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Dim light, sleep tight, and wake up bright – Sleep optimization in athletes by means of light regulation

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Abstract

Despite an elevated recovery need, research indicates that athletes often exhibit relatively poor sleep. 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, but is often disturbed due to underexposure to light in the morning (e.g. low-level indoor lighting) and overexposure to light in the evening (e.g. environmental and screen-light). This study examined whether combining fixed sleep schedules with light regulation leads to more consolidated sleep. Morning light exposure was increased using light-emitting goggles, whereas evening light exposure was reduced using amber-lens glasses.

Using a within-subject crossover design, twenty-six athletes (14 female, 12 male) were randomly assigned to start the intervention with the light-regulation-week or the no light-regulation-week. Sleep was monitored by means of sleep diaries and actigraphy.

Due to low protocol adherence regarding the fixed sleep-wake schedules, two datasets were constructed; one including athletes who kept a strict sleep-wake schedule ($N = 8$), and one that also included athletes with a more lenient sleep-wake schedule ($N = 25$). In case of a lenient sleep-wake schedule, light regulation improved self-reported sleep onset latency (Δ SOL = 8 min). This effect was stronger (Δ SOL = 17 min) 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. To conclude, light regulation may be considered a potentially effective strategy to improve subjective sleep, but less obtrusive methods should be explored to increase protocol compliance.

Keywords: *Light regulation, sleep, athletes, blue-blocker glasses, light exposure*

Highlights

- Athletes often exhibit relatively poor sleep, while interventions to optimize their sleep are scarce.
- Irregular sleep- and wake times, as well as underexposure to light in the morning and overexposure to light in the evening are common among athletes. Therefore, light regulation may be considered as a meaningful strategy to optimize sleep in athletes.
- Targeting the sleep-regulating mechanisms of the circadian system, our study showed that reducing exposure to (blue-) light in the evening and increasing light exposure upon awakening can significantly improve subjective ratings of sleep in athletes. No effect was observed for objective (actigraphy-based) sleep estimates.
- Protocol evaluation showed that athletes struggled adhering to regular sleep-wake patterns and perceived the glasses used for light-regulation as relatively uncomfortable. Less obtrusive methods targeting the same mechanisms should be examined to improve protocol compliance and further increase intervention effectiveness.

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Introduction

Recent research indicates relatively poor sleep among elite athletes and strategies are needed to mitigate this (Knufinke, Nieuwenhuys, Geurts, Coenen, & Kompier, 2018; Leeder, Glaister, Pizzoferro, Dawson, & Pedlar, 2012). The timing and consolidation of sleep is predominantly driven by the circadian system (Borbely, 1982), which requires periodic light–dark exposure for stable entrainment to the 24-hour day (Czeisler et al., 1986). Timing of exposure to (sun-)light is potentially disturbed in athletes due to unfavourable and variable training and competition schedules (Sargent, Halson, & Roach, 2014; Sargent & Roach, 2016), social and media obligations, electronic-device use (Romyn, Robey, Dimmock, Halson, & Peeling, 2016), as well as spending time (training) indoors. Assuming that adequate sleep is essential for recovery and performance (Halson, 2008), 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), helps to improve sleep in athletes.

The 24-hour light–dark cycle is the most potent "Zeitgeber" for (re)aligning the circadian rhythm to the geographical day (Czeisler et al., 1986). Morning light exposure synchronizes circadian phase and facilitates the process of waking up (e.g. increase in cortisol, increase in body temperature), while the absence of light facilitates melatonin secretion, thereby signalling optimal sleep timing in humans. For circadian entrainment, light exposure needs to be of sufficient intensity (Brainard et al., 2001; Lockley, Brainard, & Czeisler, 2003), duration (Chang et al., 2012), of a particular wavelength (Lockley et al., 2003), and occur at a suitable circadian time (phase response curve) (Khalsa, Jewett, Cajochen, & Czeisler, 2003). However, nowadays, daytime light exposure is often reduced as a consequence of time spent surrounded by low and static indoor lighting (Ancoli-Israel et al., 1997), which is most likely of insufficient intensity to entrain the circadian system. In addition, whereas day-time light exposure tends to be insufficient, light pollution in the evening is often high (Roenneberg, Wirz-Justice, & Merrow, 2003), also among athletes. 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 of blue-/green light) that may suppress melatonin secretion by the pineal gland (West et al., 2011) and result in increased alertness, delayed sleep onset and reduced sleep efficiency (Chang, Aeschbach, Duffy, & Czeisler, 2015; Fossum, Nordnes, Storemark, Bjorvatn, & Pallesen, 2014).

