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Effects of blue- and red-enriched light on attention and sleep in typically developing adolescents

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ABSTRACT

Differential effects of blue- and red-enriched light on attention and sleep have been primarily described in adults. In our cross-over study in typically developing adolescents (11–17 years old), we found attention enhancing effects of blue- compared to red-enriched light in the morning (high intensity of ca. 1000 lx, short duration: < 1 h) in two of three attention tasks: e.g. better performance in math tests and reduced reaction time variability in a computerized attention test. In our pilot study, actigraphy measures of sleep indicated slight benefits for red- compared to blue-enriched light in the evening: tendencies toward a lower number of phases with movement activity after sleep onset in the complete sample and shorter sleep onset latency in a subgroup with later evening exposure times. These findings point to the relevance of light concepts regarding attention and sleep in typically developing adolescents. Such concepts should be developed and tested further in attention demanding contexts (at school) and for therapeutic purposes in adolescents with impaired attention or impaired circadian rhythms.

1. Introduction

Light has a crucial impact on the physical and mental health of human beings [1–4]. Via the internal clock, located in the suprachiasmatic nucleus of the hypothalamus, light synchronizes the circadian rhythm with the natural day-night rhythm. These mechanisms in turn lead to a regulation of the non-image-forming functions, including initiation of wakefulness/alertness or sleep [for a review see [5]].

While natural light plays an important role for a healthy circadian rhythm, in our society artificial light also has a huge impact on the circadian system. On the one hand, artificial light at night may lead to a desynchronization of the circadian rhythm and in turn to sleep disturbances; on the other hand, the knowledge about the effects of light may be used to implement light conditions which have a positive impact on attention and sleep [1]. Current literature concerning the effects of light on attention and sleep have primarily investigated adults, but it is of high relevance to continue to study the impact of light on these domains in typically developing adolescents.

1.1. Effects of light on alertness and attention

The stabilizing effects of light on the sleep-wake rhythms are essential for cognitive functioning [6]; wavelength, duration and intensity of light exposure modulate brain responses to cognitive tasks [7]. Several studies have described the effects of nighttime light exposure on attention in adults. For short wave length light (460 nm), compared to longer wave length light (550/555 nm), a subjectively reduced sleepiness and increased attentional performance were reported after 6.5 h of light exposition [8] and a greater melatonin suppression and greater alerting response were observed after 2 h of light exposition [9]. Additionally, exposure to blue-enriched light (2 h, 40 lx) in the evening was associated with enhanced subjective alertness, and faster reaction times in tasks requiring sustained attention but not in tasks involving executive functions [10]. Similar effects were seen for night-shift workers after a longer exposure to blue-enriched light (7 night-shifts, 500 lx): reduced sleepiness, increased alertness, and improved attentional performance [11]. In summary, at night, in adults,

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light with a high percentage of blue light was reported to reduce sleepiness [8,11], and to positively affect alertness [9–11] and cognitive performance/attention [8,10,11]. Conversely viewed, it has also been examined which light conditions at night are less beneficial for attention/alertness: circadian-sensitive light (8 h, 50 lx) or wearing blue blocker glasses before bedtime (3 h, ca. 100 lx) was associated with reduced melatonin suppression, decreased attention, and reduced alertness in adults [12] and in male teenagers [13]. Overall, blue light at night had attention/alertness promoting effects beneficial for people working or studying at night. Similar effects have also been described for daytime light exposure: Enhanced alertness or enhanced cognitive performance has also been reported for adults during daytime exposure to blue-enriched light in the workplace (4 weeks, daytime, 310 lx) [14], under blue-enriched morning light (3 h, 750 lx) [15] or after dawn-simulating light (50 min, 0–250 lx) [16]. A field study in school was able to show that illumination of the classroom with variable lighting ("Concentrate" program: very bright, cold light; 1060 lx) led to improved attentional performance in school students [17]. A replication study in adults [18] with better controlled conditions yielded comparable results and was also able to show an increase in working speed (but no effects on reading) in the light exposition group compared to the control group.

Besides wavelength, illuminance has also been reported to affect alertness/attention. In the majority of studies, higher illuminance (1000 to 5000 lx vs. 5 to 200 lx for 1 to 5 h) was reported to be associated with increased alertness/reduced sleepiness ([19–22], for a review see [23]) and increased performance/attention [19,20,24]. However, a few studies did not observe beneficial effects of bright light ($>$ 1000 or 5000 lx, 0.5 h) on performance [22,25] while a study in adolescents (tablet screen, 1 vs. 80 lx, 1 h) reported mixed results [26]. Interestingly, alerting effects of bright light have also been described in the absence of blue-light [22].

