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Dose–response relationship between light exposure and cycling performance

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Light has a stimulating effect on physical performance if scheduled according to the chronotype, but dose-dependent effects on performance have not yet been examined. Three groups of healthy men (25.1 ± 3.1 years) were exposed to light for different durations in a parallel group design before a 40-min time-trial. In each group, subjects were exposed to either bright light (BL, 4420 lx) or moderate light (ML, 230 lx) in a randomized order in a crossover design. The durations of light exposure were 120 min prior to and during exercise (2HEX; $n = 16$), 60 min prior to and during exercise (1HEX; $n = 10$), or only for 60 min prior to exercise (1H; $n = 15$). Total work performed during the time-trial in kJ in the 2HEX group was significantly higher in the BL setting (527 kJ) than in ML (512 kJ) ($P = 0.002$), but not in 1HEX (BL: 485 kJ; ML: 498 kJ) or 1H (BL: 519 kJ; ML: 514 kJ) ($P = 0.770$; $P = 0.485$). There was a significant ($P = 0.006$) positive dose–response relationship between the duration of light exposure and the work performed over the three doses of light exposure. A long duration light exposure is an effective tool to increase total work in a medium length time-trial in subjects normalized for their individual chronotype.

Physical performance varies over the course of the day, with the peak performance levels between the late afternoon and early evening (Reilly & Waterhouse, 2009). Increased homeostatic sleep pressure levels and circadian-related changes in core body temperature and melatonin levels lead to a decrease of physical performance in the late evening (Schmidt et al., 2007). The human circadian timing system is synchronized to the 24-hour day by exogenous factors of which light is the most powerful (Roenneberg & Merrow, 2007). In individuals, circadian rhythms differ in terms of amplitude and phase as well as their relation to local time. This difference between local and internal time defines chronotypes. The chronotype of an individual can be determined by the midpoint of sleep on free days corrected for oversleep due to sleep debt on workdays (MSFsc) (Roenneberg et al., 2004).

There is ample evidence that light, particularly in the late evening, has acute alerting effects and increases cognitive performance, apart from phase delaying circadian rhythms (Winkler et al., 2006; Rastad et al., 2008). The strength of these effects crucially depends on the intensity of light, its wavelength, the individual light history, duration, and time of day of exposure (Hébert et al., 2002; Cajochen, 2007). Besides, the effects of light – to shift circadian rhythms in performance, to attenuate melatonin levels, and to increase alertness – hold out the prospect of a great benefit in competitive sports. This could be particularly interesting in competitions taking place in the late evening. Additionally, a higher alertness and mental activity might lead to an increased motivation, which might contribute to even better performance in competitive sports.

The effect of bright light (BL) on physical performance has only been examined in a few studies. One study (Ohkuwa et al., 2001) found no significant effect on maximal ergometric power output in a 45 s all-out test on a bicycle following light exposures of 50 and 5000 lx for 90 min. A study of exposure to three different light settings (1411, 2788, and 6434 lx) (O'Brien & O'Connor, 2000) during a 20-min time-trial also showed no effects. However, the applied intensities of light were all rather high, which may have masked the potential beneficial effects of light on physical performance (i.e., ceiling effect). In a small sample, one group (Thompson et al., 2015) showed a superiority of BL exposure with 2500 lx for 30 min in the evening over a control condition with 0 lx in a 10-km time-trial, which took place the following morning. However, O'Brien et al. and

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Ohkuwa et al. did not account for daytime, and furthermore in all three studies "chronotype" was not considered.

A recent study (Kantermann et al., 2012) showed that BL (4420 lx) increased physical performance significantly dependent on the chronotype. In more detail, BL exposure for 120 min prior to and during a 40-min time-trial increased the total ergometric power output in subjects performing ~14.8 h after their MSFsc, whereas this effect did not occur in the subgroup tested at a mean of ~11.8 h after the MSFsc. The latter BL exposure has been interpreted as being too early with respect to the internal timing system (i.e., the inner clock) and ~14.8h after the MSFsc to be a "sensitive" time.

In trying to adapt these results to the real world of competitions, the authors considered cutting the exposure time down to 60 min prior to and 40 min during the time-trial and, in a second step of dose-reduction, to solely 60 min prior to the time-trial. The individuals would therefore be exposed for a shorter period during their "sensitive" time. Thus, the hypothesis to be verified in this study was that different BL exposure regimes prior to and during a time-trial applied during the "sensitive" phase of the circadian rhythm result in a dose-dependent increase of time-trial power output. This could enable a practical and individualized application of BL in order to overcome disadvantages of unfavorable competitions with regard to the individual inner clock.

