the evening (e.g., bedtime stress and worry), and engaged in activating pre-sleep activities. These general questionnaire results were complemented by a detailed seven-day diary assessment of sleep hygiene practices, where again, only a few behaviors appeared to be suboptimal. These suboptimal behaviors included late-evening consumptions of heavy meals and caffeinated beverages, as well as engagement in sedentary activity levels of elite athletes.

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activities that involved artificial light exposure in the evening (75% of nights). A notable observation was that athletes infrequently engaged in daytime sleep (naps; 18% of days). Correlation analyses indicated that adequate sleep hygiene was indeed associated with better sleep quality and less disordered sleep among athletes. This is in line with reports among non-athletes.

Another factor that may impact sleep of elite athletes is training load. Athletes follow intense training programs that are designed to stimulate psychophysiological adaptation, so that performance capacity can be enhanced. The relation between exercise and sleep appears to be inconclusive. On the one hand, exercise can improve sleep quality on the other hand, there is evidence suggesting that prolonged periods of extreme exercise intensity may worsen sleep quantity and quality. To further the understanding of whether increases in training benefit or jeopardize sleep quantity and quality in elite athletes, Chapter 3 investigated how day-to-day variations in self-reported training load were reflected in actigraphy-based sleep estimates and one-channel EEG-based sleep staging. Self-reports of training load and sleep estimates were collected during seven consecutive days of training among a cohort of 98 elite athletes. Results revealed moderate training load (mean = 5.4, scale 1-10) across all seven days of assessment. Large intra-individual differences showed that low, medium and sometimes high levels of training load were covered. Despite relatively large variation within individuals, day-to-day differences in self-reported training load were not reflected in actigraphy-based sleep measures (e.g., sleep duration, sleep efficiency), nor in EEG-based sleep stage distributions.

Aim 3: Establishing the effects of sleep on athletic performance

While still in its infancy, prior research suggests a deterioration of cognitive and athletic performances following (partial) sleep deprivation, while performance appears to improve following sleep extension. Importantly, in their daily life, athletes usually encounter subtle day-to-day changes in sleep that are smaller than the changes employed in experimental studies (e.g., ± 4 hours). Given the lack of research, the extent to which such small changes in sleep may indeed be reflected in (sport-specific) performance as yet remains unclear. Against this background, Chapter 4 investigated the extent to which rather mild, naturally occurring day-to-day variations in sleep quantity and sleep stages (sleep quality) are reflected in the activities that involved artificial light exposure in the evening (75% of nights). A notable observation was that athletes infrequently engaged in daytime sleep (naps; 18% of days). Correlation analyses indicated that adequate sleep hygiene was indeed associated with better sleep quality and less disordered sleep among athletes. This is in line with reports among non-athletes.

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cognitive and sport-specific performance of elite athletes. The effect of (changes in) actigraphy-based sleep quantity and one-channel EEG-based sleep stage duration on psychomotor performance as well as performance of fine- and gross motor skills was assessed among 98 elite athletes during three non-consecutive occasions. Results revealed that small changes in total sleep time were immediately reflected in small but significant changes in psychomotor vigilance (i.e., reaction time) the following day. Additionally, small and inconsistent effects of sleep quantity and sleep stages on gross motor skill performance were observed, but no effects were established for fine motor skill performances.

**Aim 4: Optimizing Sleep**

While there is good reason to believe that optimized sleep may benefit recovery, overall health and well-being, and performance capacity in athletes, the number of interventions tested among a healthy population such as elite athletes, is limited. Thus far, the few studies aiming at sleep optimization in athletes concern interventions focusing on nutrition\(^1\), specific sleep hygiene practises\(^{50-62}\), brain-wave entrainment\(^{64}\), or sleep extension\(^{23, 24}\). Based on the analyses of elite athletes sleep and potential sleep-disturbing factors reported in Chapters 2 and 3, Chapters 5a, 5b, 5c and 6 present practical sleep hygiene guidelines (Chapter 5a) and report experimental tests of several chronobiological sleep interventions (Chapters 5b, 5c and 6).

For many, adequate sleep hygiene practices are the very foundation for good quality sleep. Sleep hygiene are the “conditions and practices that promote continuous and effective sleep” (p. 347, American Academy of Sleep Medicine 2001\(^{66}\)). To that end, in Chapter 5a sleep hygiene guidelines that are tailored to the unique demands that elite athletes face in their daily routines are provided. These sleep hygiene recommendations were organized around regularity, stimulants and substances, psychological strain, active (pre-) sleep behavior and environment. Furthermore, sleep as well as sleep hygiene practices may differ considerably during periods of training and competition and may depend on the sleep location. Therefore, a smartphone application was developed that athletes can use to self-monitor their sleep hygiene and sleep quality during different periods (training versus competition) and environmental circumstances (e.g., sleep location).
One of many factors involved in sleep initiation and maintenance is thermoregulation. Body temperature fluctuates during the 24 hour day. Close to sleep onset, skin temperature increases which causes vasodilatation and a drop in core body temperature. More specifically, research has shown that increasing the distal to proximal gradient in skin temperature (DPG) before bedtime predicts sleep onset latency under strict experimental conditions\(^{121, 125-127}\). Chapter 5b provides the results of a field-based pilot study that was conducted among sub-elite athletes to examine the effectiveness of distal skin warming by means of heated bed socks on DPG and its potential effect on sleep latency. Results revealed that wearing heatable socks (vs. conventional socks) during the last 30 minutes before bedtime effectively increased distal to proximal skin temperature gradient (DPG) in sub-elite athletes. However, against expectations, the augmented DPG did not result in shorter sleep onset latency or improvement of the remaining actigraphy- and one-channel EEG-based sleep estimates.

Besides temperature, the initiation and consolidation of sleep is predominantly regulated by the circadian system, which requires periodic light-dark exposure for stable entrainment to the 24 hour day\(^{140, 158}\). Exposure to light in the evening, and especially to short wavelength light (e.g., emitted by electronic screens), delays circadian phase by suppressing melatonin secretion by the pineal gland\(^ {153}\). In humans, melatonin indicates the biological night and is crucial for sleep initiation and maintenance\(^{26}\). In line with this observation, prior studies have shown that blocking short-wavelength light in the evening can preserve melatonin secretion and potentially improve sleep\(^ {129, 130}\). In Chapter 5c, a pilot study is described in which the effectiveness of blocking short-wavelength light in the evening on sleep under natural conditions was assessed among a group of recreational athletes. Results showed that wearing amber-lens (short wavelength blocking) glasses during three hours before bedtime had no effect on actigraphy-based sleep estimates. However, subjective estimates revealed shorter sleep onset latencies, improved sleep quality and alertness in the morning, as compared to habitual evening light exposure.