Overall, despite clear effects of light on attention described mainly in adults, only a few studies have examined the effects of light on attention in adolescents. Continuing to study the effects of light on adolescents is highly relevant, both in home and school settings, in order to provide beneficial light conditions for learning in this demographic.

1.2. Effects of light on sleep

Sleep is important for well-being, social competence, and academic performance. Irregular sleep and light exposure patterns have been related to delayed circadian rhythms and lower academic performance in college students [27]. Additionally, sleep problems have been associated with reduced social functioning in children [28].

Screen light also has an effect: Unrestricted access to social media in teenagers' bedrooms was reported to reduce sleep time and had negative effects on daily functioning and mood [29]. Moreover, screen-based media consumption in children and adolescents is known to be adversely associated with effects on sleep health [30–32]. This effect is possibly related to time displacement, psychological stimulation by media content, and "the effects of light emitted from devices on circadian timing, sleep physiology, and alertness" [30]. The last aspect is of high importance since nighttime exposure to artificial light with a high percentage of blue light, via both room illumination and electronic devices, has become more and more common in our society [33]. This exposure may lead to a large disruption of circadian rhythms, melatonin onset and sleep [1]. These issues are especially relevant for adolescents who often spend a large amount of time in front of a screen, which negatively affects daytime functioning and sleep (for a review see [34]). Thus, studying the extent to which the use of light, in line with the circadian rhythms, may have beneficial effects on sleep in typically developing adolescents is essential.

Several studies in adults have shown that exposure to blue-enriched light in the evening may lead to a distortion of sleep: altered dynamics of sleep EEG [35]; negative effects on sleep, circadian timing, and next-morning alertness [36]; reduced sleep continuity and morning attention [33]; reduced total sleep times [15]; increased wake time and activity during sleep, reduced sleep efficiency and quality [37]. In addition, an increased circadian sensitivity to blue light was associated with delayed sleep schedules in young adults [38]. Besides nighttime light, daytime light exposure can also have an impact: Receiving high levels of circadian effective light in the morning had a positive impact on sleep onset latency and sleep quality [39]. Moreover, individuals with the $PER3^{5/5}$ polymorphism of the clock gene have been reported to be more sensitive to light effects on alertness [40] and sleep [41].

While many studies find effects of light exposure on sleep, this is not always the case. In adults, circadian-sensitive light compared to fluorescent light in the bedroom did not have beneficial effects on total sleep time or sleep efficiency [12]. Additionally, two studies in adolescents did not observe differential effects of different light conditions on subsequent sleep: Using bright, dim, or short-wavelength filtered screens before bedtime did not result in differences in sleep parameters [26]; wearing blue-light blocking glasses did not affect sleep [13].

Overall, only few studies have examined the effects of light on sleep in typically developing adolescents, despite this topic being well described in adults. Taking into account both the importance of sleep for daily functioning and the negative effects of electronic media use on sleep described in adolescents, it is of high relevance to examine both the disruptive and beneficial effects of light on sleep in this demographic group.

1.3. Purpose of our study

To date, only a few studies have evaluated the effects of light on attention and sleep in adolescents; our study aimed at examining differential effects of red- vs. blue-enriched light in this demographic group. Typically developing adolescents participated in morning and evening experimental sessions under different light conditions (single-blind, randomized, cross-over design). We expected better performance in attention tasks (i.e. reduced number of errors, reduced reaction times, or reduced variability of reaction time) in the blue- compared to the red-enriched light condition in the morning. Regarding sleep in typically developing adolescents, our study was a first attempt to examine whether better sleep quality (assessed by actigraphy measures) was observed after the light condition with blue-enriched light in the morning and red-enriched light in the evening compared to vice versa.

2. Methods

2.1. Participants

Twenty-eight typically developing adolescents, 11–17 years old (mean age 14.64 ± 1.89 years), participated in this study (17 male, 11 female). Exclusion criteria were a psychiatric or neurologic diagnosis, a sleep disorder, learning disabilities, and attentional deficits. Participants were recruited from the personal environment of employees of the clinic and all had normal or corrected-to-normal vision. All participants, except for one, attended a college preparatory school, the highest level of pre-college education in Germany.

Written informed consent was obtained from the adolescents and their parents. The experiment was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Medical Faculty of the University of Erlangen–Nuremberg.