Material and methods

This study consisted of three separate parts. In all three parts, subjects were exposed to the same two different intensities of light in a crossover design, with a randomized sequence and each participant serving as its own control (within-subject design). To further avoid an accumulation of possible small carry-over effects, to reduce time investment for subjects, the drop-out rate as well as possible learning effects, the different durations of light exposure were tested in three different groups. The durations of light exposure differed between each of the three parts and were compared in a parallel group design (between-subject design). Through detailed behavioral instructions regarding the wash-out phase of 1 week between the test sessions, an attempt was made to reduce possible carry-over effects to a minimum.

All participants were healthy, young males with a mean (standard deviation) age of 25.1 (± 3.1) years, mean body mass index (BMI) of 23.1 (±1.8) kg/m^2 and mean peak oxygen uptake (VO_2peak) of 54.9 (±6.7) mL/kg/min.

Every participant performed a baseline test to measure VO_2peak. Seven days later, the first test session [bright (BL) or moderate light (ML) exposure + time-trial] was conducted and another 7 days later the second test session (opposite: BL or ML exposure + time-trial). During the test sessions, participants were exposed to either BL (~ 4420 lx) or ML (~ 230 lx) following three different regimens in randomized order (Fig. 1).

Participants in the first group were exposed to light for 120 min (2H) prior to and during the 40-min time-trial exercise (EX) (2HEX). In the second group, participants were exposed to light for 60 min (1H) prior to and 40 min during exercise (EX) (1HEX) and in the third group light exposure only took place for 60 min (1H) prior to exercise (1H). The study was approved by the respective local ethics committees, and written informed consents were collected from all study participants. The study complied with the Declaration of Helsinki.

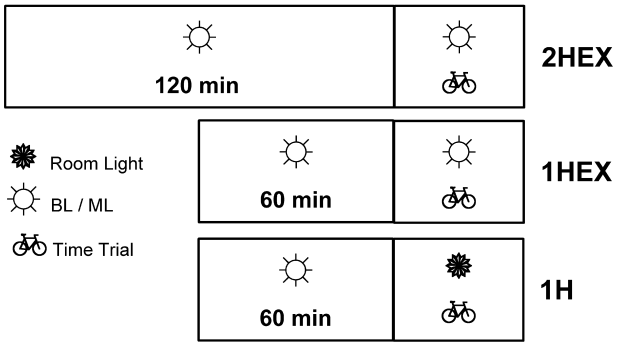

Fig. 1. Study protocol for 2HEX, 1HEX, and 1H. Time-trial: 40 min in duration; bright light/moderate light (BL/ML): continuous randomized exposure.

The individual chronotype was estimated based on the Munich Chronotype Questionnaire. The MSFsc was used as a reference for internal time (Roenneberg et al., 2004). With increasing time elapsed after wake-up (time after the MSFsc), homeostatic sleep pressure increases (Schmidt et al., 2007). This suggests that the light administered later has a stronger alerting response. However, around 18–21 h after the MSFsc (which is called the wake maintenance zone), a high circadian alerting drive keeps alertness and performance levels relatively stable at this time point (Lavie, 2001), which would attenuate the positive impact of light on physical performance. Thus, the time-trials started 14.3 h ± 0.85 h (2HEX), 14.5 h ± 0.22 h (1HEX), and 14.5 h ± 0.21 h (1H) after MSFsc, respectively. This corresponded to mean local times 18:29 (2HEX), 19:06 (1HEX), and 18:35 (1H), respectively. This time point has also been shown to be the effective interval from MSFsc for beneficial effects of BL on cycling performance (Kantermann et al., 2012), which usually represents a time in the late afternoon or early evening, where most athletes achieve their peak performance (Reilly & Waterhouse, 2009).