Proceeding from the promising evidence provided in Chapter 5c, Chapter 6 showed the results of an intervention study in which evening light restriction was combined with bright light exposure in the morning. Effects of the intervention were compared to a condition that involved no light regulation. Although athletes had difficulties to keep strict bed- and wake times, which was a requirement in...
both conditions, results of the intervention were promising, indicating a significant reduction of 8 minutes in sleep onset latency following light regulation. When athletes kept a stricter sleep-wake schedule during both conditions, self-reported sleep onset latency was even shorter ($\Delta$ SOL = 17 minutes), and accompanied by a significant improvement in self-rated sleep quality.

**CONTRIBUTIONS OF THIS THESIS**

To guide the interpretation of the above-mentioned findings, a series of strengths and limitations needs mentioning. First, a strong point of this thesis is that the studies depicted in Chapters 2, 3 and 4 are unique in that they entail a large and representative sample of elite level athletes ($N = 98$). The size and the high skill proficiency of the sample contributed positively to the validity of performance test outcomes and made it possible to differentiate the effects of sleep on specific skill-types (fine vs. gross motor skill performance; Chapter 4). Nevertheless, the intervention studies reported in Chapters 5b, 5c and 6 were conducted with convenience samples of recreational and sub-elite athletes. While the targeted mechanisms (temperature and light regulation) are independent of elite-status, results may be less representative for and generalizable to elite athletes. Second, a strength of the current studies lies in the use of a wide array of mixed-methods to assess sleep, that is, both subjective (questionnaire, diary) and objective (actigraphy, one-channel EEG) sleep measures, which contributed to the current understanding of sleep in elite athletes. Third, sleep was monitored in the field using unobtrusive measures, thereby providing more representative findings as compared to a laboratory setting. At the same time, and although ambulatory measurement devices such as actigraphy are frequently used in field settings\textsuperscript{25, 26}, measurement sensitivity is compromised and absolute values may slightly deviate from the gold standard polysomnography\textsuperscript{19}. The chosen measurement instruments were adequate, though, for the aims of this thesis. However, caution is warranted in drawing clinical conclusions or in comparing the absolute values reported here to (laboratory-based) PSG estimates reported elsewhere. Fourth, while conducting intervention studies in the field carried the advantage of "capturing life as it is lived"\textsuperscript{194}, a lack of control over environmental factors potentially added noise to the results. Lastly, the deliberate choice to solely monitor instead of manipulate sleep...
and training load allowed for ecologically relevant conclusions, but also carried the disadvantage of small effect sizes as a result of smaller and unbalanced variation in sleep or training load.

Based on the results provided in this thesis, several suggestions for future research were detailed in Chapter 7. First, after having identified the association between sleep and sleep hygiene practices in elite athletes, it is time to assess how changing specific sleep hygiene practices is reflected in sleep of elite athletes. Second, the association between alterations in training load and sleep need more thorough investigation, including a differentiation between different training activities (e.g., strength, endurance, high intensity (interval) training), as well as variables such as training duration and frequency. Third, to strengthen the understanding of sleep extension as a potential performance enhancer for athletes, future research should investigate the merit of daytime sleep as performance enhancer. On a related term, future research could examine whether sleep banking, and sleep history in general, has the potential to mitigate the negative effects of one night of (acute) sleep loss on recovery and performance. Lastly, based on the prominent role of daytime light regulation on sleep, future research should investigate more subtle methods of light optimization during the waking day and its value for sleep and performance improvement for athletes.

Finally, several practical implications for athletes and sport professionals can be formulated (see Chapter 7 for a more elaborate overview). First, athletes should be properly educated about the relevance of adequate sleep hygiene strategies for optimal sleep, with special attention devoted to reducing psychological strain, bed- and wake times should be regular and standardized. The guidelines provided in Chapter 5a and the sleep hygiene app can aid in this endeavor. Furthermore, training and competition timing should be rescheduled such to minimize interference with the preferred sleep period. A schedule is preferred that allows for standardized bed- and wake times during training and rest days. Next, adding information on sleep duration, timing, and the feeling of being refreshed to the daily training logs is recommended, given that a substantial proportion of athletes reported ‘poor’ sleep quality and felt insufficiently recovered in the morning (Chapter 2). Moreover, previous studies have reported athletes to experience performance decrements as a result of dysfunctional thoughts, that is fear of underperformance as a consequence of a poor night of sleep. The study reported in Chapter 4 showed
that this concern may be ill-founded, given that small variations in sleep are unlikely to have a large impact on (athletic) performance, supposed that sleep quantity was sufficient overall on previous days. Finally, the regulation of morning and evening light exposure revealed promising improvements in sleep (Chapters 5c and 6). Based on these findings, athletes are recommended to increase (natural) light exposure in the morning and during the day and to reduce exposure to light, and especially to short-wavelength (blue) light, in the evening.

**CONCLUSION**

While elite athletes appear to sleep an average of almost eight hours per night, their sleep tends to be fragmented and ratings of feeling refreshed and alert were modest at best. Subtle changes in sleep quantity were immediately visible in cognitive performance. The current thesis shows that good sleep hygiene practices and light regulation are promising strategies in optimizing athletes’ sleep and increasing their performance capacity. Reducing light exposure in the evening combined with increasing light exposure in the morning, helps to facilitate sleep onset and improve perceptions of sleep quality.
INLEIDING

Topsporters hebben met hun intensieve trainingsschema’s bij uitstek belang bij goede slaap en de herstel- en prestatieopbrengsten hiervan. Gezien het feit dat slaap het belangrijkste herstelmechanisme van het menselijk lichaam is – en onontbeerlijk voor de algehele gezondheid en het prestatievermogen – was het doel van dit proefschrift om (1) meer inzicht te krijgen in de slaapkwantiteit en kwaliteit bij topsporters, (2) factoren te identificeren die hun slaap nadelig kunnen beïnvloeden, (3) meer kennis te vergaren over de effecten van slaap op sportprestatie, en (4) gerichte interventies te onderzoeken die de slaap van sporters verder kunnen optimaliseren.