2.2. Procedure and task design

Our study was designed as a single-blind, randomized, and balanced cross-over design with respect to the order of the light conditions. The adolescents participated in two lab days, which took place 1 week apart. A lab day consisted of two sessions in the light lab, one in the morning and one in the evening, each lasting for about 1.5 h (see

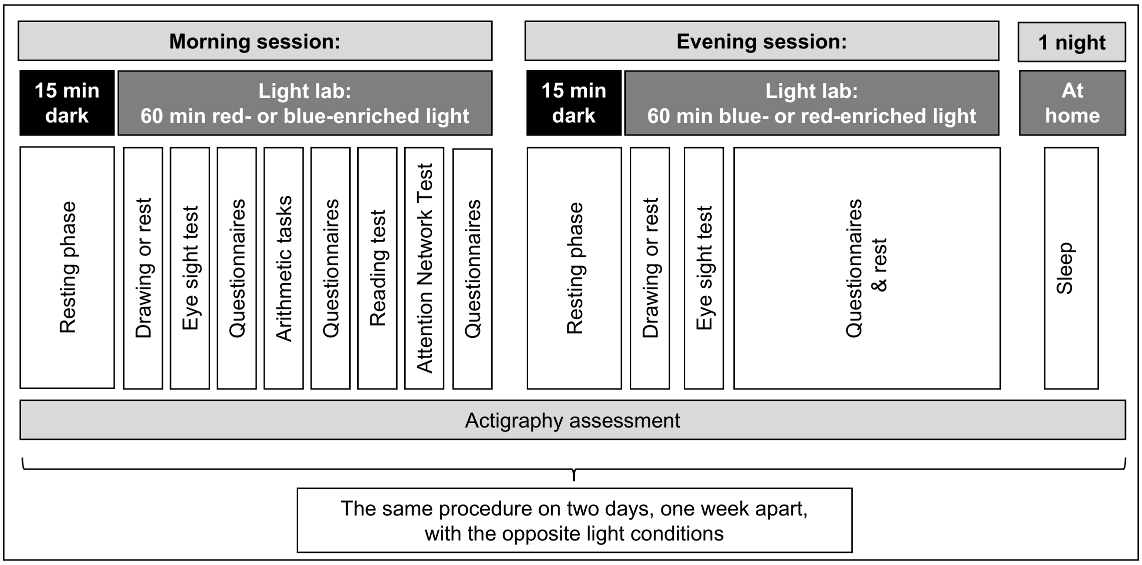

Fig. 1. Procedure of the study. The figure depicts the procedures applied during morning and evening sessions and through the night after a lab day. The study was designed as a single-blind, randomized, cross-over study with respect to the light conditions.

Fig. 1). Two to three adolescents participated simultaneously. Light conditions were either red- or blue-enriched light. The order of the light conditions was either blue-enriched light in the morning and red-enriched light in the evening (i.e. corresponding with the circadian rhythm) or red-enriched light in the morning and blue-enriched light in the evening (i.e. contrasting with the circadian rhythm). Participants either received the circadian corresponding light condition on the first lab day and the circadian contrasting light condition on the second lab day or vice versa (randomized order, balanced cross-over design). Regarding the assessment of attention in the morning, the red-enriched light condition was designed as a neutral light condition while the blue-enriched light condition was designed as corresponding with the circadian rhythm. As such, the blue-enriched light condition was expected to be associated with increased attention. With respect to the assessment of sleep, we expected the red-enriched light condition in the evening to be beneficial for sleep and the blue-enriched light condition to negatively affect some aspects of sleep. Beyond light exposition during the evening, we considered light conditions in the morning to also be relevant for sleep: we combined light in the morning and in the evening as corresponding or contrasting with the circadian rhythm.

In addition to the lab sessions, sleep actigraphy was recorded during the night after a lab day using an actimeter (Actiwatch by Philips, Respironics, Herrsching, Germany) which was attached to the wrist. The study was performed using a single-blind design, i.e. adolescents and their parents were not informed about the different expectations of effects of red- vs. blue-enriched light on attention and sleep, in order to prevent expectations from influencing the results. Adolescents received 50 Euro for study participation. The study was conducted during winter time (a procedure also applied in previous studies (e.g. [15,35,42])) to reduce confounding effects of seasonal differences in intense daylight; e.g. reduced sleep during the spring compared to the winter has been reported in adolescents due to more evening daylight [43]. Additionally, the study was not conducted during school holidays due to differences in sleep parameters for adolescents on non-school days [44].