Clinical examination and performance tests

Data recorded during medical pre-examinations included the health status based on the medical history and a medical examination, height (cm), body mass (kg), BMI (kg/m^2), resting blood pressure (mmHg), and electrocardiogram. For baseline measurements of exercise capacity, participants performed a standardized step incremental bicycle ergometer test (Sport Excalibur, Lode Medical Technology, Groningen, The Netherlands) with self-chosen cadence and a minimum of 60 rpm, starting at 50 W with 25 W increments per 3-min interval until exhaustion. Because experimenters were not blinded to light condition, participants were motivated by standardized encouragement "great, keep going" every 4 min in both light settings. Exercise capacity (peak oxygen uptake, VO_2peak) was measured as the average of three highest consecutive values of oxygen uptake being reached during test. VO_2 was measured every 10 s with ZAN metabolic cart (ZAN 600 USB CPX, nSpire Health GmbH, Oberthulba, Germany) in group 2HEX in a laboratory in Munich and breath by breath with MetaMax 3B (Cortex Biophysik GmbH, Leipzig, Germany) in groups 1HEX and 1H in a laboratory in Basel. Both laboratories fulfilled the standard laboratory criteria for room temperature, humidity, and air pressure according to the accepted guidelines (ESC Working Group on Exercise Physiology, Physiopathology and Electrocardiography 1993; Myers et al., 2009) in order to exclude effects of the exercise laboratory. Additionally, luminance

was controlled in both laboratories. Heart rate (HR) was monitored continuously during the step incremental test with a 12-lead ECG. The rating of perceived exertion (RPE) (Löllgen, 2004) on a scale from 6 to 20 and blood lactate concentration (Lac) (analyzed by Biosen 5040 EKF Diagnostic, Magdeburg, Germany in group 2HEX and SuperGL Ambulance Hitado Diagnostic Systems, Möhnesee, Germany in groups 1HEX and 1H) were assessed in the middle of the third minute of every step on the ergometer. Exhaustion was accepted if two of the following criteria were fulfilled: respiratory exchange ratio > 1.1, RPE ≥ 18, maximum heart rate > 90% of predicted maximal heart rate.

One week after the baseline test, participants performed the first test session including a 40-min time-trial on the same ergometer as during the baseline test. To avoid confounding factors, participants were advised to refrain from intense training 2 days prior to the time-trial and alcohol 1 day prior to the time-trial. Participants were told to keep up their normal sleeping routine the night before the time-trial. Because the participants were all well-trained and the test-retest coefficients of variation in time-trial protocols are found to be highly reliable (Atkinson & Nevill, 2001), a familiarization trial was not performed. Prior to the time-trial, the participants completed a warm-up phase of 10 min at 40% of the individual anaerobic threshold (Dickhuth et al., 1999) determined in the baseline test by lactate analysis with the Ergonizer Software (Version 2.5.9, Freiburg, Germany). For the time-trial, participants were advised to choose a pedaling frequency above 70 rpm and to pedal "as far as possible" (generate as much work as possible). To ensure that every participant was able to pedal with his favored pedaling frequency in the time-trials, resistance was set at the level of the individual anaerobic threshold measured during the baseline ergometric test. Workload (P) increased quadratic (factor α) with increasing pedaling cadence (C) according to the formula:

$$P = \alpha(C)^2$$

RPE (questioned while showing RPE-Scale to subjects), lactate samples, and core body temperature (CBT) (measured tympanally) were taken every 4 min while heart rate was monitored continuously. To control study compliance, participants kept a daily training diary for the complete duration of their participation in the study. Differences in exercise before the time-trial under BL compared to ML condition ≥ 3 h in the last 2 days before the test sessions, as well as discrepancies in the beginning of time-trials ≥ 45 min and deviation from the predetermined starting point (14.5 h after MSFsc) of ≥ 2 h, were not accepted – to ensure the comparability of study groups.

Light exposure

The same two experimental lights (HF3309 PL-L 36 W Philips EnergyLights, Eindhoven, The Netherlands) were used in all three studies. The luminance, measured at the level of the eye in the direction of gaze with a lux meter, was ~ 4420 lx (3.9119 photons/m^2 and 1.4201 W/m^2 in 380–740 nm light spectrum range) under BL and ~230 lx (2.0318 photons/m^2 and 7.3801 W/m^2 in 380–740 nm light spectrum range = ML) under ML before the time-trial. To avoid a possible placebo effect, ML was equipped with four additional red LEDs in each lighting device (EnergyLight) and was referred to as "special light" in the participants' presence. The four red LEDs have no physiological effect (Figueiro et al., 2009).