Doelstelling 1: Karakteriseren van de slaap bij topsporters

Tot nu toe wees bestaand onderzoek erop dat objectieve maten van slaapkwantiteit en slaapkwaliteit van topsporters inferieur is aan die van niet-atleten en mogelijk ontoereikend is voor adequaat herstel en het leveren van optimale prestaties. Om een vollediger beeld te krijgen van slaap bij topsporters, was een van de onderzoeksdoelen van het huidige proefschrift om de bestaande inzichten uit te breiden door (1) ook subjectieve maten van slaapkwantiteit en -kwaliteit in kaart te brengen (gebaseerd op subklinische vragenlijsten en dagboeken), (2) objectieve slaapmetingen te baseren op een actigrafie-instelling met een hogere slaapgevoeligheid, en (3) inzicht te verschaffen in de verdeling van op EEG-gestructureerde slaapstadia. In een grootschalige monitorstudie werd de slaap van 98 topsporters (teamsporters en individuele sporters) in kaart gebracht gedurende zeven opeenvolgende trainingsdagen, door middel van dagelijkse ochtend- en avonddagboeken, pols-actigrafie, en een draadloze één-kanaals EEG-hoofdband-sensor.

Over het algemeen bleken de topsporters gezonde slapers te zijn. Op basis van de subklinische vragenlijsten liet het onderzoek in Hoofdstuk 2 echter zien dat een substantieel deel van de topsporters (41%) als slechte slaper geclassificeerd werd (PSQI; cutoff slechte slaper ≥ 5) en dat bij 12% van de sporters een potentiële slaapstoornis geïdentificeerd werd (HSDQ; cutoff ≥ 2.02). Rusteloze benen syndroom / periodiek bewegen van ledematen (‘restless legs syndrome / periodic limb movement disorder’) was de meest voorkomende ‘slaapstoornis’. Dagelijkse
zelfrapportage gaf een gemiddelde slaapduur van 8 uur aan, ruim binnen de aanbevolen slaapduur van 7-9 uur\textsuperscript{12, 13}. Toch lieten de subjectieve inslaaptijd (20 minuten) en aantal minuten wakker na aanvang van de slaap (‘wake after sleep onset’; 13 minuten) ruimte voor verbetering. Ten slotte bleek uit de slaapdagboeken dat de sporters zich, met de gegeven slaapduur van bijna 8 uur, ‘s ochtends slechts matig uitgerust, alert en energiek voelden\textsuperscript{99}.

De slaapvragen op basis van actigraphy, die in Hoofdstuk 3 zijn gerapporteerd, lieten een vergelijkbaar patroon zien. Zoals te verwachten was, verschilden de absolute waarden van de subjectieve metingen\textsuperscript{83, 170, 171}. De gemiddelde slaapduur over de zevendagen was bijna 8 uur. Het aantal minuten wakker na aanvang slaap laat ruimte voor verbetering (33 minuten) en de slaapefficiëntie (88%) was lager dan het gemiddelde voor deze leeftijdsgroep (d.w.z., 92%)\textsuperscript{94}. De laatste bevinding duidt op een relatief gefragmenteerde slaap. Gedurende 22% van de nachten waren de scores voor slaapefficiëntie lager dan 85%, een drempel die over het algemeen wordt aangehouden als de bovengrens voor slechte slaap\textsuperscript{95}.

Analyse van de EEG-gebaseerde deling van slaapstadia onthulde gangbare waarden voor de hoeveelheid lichte en REM-slaap\textsuperscript{5, 94} (Hoofdstuk 3). Echter, en in overeenstemming met het hoge activiteitsniveau van topsporters\textsuperscript{65}, lag de hoeveelheid diepe slaap aan de hoge kant (21%). Volgens de herstelhypothese van slaap past de diepe slaap zich aan de herstelbehoefte van het lichaam aan. Dat wil zeggen dat de hoeveelheid diepe slaap gewoonlijk toeneemt bij langere waaktijden of na zware inspanning\textsuperscript{10}. Als zodanig kan het relatief hoge percentage diepe slaap een verhoogde behoefte aan herstel bij topsporters weerspiegelen.

Doelstelling 2: Identificeren van slaap belemmerende factoren

In de literatuur zijn individuele en omgevingsfactoren zoals jetlag\textsuperscript{64}, psychologische en fysiologische arousal\textsuperscript{15, 52, 53}, trainings- en wedstrijdschema’s\textsuperscript{15, 46, 50, 51} geassocieerd met een aangetaste slaapkwaliteit en -kwaliteit bij atleten. Een brede inventarisatie van de algemene slaaphygiënestrategieën van topsporters (d.w.z. gedragingen overdag en omgevingsfactoren die slaap bevorderen) ontbrak echter. Een kwantificatie van dergelijke factoren en het berekenen van een associatie met slaapkwaliteit en kwantiteit is belangrijk voor het opstellen van een op maat gemaakte slaaphygiënestrategie. Vandaar dat in Hoofdstuk 2 zelfgerapporteerde schattingen van slaaphygiënestrategie, slaapkwaliteit en slaapkwantiteit gemaakt werden.

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van 98 topsporters gedurende zeven opeenvolgende trainingsdagen in kaart werden gebracht.

De resultaten van een algemene vragenlijst toonden aan dat de slaaphygiëne van topsporters over het algemeen acceptabel was. Toch rapporteerden de sporters moeilijkheden om een regelmatig slaap-waakpatroon aan te houden, ervoeren ze psychologische belasting in de avond (bijv. stress en zorgen maken voor het slapen gaan), en hielden ze zich voorafgaand aan de slaap bezig met alertheid verhogende activiteiten. Deze algemene vragenlijstresultaten werden aangevuld met een gedetailleerde zevendaagse evaluatie van de slaaphygiëne, waarbij wederom slechts enkele gedragingen suboptimaal bleken te zijn. Deze suboptimale gedragingen omvatten onder meer de consumptie van zware maaltijden en cafeïne houdende dranken in de late avond en blootstelling aan kunstmatig licht tijdens sedentaire activiteit in de avonduren (75% van de nachten). Een opmerkelijke observatie was dat de sporters zelden overdag dutjes deden (bijv. powernap; 18% van de dagen). Correlatieanalyses gaven aan dat adequate slaaphygiëne over het algemeen geassocieerd was met een betere slaapkwaliteit en minder verstoorde slaap. Dit komt overeen met bevindingen onder niet-sporters26.