Arrival time in our department was 8 a.m. in the morning and 6 p.m. in the evening. Since intermediate analysis ($n = 11$) indicated no effects on sleep parameters, the arrival time was changed to between 7 and 8 p.m. for all further participants. Thus, regarding effects of light on sleep, our study is considered a pilot study.

Upon arrival, participants were seated in a quiet room for an initial dark phase (15 min) while wearing black goggles (which prevented light from entering the eye), since the effects of light exposition depend on the previous light history [45]. Then, subjects were guided into the light lab which was illuminated in the respective light condition and were seated at a PC work station. The desks of the participants were located in different parts the room and were additionally separated by mobile dividing walls in order to reduce distraction by other participants.

The light exposition lasted for 60 min. During morning sessions, subjects first adjusted to the light setting/colored a drawing, performed an eye sight test (after 15 min), and filled out self-evaluation questionnaires. After 20 min, participants performed school-like tasks (two arithmetic tasks) and filled out questionnaires. After about 35 min, another school-like task was performed (reading test). After 45 min, participants performed a computerized attention task and filled out questionnaires.

During evening sessions the procedure was similar, but the light lab was illuminated with the other light condition. The school-like tasks were not performed in the evening session in order to reduce attentional effort in the evening. Instead, subjects filled out some sleep-related questionnaires after about 20 min of light exposition.

For a lab day, adolescents were instructed not to use a PC, TV, or smartphone after 8 p.m., to go to bed at usual times (typical for a school day) and not to drink alcohol or energy drinks. Children were picked up from their homes by car in order to reduce confounding effects of physical activity before a lab session, and were driven back home after lab sessions in the evening.

2.3. Instruments

2.3.1. Light lab

Our light lab was designed to guarantee uniform illumination of the whole room (see Fig. 2) by means of fluorescent tubes, attached on the light panels on both longitudinal sides of the room (at 2.2 m height), which emit light toward the ceiling (3.5 m height). For the red-enriched light condition 16 fluorescent tubes (red, 54 watt), eight on each side of the room, were switched on (spectrometer assessment: peak at 611 nm). For the blue-enriched light condition 32 fluorescent tubes (blue, 54 watt), 16 on each side of the room, were switched on (spectrometer assessment: peak at 458 nm). The Powermeter Nova II Ophir was used to assess the parameters of the two light conditions (red-enriched: 876 lx; blue-enriched: 1063 lx). In addition, each of the three working stations of the participants was illuminated with a white spotlight. Control variables regarding the light conditions were the subjective sensation of the light condition and the eye sight test.

Fig. 2. Setup of the light lab. Left: red-enriched light condition, right: blue-enriched light condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3.2. Eyesight test

The eyesight test was performed based on a Landolt C eye chart [46] with a normed distance (5 m). It was performed to assess that visual acuity was comparable for the different light conditions and not a confounding factor for potential light related differences in attentional performance. Results of the eyesight test will be reported for morning sessions.

2.3.3. Self-evaluation questionnaires

All questionnaires were filled out by the participants in the lab during the light exposition with paper and pencil. Only the questionnaires that are reported in this paper are listed here.

During both morning and evening sessions, subjects were asked three times in the course of the 1 h lab session to rate their subjective sensation of the light condition on a visual analogue scale ranging from 0 (very unpleasant) to 10 (very pleasant). These ratings were used as control variables.

During evening sessions, subjects filled out the Pittsburgh sleep quality index (PSQI: [47]). Subjects were asked to fill out the self-evaluation questionnaire based on the week before the first lab day and based on the week before the second lab day. Compared to the original version, the time period was reduced to 1 week since the two lab sessions were designed to be 1 week apart. The mean value of both days was used as a descriptive measure of sleep quality for the participants included in the study. Analysis is based on 18 items which are scored from 0 to 3. These items are assigned to 7 subcomponents which are scored from 0 to 3. Data are presented based on the total score (sum of the 7 subcomponents) ranging from zero to 21. Lower scores represent better sleep quality with five as a cutoff value. Due to the reduced time period for ratings of the questionnaire in our study (1 week), the cutoff value is of limited informative value and will only be used for orientation.

2.3.4. Attention tasks

The first two attention tasks were selected to demand attention similarly to relevant aspects of tasks applied in school contexts. These tasks included arithmetic and reading. In addition, the attention network test was performed as a computerized attention task.