Additionally, subjects in groups 1HEX and 1H were asked if they expected any improvement, decline, or no effect of light exposure after the light exposure prior to the time-trial. Furthermore, the Karolinska Sleepiness Scale (KSS) (Akerstedt & Gillberg, 1990) ranging from 1 "very awake" to 9 "very sleepy" was handed out to subjects in all three groups before light exposure and after light exposure prior to exercise.

Because subjects may have been exposed to different amounts of light during the day before the onset of the test session, subjects in groups 1HEX and 1H were exposed to complete darkness (0 lx) for 30 min before the light exposure (i.e., dark adaptation).

Inclusion and exclusion criteria

Inclusion criteria were male gender (18–35 years) (females were excluded because changes in the body temperature during exercise vary with the menstrual cycle) (Shephard, 1984) and good general health with normal resting electrocardiogram. Exclusion criteria or circumstances with potential disturbing effects on the inner clock or an effect on the performance encompassed diagnosis of skin, eye or psychiatric diseases, medication interfering with photosensitivity, time-zone travels for four weeks prior to and during the study, and shift-work during and four weeks before the study, as well as an incomplete baseline testing (no exhaustion reached).

Statistics

Paired t-test was used for the intra-subject comparison to compare differences between the work performed after BL exposure and ML exposure within one group. For the inter-subject comparison (between the groups), an analysis of variance (ANOVA) was run with the "difference between work performed (kJ) after BL and ML exposure" as dependent variable and the "dose of light exposure (2HEX = long; 1HEX = medium; 1H = short)" as ordinal factor. Post-hoc tests were performed to identify differences between the groups. Additionally, an analysis of covariance (ANCOVA) was run to calculate the difference between work performed (kJ) after BL and ML exposure, the dose of light exposure, and the VO_2peak from baseline. In an additional exploratory analysis, we assessed changes in the difference between the work performed under BL and ML over time. Work performed during the 40-min time-trial [in kilojoules (kJ)] was defined as the main outcome parameter. Due to the fact that the graphical analysis showed the highest effect of BL on work performed for the initial 12 min of the time-trial, this time interval was analyzed post-hoc as secondary outcome parameter in an exploratory analysis. Data analysis was performed using SPSS version 21.0 for Windows (SPSS Inc., Chicago, Illinois, USA). The distribution of continuous characteristics was described by median (interquartile range). Estimated effects were reported with 95% confidence intervals (CI).

Results

Study participants

Characteristics of the participants of the three groups are presented in Table 1. Group 1HEX achieved significantly ($P = 0.025$) lower VO_2peak at baseline test than 2HEX. No additional significant group differences were observed.

Questionnaires

The answers stated by the participants (amount of answers) showed no significant differences with regard to the expected improvement/ decline/ or absence of an effect of light exposure between BL vs ML in 1H (2/ 2/ 11 vs 4/ 2/ 9) or 1HEX (1/ 0/ 9 vs 2/ 1/ 7).

Reported sleepiness rated on KSS in mean and standard deviation before BL exposure vs after BL exposure

Table 1. Baseline characteristics of the 2HEX, 1HEX, and 1H groups presented as mean (interquartile range)

	2HEX (n = 16)	1HEX (n = 10)	1H (n = 15)
Age (years)	24.0 (23.0; 25.0)	25.0 (24.0; 28.8)	25.0 (23.0; 28.0)
Height (cm)	179 (176; 183)	178 (172; 180)	179 (174; 183)
Weight (kg)	75.9 (67.9; 81.2)	72.7 (66.5; 75.7)	73.3 (69.1; 75.1)
BMI (kg/m^2)	23.7 (22.8; 24.8)	23.4 (22.9; 24.1)	22.3 (21.1; 24.5)
HR (bpm)	61 (57; 72)	66 (57; 71)	62 (55; 66)
BPsys (mmHg)	123 (116; 130)	131 (130; 136)	125 (119; 138)
BPdia (mmHg)	70 (70; 80)	81 (75; 85)	77 (70; 88)
VO_2peak (mL/kg/min)	57.5 (52.0; 61.8)	51.5 (46.0; 55.3)	56.0 (48.0; 59.0)

BMI (kg/m^2), body mass index (kilogram/meter^2); HR (bpm), heart rate (beats per minute); BPsys (mmHg), systolic blood pressure (millimeter hydragyrum); BPdia (mmHg), diastolic blood pressure (millimeter hydragyrum); VO_2peak (mL/kg/min), peak volume oxygen uptake (milliliter/kilogram/minute).