In an attempt to improve circadian entrainment and sleep timing, several studies have investigated the effects of increasing daytime light exposure and reducing evening light exposure. These studies show that increasing daytime bright light exposure may effectively improve sleep continuity, supposedly by increasing the SCN amplitude (Figueiro, Bierman, Bullough, & Rea, 2009), reduce sleep onset latency, advance sleep onset time, increase sleep duration, improve daytime functioning and lower daytime sleepiness (Lack, Wright, & Paynter, 2007). In addition, reducing evening exposure to short-wavelength light has been shown to secure individuals' habitual melatonin secretion, and supposedly circadian phase (Burkhart & Phelps, 2009).

While both morning light exposure and evening light restriction may thus promote sleep, to date, their combined effect has only rarely been evaluated (Geerdink, Walbeek, Beersma, Hommes, & Gordijn, 2016). Furthermore, while positive effects have been observed in clinical populations that suffered from pathology-related sleep problems (e.g. Alzheimer's disease, delayed/advanced sleep phase disorder, sleep onset insomnia), effects of light regulation on the sleep of young and healthy individuals such as athletes, remain largely unknown (cf., Knufinke, Fittkau-Koch, Møst, Kompier, & Nieuwenhuys, 2019).

Knowing that exposure to the natural light–dark cycle is often disturbed in athletes, 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. Recreational athletes were defined as athletes who are non-competitive or competing at a local (sub-national) level and who are engaged in organized physical activity or sport on a weekly basis. Participants (14 female, 12 male) were aged between 19 and 32 years ($M \pm SD$; 24.64 ± 3.43 years), and had an average body mass index of 21.83 ± 2.27. All participants were physically active, exercising on average 8.90 ± 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 (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989): 5.19 ± 3.07; $M \pm SD$; cutoff ≥ 5), but were without severe subjective sleep complaints (Holland Sleep Disorder Questionnaire (Kerkhof et al., 2013): $1.46 \pm .51$; $M \pm SD$; cutoff ≥ 2.02). Participants were free of sleep medication, and, based on the Munich ChronoType Questionnaire (Roenneberg et al., 2007), showed no extreme chronotypes (midpoint of sleep on free days, corrected for "oversleep" on free days: MSF_{sc}: $4:07 \pm 0:28$ h:min, range 3:06–5:00 h:min). Data was collected between February and May 2017, except for the week following the switch to daylight saving time (26th of March). 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 (see section: sleep estimates).

Behavioural 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 behavioural guidelines, including: (1) a regular sleep-wake pattern, in which a maximal deviation in bed and rise times of 30 min 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 PM 5.00, 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 behavioural 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 min upon final awakening (morning light exposure) (Chang et al., 2012), whereas in the evening, blue-light blocking amber-lens glasses were worn during the last three hours before bedtime (evening light restriction) (Sasseville, Paquet, Sévigny, & Hébert, 2006). 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™, Bedford Park, SA, Australia). The device emitted blue–green light (500 nm) at an intensity of 506 lm/m^2 and 230 $\mu W/cm^2$ (i.e. "high intensity" setting), and has been shown to effectively shift circadian phase (Lovato & Lack, 2016). 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 (Sasseville et al., 2006).

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 behavioural 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 behavioural guidelines and potential differences in sleep hygiene were assessed daily, using items adapted from the Sleep Hygiene Index (SHI; Mastin, Bryson, & Corwyn, 2006). Items on competition, sleep environment, and physical training load were added. Training load was measured on a scale from 1 to 10, with 10 indicating the highest possible training load (Knufinke, Nieuwenhuys, Geurts, Møst, et al., 2018), 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 et al. (2015): 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 upon awakening using the morning section of the Consensus Sleep Diary (CSD-M; Carney et al., 2012). 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 used. 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 upon awakening using the corresponding item on sleep quality and feeling of being refreshed from the CSD-M (Carney et al., 2012), with scores ranging from 1 to 10, with 10 indicating high sleep quality/refreshment. Alertness/sleepiness upon awakening was assessed using the Karolinska Sleepiness Scale (KSS; Akerstedt & Gillberg, 1990), with scores ranging from 1 to 9, with higher scores indicating higher sleepiness.