2.3.4.1. Arithmetic tasks. Two mathematical subtests (task 8 and 9) of the German PSB-R 6–13 intelligence test ("Prüfsystem für Schul- und Bildungsberatung für 6. bis 13. Klassen – revidierte Fassung"; [48]) were performed as school-like tasks that, according to the intelligence test, were designed as a measure for attention. Task 8 ("addition task") involved the addition of 7 numbers between 1 and 9. The instructions were to solve as many items as possible within 3 min. In task 9 ("number comparison task"), two rows of 7 numbers had to be compared and the one number that differed had to be marked in the second row. Subjects were instructed to solve as many items as possible within 1.5 min. The test includes these tasks in two versions (A and B). During the first morning session, participants were administered the two tasks from version A and during the second morning session from version B, or vice versa. The order of the two versions was randomized between subjects. The number of correctly solved items was used as an analysis parameter.

2.3.4.2. Reading test. Participants performed a German reading test (SLS: "Salzburger Lesescreening für die Schulstufen 2-9"; [49]) as a school-like task. Two versions (A1 and B1)of this reading test are available, allowing for a repeated measurement at two time points (randomized order between subjects). Each version consisted of 100 grammatically correct sentences that had to be judged based on the accuracy of their content by marking either a check (correct) or cross (incorrect), that were printed next to the sentence. The total score was assessed as the total number of solved sentences minus the number of incorrectly solved sentences.

2.3.4.3. The attention network test. Subjects performed the Attention Network Test (ANT), an attention demanding task with preceding cues [50]. The ANT was realized with the software Presentation (Neurobehavioral Systems, Albany, CA, USA), presented to the adolescents via a PC monitor. Reaction times were recorded via mouse clicks.

Target stimuli were presented slightly above or below the middle of the screen and consisted of five arrows. Viewing distance was about 72 cm, and one arrow subtended 0.52° of visual angle. Depending on the direction of the arrow in the middle (left vs. right), adolescents were asked to press the respective mouse button (left vs. right). The four flanking arrows appeared 100 ms before the middle arrow was presented. Target stimuli were preceded by cues which were presented 500 ms before the target stimulus was presented. The inter-trial interval varied randomly between 3.5 and 5.0 s. Participants were given standardized instructions and performed 12 practice trials. The task consisted of three blocks with 36 trials each (108 trials in total). Only trials with correct responses were considered for the calculation of reaction time measures.

In the present study, analysis is based on general measures of attention (number of hits, reaction time, variability of reaction time), without differentiating the attention networks. The cues consisted of three conditions with equal probability: no cue, neutral cue and spatial cue. In the "no cue" condition, no cue was presented, i.e. participants did not know when the next target stimulus would be presented. In the "neutral cue" condition, a star is presented in the middle of the screen indicating that the target stimulus is about to appear. In the "spatial cue" condition, a star is presented at the exact position where the target stimulus is about to appear. During congruent trials, the four arrows flanking the arrow in the middle were pointing in the same direction, during incongruent trials they were pointing in the opposite direction. Each block consisted of an equal number of trials for each condition: left/right, congruent/incongruent, no cue/neutral cue/spatial cue which were presented in a randomized order.

2.3.5. Actigraphy

Wrist-actigraphy [51] was used to assess sleep related parameters based on activity measures by means of an actimeter (Actiwatch Spectrum PRO, Phillips, Respironics, Herrsching, Germany) which was attached to the wrist of the non-dominant hand. Data was collected in 15-s epochs and analyzed by Philips ActiWare software version 6.0.1 using the medium sensitivity threshold (compare e.g. [52]) provided by the manufacturer (wake threshold 40, ten inactive minutes for sleep onset and offset). Bedtime and wake-up time were assessed to describe the sample. The following sleep related parameters were used for statistical analysis: total sleep time (h:m:s; threshold: 10 inactive minutes), sleep onset latency (in minutes), sleep efficiency (percent time asleep divided by time in bed), wake-after-sleep onset (WASO; in minutes), number of awakenings (threshold: 40 counts of activity within an epoch). The measure "number of awakenings", as it is labeled within the software, reflects the number of phases with movement activity during sleep; however, in our opinion, it is not able to differentiate between movement during sleep and awakening. Thus, in the following text, we will refer to this measure as number of phases with movement activity after sleep onset.