and before ML exposure vs after ML exposure did not significantly differ in 1H (BL: 3.8 ± 1.2 vs 4.0 ± 1.1; ML: 4.1 ± 1.6 vs 3.9 ± 1.3), 1HEX (BL: 3.8 ± 1.5 vs 4.1 ± 1.4; ML: 3.5 ± 1.5 vs 4.0 ± 1.2), and 2HEX (BL: 3.8 ± 1.4 vs 3.9 ± 1.5; ML: 3.4 ± 1.5 vs 3.7 ± 1.6), respectively.

Effect of light exposure on CBT, RPE, HR, and Lac

In the two groups 1H and 1HEX, there were no significant differences in CBT, RPE, HR, or Lac between the time-trial under/after BL and the time-trial under/after ML exposure. In the 2HEX group, HR and Lac were significantly higher under/after BL exposure compared to ML exposure in every measured 4-min interval with no significant changes in RPE or CBT.

Effect of light exposure on work performed

In the 2HEX group, median (interquartile range) of total work in BL 527 kJ (492; 573) was significantly ($P = 0.002$) higher than in ML exposure 512 kJ (468; 544). There were no significant differences in the work performed between BL and ML for 1HEX [485 kJ (463; 590) vs 498 kJ (458; 574)] and 1H [520 kJ (443; 594) vs 514 kJ (449; 595)], respectively.

Dose–response relationship

The ANOVA for the difference between the work performed (kJ) after BL and ML exposure as dependent variable and the dose of light exposure as a factor (2HEX = long; 1HEX = medium; 1H = short) showed a significant ($P = 0.006$) positive dose-dependent influence of light on physical performance. The differences between the doses of light exposure are presented in Table 2. There was a significant effect for "long vs medium" (2HEX vs 1HEX) and "long vs short" (2HEX vs 1H) duration of light exposure, but not for "medium vs short" (1HEX vs 1H) duration of light exposure. In the ANCOVA, the effect of the different doses were adjusted to the baseline VO_2peak and also showed a significant positive dose–response relationship ($P = 0.012$).

Table 2. Effect of different durations of light exposures in mean (95% confidence interval)

Difference in work performed between BL and ML (kJ)	Estimate (95% CI)
2HEX vs 1HEX	26 (1, 51)
1HEX vs 1H	2 (–23, 27)
2HEX vs 1H	28 (6, 50)

BL, bright light; ML, moderate light; CI, confidence interval; 2HEX, group exposed to light for 2 h prior and during exercise; 1HEX, group exposed to light for 1 h prior and during exercise; 1H, group exposed to light for 1 h prior to exercise.

The estimated difference in the effect of BL over ML on work performed during the 40-min time-trial between 2HEX and 1HEX was 26 kJ (95% CI: 1 kJ, 51 kJ), between 1HEX and 1h was 2 kJ (95% CI: –23 kJ, 27 kJ), and between 2HEX and 1 h was 28 kJ (95% CI: 6 kJ, 50 kJ) (Table 2).

Explorative analysis for effect over time during exercise

In an explorative analysis (Fig. 2), the work performed during the 40-min time-trial was subdivided into 4-min intervals for the different light regimens. Significant differences for single time points were observed only in 2HEX, but not for 1HEX and 1H.

For the 40-min time-trial, the difference in the work performed between BL and ML was –4 kJ (95% CI: –17 kJ, 9 kJ) for 1H, –2 kJ (95% CI: –20 kJ, 16 kJ) for 1HEX, and 23 kJ (95% CI: 10 kJ, 36 kJ) for 2HEX (Fig. 3).

For the initial 12 min of the time-trial, the difference in the work performed between BL and ML was 2 kJ (95% CI: –4 kJ, 8 kJ) for 1H, 4 kJ (95% CI: –5 kJ, 13 kJ) for 1HEX, and 10 kJ (95% CI: 5 kJ, 15 kJ) for 2HEX (Fig. 3). While a significantly higher work load under BL was apparent for the initial 12-min phase and in total in 2HEX, the other light regimens showed no significant