Een andere factor die van invloed kan zijn op de slaap van topsporters, is trainingsbelasting. Sporters volgen intensieve trainingsprogramma’s die zijn ontworpen om psychofysiologische aanpassing te stimuleren en prestatievermogen te verbeteren. De relatie tussen fysieke inspanning en slaap lijk echter niet geheel eenduidig te zijn. Gematigde tot zware fysieke inspanning kan de slaapkwaliteit verbeteren26. Echter, langdurige periodes van extreme inspanning kunnen de slaapkwantiteit en kwaliteit ook aantasten48, 49, 56. Om beter te begrijpen of een toename van de trainingsbelasting de slaapkwaliteit en -kwantiteit bevoordert of juist niet, werd in Hoofdstuk 3 onderzocht of en hoe dagelijkse variatie in zelfgerapporteerde trainingsbelasting weerspiegelde in de slaapkwantiteit, zoals gemeten met behulp van actigram en de verdeling van slaapstadia (slaap kwaliteit), zoals gemeten met behulp van één-kanaals EEG. Zelfevaluaties van trainingsbelasting en slaapmetingen werden verzameld gedurende zeven opeenvolgende trainingsdagen in een cohort van 98 topsporters. De resultaten lieten over de zeven meetdagen een matige trainingsbelasting zien (gemiddelde = 5.4, schaal 1-10). Grote verschillen in trainingsbelasting binnen personen en tussen dagen impliceren een breed pallet van zowel lage, gemiddelde en soms
hoge trainingsbelasting. Ondanks de relatief grote variatie werden de dagelijkse verschillen in zelf gerapporteerde trainingsbelasting niet weerspiegeld in de op actigraphie gebaseerde slaapmetingen (bijv. slaapduur, slaapefficiëntie), noch in de verdeling in slaapstadia zoals gemeten met behulp van één-kanaals EEG.

Doelstelling 3: De effecten van slap op atletische prestaties
Hoewel het onderzoek nog in de kinderschoenen staat, wijzen eerdere studies op een verslechtering van de cognitieve en sport-specifieke prestaties na (gedeeltelijke) slaapdeprivatie⁴, terwijl slaapextensie de prestatie juist lijkt te bevorderen⁵⁶-⁶². We moeten ons echter realiseren dat topsporters in hun dagelijkse leven over het algemeen veel subtiere fluctuaties in slaap ervaren (bijvoorbeeld ± 4 uur) dan de slaapdeprivatie die wordt opgelegd in experimentele studies. Het is nog onduidelijk in hoeverre dergelijke relatief kleine veranderingen in slaapkwantiteit inderdaad tot uiting kunnen komen in veranderingen in (sport-specifieke) prestaties.

In Hoofdstuk 4 is onderzocht in hoeverre tamelijk milde, natuurlijk voorkomende variatie in slaapkwantiteit en slaapstadia van dag tot dag worden weerspiegeld in de cognitieve en sport-specifieke prestaties van topsporters. Bij 98 topsporters werd gedurende drie niet-opeenvolgende gelegenheden het effect onderzocht van slaapkwantiteit (actigraphie) en de totale duur van slaapstadia (één kanaals EEG) op psychomotorische prestatie en prestaties van fijne- en grove motorische vaardigheden. De resultaten toonden aan dat kleine veranderingen in de totale slaapduur (d.w.z. wanneer een sporter korter of langer slaapt dan zijn/haar eigen gemiddelde) onmiddellijk werden weerspiegeld in kleine maar significante veranderingen in psychomotorische prestatie (d.w.z. reactietijd) de volgende ochtend. Daarnaast werden kleine en inconsistentie effecten van verandering in slaapkwantiteit en slaapstadia op grof-motorische prestatie waargenomen. Er werden geen effecten vastgesteld voor fijn-motorische prestaties.

Doelstelling 4: Slaapoptimalisatie
Hoewel er goede redenen zijn om aan te nemen dat optimale slaap kan bijdragen aan herstel, algehele gezondheid, welzijn, en het prestatievermogen van atleten, is het aantal interventies dat is getest bij een gezonde populatie zoals topsporters beperkt. Interventies gericht op slaapoptimalisatie bij sporters richtten zich tot op heden op onderwerpen als voeding¹, specifieke slaaphygiënestrategiën⁶⁰-⁶², ‘brain-
wave entrainment\textsuperscript{64}, of slaapextensie\textsuperscript{23, 24}. Op basis van de karakterisering van slaap bij topsporters en potentiële slaap-verstorende factoren, zoals beschreven in Hoofdstuk 2 en 3, presenteren Hoofdstukken 5a, 5b, 5c en 6 praktische richtlijnen voor slaaphygiëne (Hoofdstuk 5a) en experimentele veldstudies van verschillende chronobiologische interventies (Hoofdstuk 5b, 5c en 6).

Vaak worden adequate slaaphygiëne strategieën gezien als de belangrijkste basis voor een goede nachtrust. Slaaphygiëne verwijst naar de ‘omstandigheden en gedragingen die continue en effectieve slaap bevorderen’ (p. 347, American Academy of Sleep Medicine 2001\textsuperscript{65}). In Hoofdstuk 5a worden slaaphygiëne richtlijnen gepresenteerd die zijn afgestemd op de dagelijkse routine en specifieke eisen waaraan topsporters worden blootgesteld. De richtlijnen zijn georganiseerd rondom de thema’s ‘regelmaat’, ‘genotmiddelen en substanties’, ‘psychologische belasting’, ‘actief gedrag voor bedtijd’ (alertheid bevorderende activiteiten) en ‘omgeving’. In de praktijk kunnen slaap en slaaphygiëne aanzienlijk verschillen tussen periodes van training en competitie en kunnen daarnaast afhankelijk zijn van de betreffende slaaplocatie (bijv. eigen bed of hotelkamer). De smartphone applicatie die in Hoofdstuk 5 werd geïntroduceerd ter monitoring van de slaaphygiëne, slaapkwaliteit en slaapkwantiteit van sporters, biedt daarom de gelegenheid om ervaringen tijdens verschillende periodes (training vs. competitie) en locaties bij te houden en te vergelijken.