Process evaluation

Wearing of the glasses (yes/no) and the duration of use (hrs: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 Joshi (2005), 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 Lack (2016). 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 naps that were consistently taken 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 min (3 out of 350 nights) or the evening goggle for less than 90 min (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. As preliminary analyses indicated low overall compliance, we created two datasets: one that included individuals who adhered to the instructed sleep-wake schedule for at least three nights in both conditions (i.e. maximal deviation in bed and rise times ≤30 min; SW30, $N = 8$) and one that also included individuals when their sleep-wake schedule was more variable (i.e. maximal deviation in bed- and rise times ≤120 min; SW120, $N = 25$), thereby allowing the evaluation of intervention effectiveness across different degrees of sleep-wake regularity. At the individual level, only nights on which participants met the respective inclusion criteria (SW30 or SW120) were included.

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

Results

Behavioural 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 behavioural) 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 ($\Delta = 27$ min, $t(21) = -3.535$, $p = .002$), and lights-on times ($\Delta = 23$ min, $t(21) = -3.363$, $p = .003$), 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 7–8 hours per night (see Table I and Table II).

Results of the statistical testing are displayed in Table I (strict; SW30) and Table II (lenient;

Table I. Results obtained from the dataset including nights with regular sleep-wake patterns (SW30, $N = 8$).

	No-light regulation		Light regulation		Results of statistical analysis			
	M	*SD*	*M*	*SD*	*Df*[2]	*F*	*p*	$\eta^2 p$
Actigraphy-based								
SOL (h:min)	0:12	0:11	0:16	0:23	7	.005	.944	.001
WASO (h:min)	1:02	0:25	1:02	0:27	7	.000	.995	.000
Fragmentation (%)	32.02	10.77	35.61	11.29	6[a]	.175	.690	.028
TST (h:min)	7:24	0:51	7:10	0:44	6[a]	3.148	.126	.344
SE (%)	83.53	5.96	81.27	6.71	6[a]	.960	.365	.138
Diary-based								
SOL (h:min)	0:34	0:27	0:17	0:10	7	14.641	**.006**	.677
WASO (h:min)	0:25	0:22	0:24	0:21	7	.023	.885	.003
TST (h:min)	7:41	0:40	7:52	0:39	7	1.533	.256	.180
SE (%)	89.19	8.18	91.25	7.96	7	1.508	.259	.177
Sleep Quality								
Sleep Quality (1–10)	6.63	0.88	7.05	0.67	7	11.882	**.011**	.629
Refreshed (1–10)	6.20	1.15	6.38	1.32	7	3.933	.088	.360
KSS (1–9)	5.51	1.42	5.16	1.28	7	1.318	.289	.158

Note: [a]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.

Table II. Results obtained from the dataset including irregular sleep-wake patterns (SW120, $N = 25$).

	No-light regulation		Light regulation		Results of statistical analysis			
	M	*SD*	*M*	*SD*	Df^2	*F*	*p*	$\eta^2 p$
Actigraphy-based								
SOL (min)	0:16	0:20	0:11	0:13	21	3.362	.081	.138
WASO (min)	0:58	0:23	1:03	0:33	21	1.340	.260	.060
Fragmentation (%)	34.90	15.10	36.71	14.62	21	2.673	.117	.113
TST (h:min)	7:04	0:49	6:55	0:59	21	2.89	.104	.121
SE (%)	82.37	9.81	80.99	11.15	21	3.654	.070	.148
Diary-based								
SOL (min)	0:24	0:20	0:16	0:09	22	5.984	**.023**	.214
WASO (min)	0:21	0:20	0:20	0:21	22	.000	.984	.000
TST (h:min)	7:40	0:45	7:42	0:53	22	.176	.679	.008
SE (%)	92.10	6.24	92.45	6.74	22	.123	.729	.006
Sleep Quality								
Sleep Quality (1–10)	6.81	.83	6.95	.94	22	1.103	.305	.048
Refreshed (1–10)	6.37	1.01	6.43	1.06	22	.194	.664	.009
KSS (1–9)	4.90	1.38	4.75	1.1	22	.725	.404	.032

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

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 min shorter in the LR condition compared to the nLR condition ($F(1,7) = 14.641$, $p = .006$, $\eta^2 p = .677$). In the lenient dataset (SW120), this effect was smaller (ΔSOL = 8 min, $F(1,22) = 5.984$, $p = .023$, $\eta^2 p = .214$). No other sleep quantity estimates differed significantly between conditions (all p's > .07). Finally, in the strict dataset, the self-reported faster sleep onset latencies in the LR condition were accompanied by significantly better subjective 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 > .088).