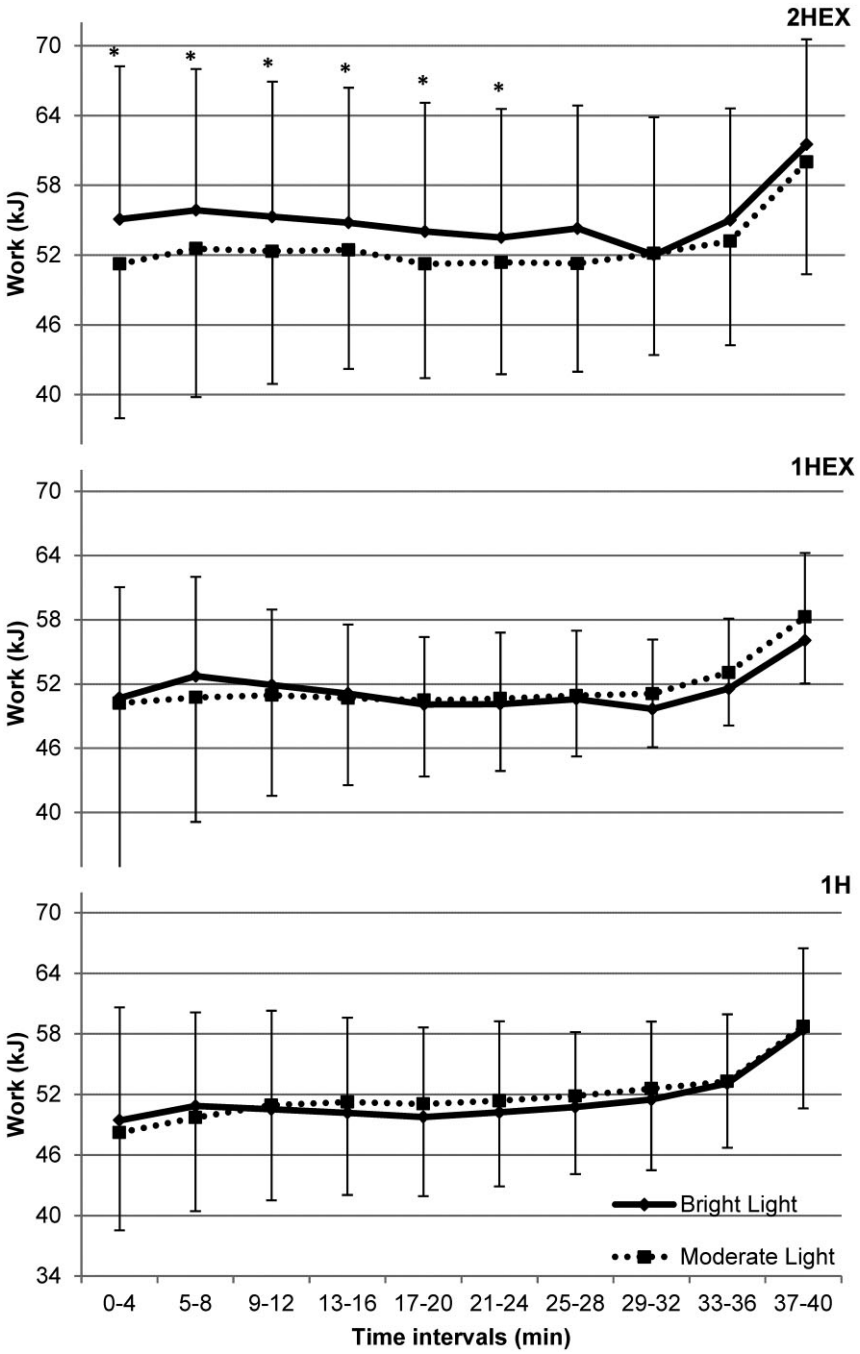

Fig. 2. Mean and SD of work performed (kJ) after/under bright light exposure and after/under moderate light exposure for each interval of four minutes in the 2HEX, 1HEX, and 1H groups.

differences between BL and ML light conditions. However, the confidence intervals from the initial 12 min of 1H and 1HEX were shifted toward a positive effect of BL compared to the confidence intervals for the complete time-trial of 40 min.