Een van de vele factoren die een rol heeft bij het in- en doorslapen is thermoregulatie. De lichaamstemperatuur schommelt gedurende een etmaal. Kort voor het inslappen stijgt de huidtemperatuur, wat leidt tot vasodilatatie (verwijden van de bloedvaten) en een verlaging van de kerntemperatuur van het lichaam. Eerder onderzoek heeft aangetoond dat het kunstmatig verhogen van de distale tot proximale gradiënt in huidtemperatuur (DPG) voor het slapen gaan (i.e., om vasodilatatie te bevorderen en een verlaging van de kerntemperatuur te faciliteren) de inslaaptijd onder strikte experimentele omstandigheden kan voorspellen\textsuperscript{125-127}. Hoofdstuk 5b beschrijft een pilot studie onder sub-topporters waarin de effecten van distale huidverwarming door middel van verwarmde bedsokken op de inslaaptijd is onderzocht. De resultaten toonden aan dat het dragen van verwarmbare bedsokken (vergelken met conventionele sokken) tijdens de laatste 30 minuten voor het naar bed gaan, effectief de distale tot proximale huidtemperatuurgradiënt (DPG) kan verhogen. Tegen de verwachting in, resulteerde de verhoogde DPG echter voor het naar bed gaan, effectief de distale tot proximale huidtemperatuurgradiënt (DPG) kan verhogen. Tegen de verwachting in, resulteerde de verhoogde DPG echter voor het naar bed gaan, effectief de distale tot proximale huidtemperatuurgradiënt (DPG) kan verhogen. Tegen de verwachting in, resulteerde de verhoogde DPG echter
niet in een verkorte inslaaptijd, noch in overige verbeteringen in slaapkwantiteit (actigrafie) of verdeling van slaapstadia (een-kanaals-EEG).

Naast temperatuur wordt het in- en doorslapen voornamelijk gereguleerd door het circadiane ritme, welke periodieke blootstelling aan licht en donker vereist om in pas te kunnen lopen met de 24 uur dag\textsuperscript{140, 158}. Blootstelling aan licht in de avond, en in het bijzonder aan licht van een korte golflengte (bijvoorbeeld uitgezonden door elektronische schermen), vertraagt de circadiane fase doordat de melatoninesecretie in de pijnappelklier wordt onderdrukt\textsuperscript{33}. Bij mensen markeert melatoninesecretie de aanvang van de biologische nacht en is cruciaal voor het in- en doorslapen\textsuperscript{123}. Eerdere onderzoeken hebben aangetoond dat het blokkeren van licht van korte golflengte in de avond, het onderruiken van de melatoninesecretie kan voorkomen en mogelijk slaap kan verbeteren\textsuperscript{129, 130}. In Hoofdstuk 5c wordt een veldonderzoek beschreven waarin getest werd in welke mate het blokkeren van licht van korte golflengte in de avond, een positief effect heeft op de slaap van (recreatieve) sporters. De resultaten toonden aan dat het dragen van amber-lens brillen (die het licht van een korte golflengte blokkeren) gedurende drie uur voor het naar bed gaan geen effect had op slaapmetingen gebaseerd op actigrafie. Echter, zelf-rapportages lieten wel kortere inslaaptijden en verbeterde slaapkwaliteit en alertheid in de ochtend zien, na het dragen van de amber-lens bril in vergelijking met het dragen van een (neutrale) controlebril.

Voortbouwend op de veelbelovende resultaten in Hoofdstuk 5c, toont Hoofdstuk 6 de resultaten van een interventiestudie waarin de restrictie van licht in de avond werd gecombineerd met de blootstelling aan fel licht in de ochtend. Effecten van de interventie werden vergeleken met een conditie waarin de blootstelling aan licht niet werd gemanipuleerd. Hoewel sporters moeite hadden om zich aan de strikt opgelegde bed- en waaktijden te houden, een vereiste binnen beide condities, waren de resultaten van de interventie veelbelovend. In de lichtregulatie conditie vielen sporters gemiddeld 8 minuten sneller in slaap dan in de conditie waarin licht niet werd gemanipuleerd. Wanneer sporters tijdens beide condities een meer regelmatig slaap-waak schema aannamen, was de verbetering van zelf-gerapporteerde inslaaptijd zelfs nog groter (Δ SOL = 17 minuten), en was er tevens sprake van een significante verbetering van ervaren slaapkwaliteit.

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Hoofdstuk 7 beschrijft een aantal sterke en zwakke punten van het onderzoek. Allereerst is een sterk en uniek punt van deze thesis dat de onderzoeken in Hoofdstuk 2, 3 en 4 zijn uitgevoerd onder een grote en representatieve steekproef van topsporters ($N = 98$). De grootte van de steekproef en het vaardigheidsniveau dragen in positieve zin bij aan de validiteit van de prestatietesten en maakten het mogelijk om te differentiëren tussen effecten van slaap op verschillende sport-specifieke prestaties (fihn-versus grof-motorische prestatie, Hoofdstuk 4). De interventiestudies gerapporteerd in Hoofdstukken 5b, 5c en 6 werden echter uitgevoerd onder een steekproef van recreatieve en sub-topsporters. Hoewel de onderzochte mechanismen (temperatuur- en lichtregulatie) onafhankelijk zijn van ervaring, vaardigheid en topsportstatus, zijn de resultaten van deze studies mogelijk niet zonder meer te generaliseren naar topsporters. Een tweede sterk punt van het huidige onderzoek is het gebruik van een breed pallet aan verschillende meetmethoden om slaap in kaart te brengen, namelijk zowel subjectieve (vragenlijst, dagboek) als objectieve (actigrafie, één kanaal EEG) slaapmetingen. Dit heeft bijgedragen aan een rijker begrip van slaap onder topsporters. T en slotte heeft de bewuste keuze om slaap- en trainingsbelasting alleen te monitoren en niet experimenteel te manipuleren mogelijker om te differentiëren tussen effecten van slaap op verschillende sport-specifieke prestaties (fihn-versus grof-motorische prestatie, Hoofdstuk 4). De interventiestudies gerapporteerd in Hoofdstukken 5b, 5c en 6 werden echter uitgevoerd onder een steekproef van recreatieve en sub-topsporters. Hoewel de onderzochte mechanismen (temperatuur- en lichtregulatie) onafhankelijk zijn van ervaring, vaardigheid en topsportstatus, zijn de resultaten van deze studies mogelijk niet zonder meer te generaliseren naar topsporters. Een tweede sterk punt van het huidige onderzoek is het gebruik van een breed pallet aan verschillende meetmethoden om slaap in kaart te brengen, namelijk zowel subjectieve (vragenlijst, dagboek) als objectieve (actigrafie, één kanaal EEG) slaapmetingen. Dit heeft bijgedragen aan een rijker begrip van slaap onder topsporters. Ten derde, slaap in het veld werd in kaart gebracht met behulp van nauwelijks verstorende meetinstrumenten. Hierdoor zijn de resultaten meer ecologisch valide dan slaapmetingen die verkregen worden in het slaaplaboratorium. Hoewel ambulante meetinstrumenten zoals actigrafie vaak in veldonderzoek worden gebruikt, is het belangrijk om te vermelden dat deze over het algemeen een lagere meetgevoeligheid hebben dan de gouden standaard polysomnografie (PSG) en dat absolute waardes enigszins kunnen afwijken. De gekozen meetinstrumenten waren geschikt voor de doelstellingen van dit proefschrift. Voorzichtigheid is echter geboden bij het trekken van klinische conclusies of bij het vergelijken van de hier gerapporteerde absolute waarden met – in andere studies gerapporteerde – waarden die verkregen zijn op basis van PSG. Het uitvoeren van interventiestudies in het veld heeft daarnaast als voordeel dat het leven wordt vastgelegd “zoals het geleefd wordt”. Een keerzijde is dat gebrek aan controle over omgevingsfactoren mogelijk wel voor ruim heeft gezorgd waardoor minder snel significante effecten gevonden konden worden. Tenslotte heeft de bewuste keuze om slaap- en trainingsbelasting alleen te monitoren en niet experimenteel te manipuleren mogelijker wel voor ruim heeft gezorgd waardoor minder snel significante effecten gevonden konden worden. Tenslotte heeft de bewuste keuze om slaap- en trainingsbelasting alleen te monitoren en niet experimenteel te manipuleren.
bijgedragen aan de ecologische validiteit van de conclusies. Een nadelig bijeffect is echter de kleine effectgroottes als gevolg van kleinere en ongebalanceerde variatie in de bijvoorbeeld slaap en trainingsbelasting.