Process evaluation

Across both datasets ($N = 25$), the light-emitting goggles were rated as rather uncomfortable ($M \pm SD$; 4.88 ± 1.87; scale 1–10), but relatively easy to use ($M \pm SD$; 6.59 ± 1.66; scale 1–10). The amber-lens glasses (LR) were rated more comfortable than the transparent glasses (nLR), with $M \pm SD$; 6.31 ± 1.78 and 6.00 ± 1.46, respectively, but without reaching statistical significance ($t(15) = -.573$ $p = .575$). With regard to ease of use, there was no difference in ratings between both glasses ($t(15) = .000$, $p = 1.00$), 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 ($M \pm SD$; 6.79 ± 2.36), with 18 participants scoring >6 and six participants scoring ≤6 on a scale from 1 to 10, with 10 indicating a very high need for sleep optimization. Two participants had missing data on this item. Table III 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.

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 showed comparable sleep estimates in the current sample as compared to estimates in other athlete samples (see Table I; cf. Leeder et al., 2012; Knufinke, Nieuwenhuys, Geurts, Møst, et al., 2019) and – importantly – 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 sleep onset latency in the no light regulation condition. This effect was stronger and complemented by improved subjective sleep quality when athletes kept a strict sleep-wake schedule. However, no significant differences between conditions were

Table III. Process evaluation outcomes and list of identified symptoms.

	Light goggles	Amber glasses	Transparent glasses
Headache	2/26	0/26	0/26
Dizziness	1/26	0/26	0/26
Nausea	1/26	0/26	0/26
Eye irritation	3/26	1/26	2/26
Eye redness	0/26	0/26	0/26
Blurred vision	9/26	6/26	3/26
Light bothersome to eyes	5/26	1/26	1/26
Restlessness	1/26	1/26	0/26
Excessive energy	0/26	1/26	0/26
Irritability	0/26	1/26	1/26
Other:	6/26	4/26	4/26
	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
Appearance (1–10)	3.92 ± 2.17	4.12 ± 2.21	6.23 ± 1.66
Inconvenience during other activities	17/26	12/26	3/26
Reading (OK)	24/26	25/26	26/26
Distance vision (OK)	23/26	26/26	26/26

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 (van de Water, Holmes, & Hurley, 2011). Krystal and Edinger (2008) explain that individuals may report poor sleep quality despite of objective markers indicating good quality sleep, and vice versa. A shortening of 17 min in self-reported sleep onset latency and an improved rating of sleep quality, as demonstrated in the strict light regulation condition of this study, can be considered a relevant improvement (cf. 20 min post full CBT-I treatment [Okajima, Komada, & Inoue, 2011]). Because of the low wake-detection capacity in actigraphy (Chae et al., 2009), it is not surprising that effects were found for subjective, but not for objective markers of sleep. Nevertheless and despite these promising results, it is worthwhile mentioning that there are two aspects that may have biased the subjective sleep ratings. First, sleep ratings were performed close to waking up to allow for accurate recall as suggested in the Consensus Sleep Diary (CSD-M; Carney et al., 2012), but athletes may have felt more sleepy due to sleep inertia. Second, athletes with higher protocol adherence may have been believers of the intervention which may have biased their response towards reporting more favourable sleep estimates. Therefore, future research is required to substantiate the current findings and complement with objective measures that are sensitive to detecting small changes in sleep onset latency (e.g. polysomnography).

Despite the above mentioned reservations, discussion of potential mechanisms responsible for the observed improvements in self-reported sleep onset latency and subjective sleep quality is warranted. 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 (Czeisler et al., 1986). 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 Stothard et al., 2017), 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 (Chang et al., 2015; Fossum et al., 2014). 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" (Figueiro et al., 2009).

While light regulation appears to be a promising intervention to facilitate sleep – especially in conjunction with other sleep hygiene related interventions –, process evaluation and protocol adherence in our study highlighted that its practical implementation 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. staying inside instead of going out) or wearing the glasses for shorter periods of time. While the current study was conducted during a training periods, athletes may perceive light-regulation as less burdensome during competition, a shorter and finite period, where active behaviour regulation may be more feasible and potential sleep and performance benefits more relevant. To conclude, future work should consider less obtrusive ways of light regulation that are feasible indoors, outdoors and without attracting much attention in public. Furthermore, given the difficulty that most athletes showed adhering 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 with practical implementation of the intervention. In addition, it should be acknowledged that the 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 effectively shortened self-reported sleep onset latencies in recreational athletes. This effect was stronger and accompanied by improved subjective sleep quality, if athletes kept a strict sleep-wake schedule. Notably, no intervention effect was shown in objective sleep estimates, an observation that requires further investigation. Although user-friendliness of the intervention may be further improved, the observed magnitude of effects (i.e. average ΔSOL between 8 and 17 min) suggests that light regulation may be considered a meaningful strategy to optimize subjective sleep in athletes.

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