Discussion

The main finding of the study was that exposure to BL led to a significant increase of performance in subjects exposed for 120 min prior to and during exercise, but not in subjects exposed for 60 min prior to and during exercise or only prior to exercise for 60 min. Furthermore, a dose–response relationship of light exposure on physical performance was visible when comparing short and medium to long duration. The absence of a significant difference between short and medium duration of light exposure indicates a nonlinear dose–response curve. These data indicate that a certain threshold should be exceeded to achieve an effect on physical performance. In contrast to the dose–response relationship between the level of illuminance and subjective alertness (Cajochen,

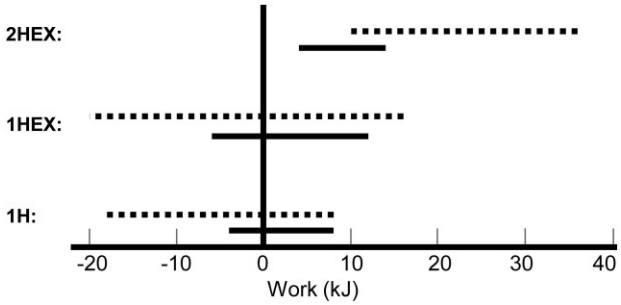

Fig. 3. 95% CI for the effect of the intervention (differences between the works performed in the time-trial after/under bright light and after/under moderate light) in kJ for the 2HEX, 1HEX and 1H groups for total time-trial (dotted lines) and for the first 12 min (continuous lines).

2007), a certain amount of light exposure seems to be necessary to affect physical performance.

The significant positive effect of BL on performance visible in 2HEX was not seen in 1HEX or 1H. Known confounding factors such as the homeostatic sleep pressure which increases with elapsed time awake (Schmidt et al., 2007) and the changes in core body temperature since MSFsc (Krauchi & Wirz-Justice, 1994) could be ruled out since MSFsc did not differ between the three tested groups.

The group with the highest VO_{2peak} (2HEX) at baseline ergometric testing showed a significant effect on performance through BL exposure, but the values for the performance after/under ML exposure did not differ significantly among the groups. This way a possible impact on the results through the different levels of fitness between the groups can be ruled out. Furthermore, an ANCOVA for the effect of BL exposure adjusted for the VO_{2peak} from baseline also showed a significant ($P = 0.012$) dose–response relationship. A placebo effect can be ruled out since most subjects reported that they did not expect any improvement through the light exposure as assessed via questionnaires about the expected effect of light. Thus, the reported differences are most likely related to the different doses of light exposure.

The self-reported level of sleepiness did not differ between the groups before the light exposure. This confirms our expectations, since we timed the tests for all participants according to the individual MSFsc, which is chronotype-dependent. Knowing the asymptotic course of the homeostatic sleep pressure (Schmidt et al., 2007), sleepiness is expected to rather increase minimally at this time of the day. Interestingly, although the BL exposure over 120 min in the group 2HEX did not lead to a reduction in sleepiness, physical performance was increased. This indicates that the sleepiness was not a factor affecting physical performance at this time of the day.

Chang et al. (2012) examined the melatonin-suppressing effects and phase shifts produced by light exposure with 10 000 lx and durations of 0.2, 1.0, 2.5, and 4.0 h, respectively. The melatonin suppression was absolutely higher after 4.0 h (80 ± 9%) than after 2.5 h (64 ± 10%), 1 h (39 ± 19%), and 0.2 h (14 ± 19%), respectively, but the rate of change was higher the shorter the duration. These results indicate that the longer light exposure in 2HEX may led to a stronger reduction of melatonin than in 1HEX and 1H, but at the time of the day the subjects were tested (14.3–14.5 h after the MSFsc), the production of melatonin is rather low (Cajochen et al., 2003). This could indicate that the dose–response relationship shown in this study is not due to a reduction in melatonin. The longer light exposure in 2HEX probably resulted in an increase of alertness or through as yet unknown functional pathways.

As presented in Fig. 3, the 95% CI for the difference between the work performed after BL and ML exposure showed a superiority of BL for the complete time-trial of 23 kJ (95% CI: 10 kJ; 36 kJ) and the initial 12 min of the time-trial of 10 kJ (95% CI: 5 kJ; 15 kJ).