Op basis van de resultaten in dit proefschrift kunnen verschillende suggesties voor toekomstig onderzoek worden geformuleerd. Ten eerste, op basis van de relatie tussen slaaphygiëne en slaapkwaliteit is het interessant om na te gaan hoe het toepassen van specifieke slaaphygiëne strategieën kan bijdragen aan het verbeteren van slaap. Ten tweede kan de samenhang tussen veranderingen in trainingsbelasting en slaap grondiger worden onderzocht. Daarbij moet onderscheid worden gemaakt tussen verschillende trainingsactiviteiten (bijv. kracht, uithouding, high intensity interval training) en verschillende componenten van trainingsbelasting, zoals trainingsintensiteit, -duur en -frequentie. Ten derde, om het inzicht in slaapextensie voor topsport prestatie te vergroten, is het interessant om meer onderzoek te doen naar de effectiviteit van power napping. Hieraan gerelateerd kan onderzocht worden of het ‘voorslapen’ (‘sleepbanking’) en, in meer algemene zin, goede slaap tijdens voorgaande nachten (slaapgeschiedenis) negatieve effecten van één nacht (acuut) slaapverlies op herstel en prestaties kan verminderen. Ten slotte zou op basis van de prominente invloed van lichtregulatie op slaap, onderzoek kunnen worden gedaan naar meer subtiële methoden voor lichtoptimalisatie tijdens de dag en de effecten hiervan op slaap en prestatieverbetering bij sporters.

Ten slotte bevatten de resultaten van het huidige proefschrift een aantal praktische implicaties voor topsporters en coaches (Hoofdstuk 7). Allereerst, en gebaseerd op Hoofdstuk 2, is het duidelijk dat sporters baat kunnen hebben bij goede educatie over slaaphygiëne, met speciale aandacht voor het verminderen van psychologische belasting (bijv. stress en zorgen) voor het naar bed gaan, en het aanhouden van regelmatige bed- en opstatijden. De richtlijnen in Hoofdstuk 5a en de slaaphygiëne-app kunnen hierbij helpen. Verder kan worden overwogen om training- en de wedstrijdtijden (waar mogelijk) dusdanig aan te passen zodat de variatie in bed- en opstatijden tussen rustdagen, trainingsdagen en wedstrijddagen tot een minimum wordt beperkt. Vervolgens wordt aanbevolen om informatie met betrekking tot slaapduur, optimale slaaptijd en het al of niet uitgerust wakker worden, toe te voegen aan trainingslogboeken – aangezien een substantieel deel van de topsporters ‘slechte’ slaapkwaliteit rapporteert en zich ‘s ochtends onvoldoende hersteld voelt (Hoofdstuk 2). Verder heeft eerder onderzoek aangetoond dat
sporters soms minder goed presteren als gevolg van zorgen naar aanleiding van een slechte nachtrust[^27]. De studie die in Hoofdstuk 4 wordt beschreven, toont aan dat deze zorgen in veel gevallen ongegrond zijn, aangezien het onwaarschijnlijk is dat incidentele kleine variaties in de slaap een groot effect hebben op (sportspecifieke) prestaties. Tenslotte geven de studies uit Hoofdstukken 5c en 6 aan dat lichtregulatie in de ochtend- en avonduren veelbelovende verbeteringen kan opleveren in termen van inslaaptijd en ervaren slaapkwaliteit. Op basis van deze bevindingen wordt sporters aangeraden om ‘s ochtends en overdag de blootstelling aan (natuurlijk) licht te vergroten en om ‘s avonds de blootstelling aan licht en vooral aan licht van korte golflengte (blauw licht) te verminderen.

CONCLUSIE

Hoewel topsporters gemiddeld bijna acht uur per nacht slapen, is hun slaap gefragmenteerd en voelen ze zich in de ochtend slechts matig uitgerust en alert. Subtiele veranderingen in slaapkwantiteit waren direct zichtbaar in cognitieve prestaties. Het huidige onderzoek laat zien dat gezonde slaaphygiëne en lichtregulatie veelbelovende strategieën zijn om de slaap van sporters te optimaliseren en hun prestatievermogen te vergroten. Het dimmen van licht in de avond en juist opzoeken van licht in de ochtend helpt om de inslaaptijd te verkorten en de ervaren slaapkwaliteit te verbeteren.

[^27]: De studie die in Hoofdstuk 4 wordt beschreven, toont aan dat deze zorgen in veel gevallen ongegrond zijn, aangezien het onwaarschijnlijk is dat incidentele kleine variaties in de slaap een groot effect hebben op (sportspecifieke) prestaties. Tenslotte geven de studies uit Hoofdstukken 5c en 6 aan dat lichtregulatie in de ochtend- en avonduren veelbelovende verbeteringen kan opleveren in termen van inslaaptijd en ervaren slaapkwaliteit. Op basis van deze bevindingen wordt sporters aangeraden om ‘s ochtends en overdag de blootstelling aan (natuurlijk) licht te vergroten en om ‘s avonds de blootstelling aan licht en vooral aan licht van korte golflengte (blauw licht) te verminderen.
EINLEITUNG

Spitzensportler haben intensive Trainingsprogramme und sind somit stark auf die Erholung und Leistungsvorteile angewiesen, die qualitativ hochwertiger Schlaf bietet. In Anbetracht der Tatsache, dass Schlaf die Erholungsstrategie ‘par excellence’ und für die allgemeine Gesundheit und Leistungsfähigkeit unerlässlich ist, war das Ziel dieser Arbeit: (1) die Schlafquantität und -qualität von Spitzensportlern zu erfassen, (2) Faktoren zu identifizieren, die den Schlaf negativ beeinflussen, (3) Wissen über die Auswirkungen des Schlafes auf die Leistungsfähigkeit zu erweitern, und (4) aussichtsreiche Interventionen zur Optimierung von Schlaf zu erforschen.

Ziel 1: Charakterisierung des Schlafes von Spitzensportlern


Im Allgemeinen wurden Elitesportler als gesunde Schläfer eingestuft. Basierend auf subklinischen Fragebögen zeigte die in Kapitel 2 berichtete Studie jedoch, dass eine substantielle Minderheit von 41% als schlechter Schläfer eingestuft wurde (PSQI; Grenzwert schlechter Schläfer ≥ 525) und dass 12% eine potenzielle Schlafstörung hatten (HSDQ; Grenzwert ≥ 2.0224). „Restless leg syndrome / periodic limb movement disorder (RLS/PLMD)” war die am häufigsten genannte Schlafstörung. Tägliche Fragebögen ergaben eine durchschnittliche Schlafdauer von 8 Stunden, die deutlich innerhalb des empfohlenen Bereichs von 7-9 Stunden.12

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13 lag. Jedoch zeigten die selbst eingeschätzte Schlaflatenzzeit (20 Minuten) und das Aufwachen nach dem Einschlafen (13 Minuten) Potential für Verbesserung. Schließlich zeigte die Auswertung der Tagebücher, dass sich die Spitzensportler bei der gegebenen Schlafdauer am Morgen nur mäßig erholt, wachsam und energiegeladen fühlten. Die in Kapitel 3 dargestellten, auf Aktigraphie basierten Schlafmessungen zeigten ein ähnliches Muster. Wie zu erwarten wichen die absoluten Werte von den subjektiven Werten ab. Die durchschnittliche Schlafdauer über sieben Tage betrug fast 8 Stunden. Das Aufwachen nach dem Einschlafen bietet Raum für Verbesserungen (33 Minuten) und die Schlaffwachzeit (88%) lag unter dem Durchschnitt dieser Altersgruppe (d.h. 92%). Letzteres deutet auf einen relativ fragmentierten Schlaf hin. In 22% der Nächte lagen die Schlaffwachzeit-Werte unter 85%, eine Schwelle, die als Untergrenze für guten Schlaf gilt.


Ziel 2: Identifizierung schlafgefährdender Faktoren


relativ großer Unterschiede innerhalb der Individuen, spiegelten sich die täglichen Unterschiede in der selbst eingeschätzten Trainingsbelastung weder in auf Aktigraphie basierten Schlafmessungen (z.B. Schlafdauer, Schlafeffizienz) noch in EEG-basierten Verteilungen der Schlafstadien wider.

Ziel 3: Ermittlung der Auswirkungen des Schlafes auf die sportliche Leistungsfähigkeit

Obwohl dieses Forschungsgebiet noch in seinen Kinderschuhen steht, deuten die ersten Hinweise auf eine Verschlechterung der kognitiven und sportlichen Leistungen nach (partiellem) Schlafentzug hin\(^2\), während sich die Leistungen nach der Schlafverlängerung zu verbessern scheinen\(^23\), \(^24\). Wichtig ist, dass Sportler in ihrem täglichen Leben in der Regel mit subtilen Veränderungen im Schlaf konfrontiert werden (z.B. ± 4 Stunden), die kleiner sind als die in experimentellen Studien verwendeten Manipulationen. Inwieweit sich solche eher subtilen Veränderungen im Schlaf tatsächlich in der (sportartspezifischen) Leistung niederschlagen können, ist angesichts fehlender Forschung noch unklar. Vor diesem Hintergrund wurde in Kapitel 4 untersucht, inwieweit sich die eher kleinen, natürlich auftretenden täglichen Schwankungen der Schlafdauer und der Schlafstadien in der kognitiven und sportartspezifischen Leistungsfähigkeit von Spitzensportlern widerspiegeln. Der Einfluss von (Veränderungen der) Schlafdauer (Aktigraphie) und Schlafstadien (einkanaliges EEG) auf die psychomotorische Leistung sowie die Leistung der Fein- und Grobmotorik wurde bei 98 Spitzensportlern während drei nicht aufeinander folgenden Anlässen untersucht. Die Ergebnisse zeigten, dass sich kleine Veränderungen der Gesamtschlafzeit sofort in kleinen, aber signifikanten Veränderungen der psychomotorischen Wachsamkeit (d.h. der Reaktionszeit) am nächsten Tag niederschlugen. Zusätzlich wurden kleine und inkonsistente Auswirkungen von Schlafdauer und Schlafstadien auf grobmotorische Leistungen beobachtet (z.B. Sprinten), allerdings wurden keine Auswirkungen auf feinmotorischen Leistungen festgestellt (z.B. Treffsicherheit).

Ziel 4: Optimierung des Schlafes


Ziel 3: Ermittlung der Auswirkungen des Schlafes auf die sportliche Leistungsfähigkeit