By contrast, in the 1H and 1HEX groups, a significant effect of BL could neither be seen over the complete 40-min time-trial nor in the initial 12 min of the time-trial. However, the mean difference of the differences between the work performed after BL and ML exposure was higher in the initial 12 min with 2 kJ (95% CI: −4 kJ, 8 kJ) in 1H and 4 kJ (95% CI: −5 kJ, 13 kJ) in 1HEX, compared to the complete 40-min time-trial with −4 kJ (95% CI: −17 kJ, 9 kJ) in 1H or −2 kJ (95% CI: −20 kJ, 16 kJ) in 1HEX. Furthermore, the effect of BL exposure in 2HEX was highest within the initial 12 min of the time-trial and decreased with further duration. The post-hoc analysis of the initial 12 min of a 40-min time-trial is not transferable to a time-trial with a total length of 12 min because with the knowledge of the shorter duration of the test, subjects may have started with a higher performance and thereby reduced the differences performed between BL and ML. Nevertheless, these findings might indicate a potential effect of light on performance mainly in the initial phase of exercise. Because further data are necessary to answer this question, the authors are currently conducting a study to address this issue.

In a study by Cajochen et al. (2005), subjects were exposed to light (2.8×10^{13} photons/cm^2/s monochromatic light of wavelength 550 nm) for 2 h before the light was dimmed to 2 lx. Only 15 min after dimming the light, sleepiness increased. This might explain the results seen in 1H where BL only showed a non-significant superiority for the first few minutes. Although exposure to BL continued during exercise in 2HEX and 1HEX, the effect decreased quickly. Internal sympathetic activation during exercise may override the effect of BL at least at the time after MSFsc examined in this study, but it cannot be excluded that BL has an additional effect via the sympathetic nervous system. However, the effect of BL on sympathetic nervous system activity has only

been shown at resting conditions (Sakakibara et al., 2000).

A previous study (Kantermann et al., 2012) showed that the inner clock is important with regard to the effect of BL on physical performance. Thus, the same performance-enhancing time interval of 14.5 h post MSFsc and duration of time-trial was chosen for the additional trials in this study and only the duration of light exposure prior to and during the time-trial was changed. Based on these results, the consequence for future studies is to increase the distance from MSFsc later into the night with higher sleep pressure and potentially higher effects of BL exposure instead of a prolongation of the light exposure.

Limitations

This study has limitations. In contrast to groups 1HEX and 1H, the 2HEX group was not exposed to complete darkness for 30 min before the light exposure. The study part in which group 2HEX was tested took place at an earlier point in time than the parts in which groups 1HEX and 1H were tested and at that point in time the authors were not aware of the impact of light history on the effect of light exposure. In the 2HEX group, the absence of the 30 min darkness phase could have led to higher variability of the effect of BL in the group. In the 1HEX and 1H groups, the 30 min of darkness could have boosted the effect of the light exposure. However, since the effect of BL was still significantly higher in the 2HEX group, a 30 min exposure to darkness might have even increased the effect of BL in 2HEX. Confounding factors such as duration and intensity of exercise on the days prior to light exposure have only been controlled subjectively by diaries. The post-hoc analysis of the initial 12 min of the time-trial does not substitute a time-trial with 12 min in total, since performance may be different in relation to the applied light regimens. Additionally, subjects in all studies had a pause of more than 10 min between light exposure and the time-trial and an additional warm-up phase. A reduction of time prior to exercise is likely to result in longer-lasting effects of more than 12 min. Participants might additionally benefit from a suppression and/or slower rate of rise of plasma melatonin levels, which has not been measured in the current study. At the internal time tested around 14.3–14.5 h after the MSFsc, there is only a minor increase in melatonin (Cajochen et al., 2003). Thus, the effects of BL seen in our study are probably solely the result from an increase in alertness due to a longer BL exposure (> 2 h). Therefore, we hypothesize that effects might be higher in tests carried out later in the evening (16 to 18 h after MSFsc).

Perspectives

A medium or short duration of BL exposure before and/or during time-trial does not enhance physical performance in athletes normalized for their individual chronotype (exercise being taken ~14.5 h after MSFsc). In contrast, a long duration of exposure to BL is an effective tool to increase total work at least for the initial phase of a medium length time-trial. Therefore, especially in short duration disciplines, an exposure to BL is likely to increase alertness and reduce sleepiness and help athletes to compensate for disadvantages in competitions at unfavorable times and improve performance. Because several competitions, and especially finals, take place in the late evening to comply with prime time on television methods, to enhance performance at this time of the day is highly relevant. The ideal duration of exposure to increase performance and simultaneously interfere as little as possible with athletes' routine still needs to be found.

Key words: Bright light, physical performance, circadian rhythm, chronotype, time-trial.

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