Obwohl dieses Forschungsgebiet noch in seinen Kinderschuhen steht, deuten die ersten Hinweise auf eine Verschlechterung der kognitiven und sportlichen Leistungen nach (partiellem) Schlafentzug hin\(^2\), während sich die Leistungen nach der Schlafverlängerung zu verbessern scheinen\(^23\), \(^24\). Wichtig ist, dass Sportler in ihrem täglichen Leben in der Regel mit subtilen Veränderungen im Schlaf konfrontiert werden (z.B. ± 4 Stunden), die kleiner sind als die in experimentellen Studien verwendeten Manipulationen. Inwieweit sich solche eher subtilen Veränderungen im Schlaf tatsächlich in der (sportartspezifischen) Leistung niederschlagen können, ist angesichts fehlender Forschung noch unklar. Vor diesem Hintergrund wurde in Kapitel 4 untersucht, inwieweit sich die eher kleinen, natürlich auftretenden täglichen Schwankungen der Schlafdauer und der Schlafstadien in der kognitiven und sportartspezifischen Leistungsfähigkeit von Spitzensportlern widerspiegeln. Der Einfluss von (Veränderungen der) Schlafdauer (Aktigraphie) und Schlafstadien (einkanaliges EEG) auf die psychomotorische Leistung sowie die Leistung der Fein- und Grobmotorik wurde bei 98 Spitzensportlern während drei nicht aufeinander folgenden Anlässen untersucht. Die Ergebnisse zeigten, dass sich kleine Veränderungen der Gesamtschlafzeit sofort in kleinen, aber signifikanten Veränderungen der psychomotorischen Wachsamkeit (d.h. der Reaktionszeit) am nächsten Tag niederschlugen. Zusätzlich wurden kleine und inkonsistente Auswirkungen von Schlafdauer und Schlafstadien auf grobmotorische Leistungen beobachtet (z.B. Sprinten), allerdings wurden keine Auswirkungen auf feinmotorischen Leistungen festgestellt (z.B. Treffsicherheit).
Bevölkerung getesteten Interventionen begrenzt. Bisher behandeln die wenigen Studien zur Schlafoptimierung bei Sportlern Interventionen mit den Schwerpunkten Ernährung, spezifische Schlafhygienepraktiken, „brain-wave entrainment“, oder Schlafverlängerung. Basierend auf den Schlafanalysen in Kapiteln 2 und 3, bieten Kapitel 5a, 5b, 5c und 6 praktische Schlafhygienerecensionen (Kapitel 5a) und experimentelle Tests verschiedener chronobiologischer Schlafinterventionen (Kapitel 5b, 5c und 6).


sogar um 17 Minuten und ging mit einer signifikanten Verbesserung der subjektiven Schlafqualität einher.

**BEITRÄGE DIESER ARBEIT**


und maskieren. Schließlich erlaubte die bewusste Entscheidung, den Schlaf und die Trainingsbelastung nur zu überwachen statt zu manipulieren, ökologisch relevante Schlussfolgerungen. Allerdings ging dies auch mit dem Nachteil kleinerer Effektgrößen als Folge kleinerer und unausgewogener Schwankungen der Schlaf- oder Trainingsbelastung einher.


da ein erheblicher Teil der Spitzensportler von einer „schlechten“ Schlafqualität berichtete und sich am Morgen nicht ausreichend erholt fühlte (Kapitel 2). Darüber hinaus haben Studien berichtet, dass Leistungssportler Leistungseinbußen infolge dysfunktionaler Gedanken, das heißt Angst vor Unterleistung als Folge einer schlechten Nachtruhe, erleiden. Die in Kapitel 4 berichtete Studie zeigte, dass diese Besorgnis unbegründet sein kann, da kleine Schwankungen im Schlaf kaum einen großen Einfluss auf die (sportliche) Leistung haben dürften, vorausgesetzt, dass die Schlafdauer an den vorangegangenen Tagen insgesamt ausreichend war. Schließlich zeigte die Regulierung der morgendlichen und abendlichen Lichtzufuhr vielversprechende Verbesserungen im Schlaf (Kapitel 5c und 6). Basierend auf diesen Erkenntnissen wird den Leistungssportlern empfohlen, die (natürliche) Lichtexposition am Morgen und am Tag zu erhöhen und sich weniger kurzwelligem (blauem) Licht am Abend auszusetzen.

**FAZIT**


86. Bompa TO, Haff GG. Periodization: theory and methodology of training, Champaign, Illinoise, Human Kinetics; 2009.


ABOUT THE AUTHOR

Melanie Knufinke was born May 27, 1989 in Gütersloh, Germany. She started her secondary-education at Freiherr-vom-Stein Realschule which was continued at Städtisches Gymnasium Gütersloh, where she received the German university-entrance diploma Abitur in 2008. Afterwards, Melanie studied Psychology at the University of Twente, The Netherlands. In 2010, she spent four month in Nairobi, Kenya to study cultural dimensions in a non-western and non-governmental organization as part of a minor program in International Management. Melanie obtained her bachelor’s degree in 2012, investigating arousal by means of electrodermal activity during a balance beam routine and observational learning thereof. Subsequently, she was admitted to the Masters track Human Factors and Media Psychology at University of Twente, during which she did a 13-month graduate research project at Philips Group Innovation - Research in the department of Brain, Body and Behaviour in Eindhoven. She investigated the effect of selective slow-wave-sleep deprivation on nocturnal electrodermal activity in the habitual sleep environment. After receiving her Master’s degree in 2013, Melanie accepted a PhD-position at the department of Work, Health and Performance at the Behavioural Science Institute of Radboud University in Nijmegen. Her research focused on optimizing sleep to improve performance in elite athletes, investigating the effects of sleep on cognitive- and athletic performance, as well as the potential sleep-promoting effects of sleep hygiene practices, temperature, and light. Besides having studied sports performance and sleep before and being fascinated about elite athletes, Melanie has always been a dedicated sleeper, which is why starting a research project on the respective topics was a welcomed challenge. The research was funded by the Netherlands Organization for Scientific Research domain Applied and Engineering Sciences (NWO-TTW) and involved active collaboration with various partners from science, industry and sports (Philips Research, Auping, Sportcentrum Papendal, and NOC*NSF). During her PhD-period, in 2017, Melanie was involved in launching a committee for young sleep scientists (Jonge Wetenschappers Commissie) within the Dutch Society for Sleep-Wake Research (NSWO), in which she still serves as an active member. Since May 2018, Melanie is employed as a sleep expert by Shleep, a company that offers corporate sleep management programs.
LIST OF PUBLICATIONS
Accepted

Submitted
National Publications


National Publications


DANKWOORD

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Tiele, Sven en Arie, jullie hebben wel wat meegemaakt in het project: voor 6 uur ’s ochtends stonden jullie gereed voor het afnemen van de fysieke prestatietests. Jullie hebben een gedeelte van de 980 ochtend- en avonddagboeken, waaronder een schaal die handmatig met een liniaal moest worden gescroond, gedigitaliseerd en ook het analyseren van actigrafiedata is ondertussen bekend terrein voor jullie. Ik kan me gelukkig achen om jullie als studentassistenten te hebben gehad; ik kon

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UITNODIGING

Voor het bijwonen van de openbare verdediging van mijn proefschrift

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Op maandag 1 oktober 2018 om 16.30 uur precies

In de Aula van de Radboud Universiteit, Comeniuslaan 2

te Nijmegen

Na afloop van de verdediging is er een receptie in de Aula

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