2.4. Statistical analysis

Statistical analyses were performed with SPSS (IBM SPSS Statistics, Version 21). To study effects of light conditions, repeated measure ANOVAS were calculated with the two-level within-subject factor LIGHT (red-enriched, blue-enriched), and the two-level between-subject factor ORDER (first red-enriched light in the morning and blue-enriched light in the evening; first blue-enriched light in the morning and red-enriched light in the evening). For significant results, as well as for trends obtained in ANOVA analyses, effect sizes were calculated as partial eta squared (η_p^2). Small effects are observed if $\eta_p^2 > 0.01$, medium effects if $\eta_p^2 > 0.06$, and large effects if $\eta_p^2 > 0.14$ [53]. For the analysis of the subjective sensation of light, two additional within-subject factors were used: TIME (first, second, third assessment within a session), and TIME OF DAY (morning, evening). For the analysis of the attention task, PSB, values of the two tasks 8 and 9 were z-transformed and TASK (task 8, task 9) was used as an additional within-subject factor. Data were checked for outliers; exclusion of participants from the analysis as outliers will be reported in the results section.

3. Results

3.1. Group characteristics

The ORDER groups did not differ significantly regarding age (t (26) = 0.56, n.s.) or gender ($\chi^2(1) = 0.70$, n.s.). Visual acuity during morning sessions did not differ significantly between the two light conditions (LIGHT: F(1,26) = 0.78, n.s.; LIGHT*ORDER: F (1,26) = 0.02, n.s.). Visual acuity was 1.22 ± 0.08 in the red- and 1.20 ± 0.13 in the blue-enriched light condition. There was no significant difference between the subjective sensation of the two light conditions (data of one subject was missing; LIGHT: F(1,25) = 0.03, n.s.; LIGHT*ORDER: F(1,25) = 0.29, n.s.). On the 10-point scale, mean values in the morning were 6.60 ± 1.93 for red- and 6.98 ± 2.09 for blue-enriched light. In the evening, values were 7.32 ± 1.00 for red- and 7.03 ± 1.92 for blue-enriched light.

Mean sleep quality of the subjects included in the study was 4.6 ± 1.8 (range 0.5 to 8.5) as assessed by the PSQI, i.e. the mean score of all 28 subjects was below the cutoff value of 5 (cutoff value gives only a rough orientation, see 2.3.3.). On average, sleep quality of participants was in the range of normal sleep.

According to actigraphy data (without outliers, see results Section 3.3), on average subjects' bedtime was 10:30 p.m. (SD: 00:43 h) and wake-up time was 6:59 a.m. (SD: 00:58 h).

3.2. Effects of light on attention

Results of the attention tasks are depicted in Table 1. For the arithmetic tasks, the reading test, and the reaction time measure of the ANT, significant interactions of LIGHT and ORDER (F > 15.00, $p \leq .001$) were obtained. These findings were mainly related to the repeated measures design and reflected improved performance when a task was performed for the second time, i.e. independent of the light condition.

3.2.1. Arithmetic tasks

For the analysis of the arithmetic tasks, one subject was excluded from the analysis because the adolescent did not understand the task correctly when performing it for the first time, which resulted in non-analyzable data. In addition, three subjects were excluded as outliers due to z-values below −2.5 or above 2.5. Thus, analysis was based on 24 subjects.

Regarding the number of correct responses in the arithmetic tasks, a significant effect was obtained for LIGHT (F(1,22) = 4.54, $p < .05$, part. $\eta^2 = 0.17$) indicating better performance in the blue- compared to the red-enriched light condition. This effect was mainly driven by the group who performed the task for the second time in the blue-enriched light condition as indicated by a significant interaction of LIGHT and ORDER.

3.2.2. Reading test (SLS 2-9)

For the reading test, no main effect of LIGHT (F(1,26) = 0.09, n.s.) was observed.

3.2.3. Attention network test

Values from two subjects were considered as outliers (deviation of more than three standard deviations from group mean in at least one of the measures) and were excluded from further analysis. Performance in this task was high with 94.19 ± 3.15% and 95.51 ± 3.85% of correct responses in the red-enriched and blue-enriched light condition, respectively. Regarding the number of correct responses in the attention network test, a trend was obtained for LIGHT (F(1,24) = 3.06, $p < .10$, part. $\eta^2 = 0.11$). No significant effect for LIGHT was observed for the measure mean reaction time (F(1,24) = 1.26). For the performance measure variability of reaction time, a significant effect was obtained for LIGHT (F(1,24) = 6.25, $p < .05$, part. $\eta^2 = 0.21$) indicating lower variability of reaction time in the blue-enriched light condition (see Fig. 3).

3.3. Effects of light on sleep assessed by actigraphy

Data of three participants could not be included in the analysis due to technical problems with the actimeter and data of three participants were excluded as outliers (going to bed after 1 a.m. ($n = 2$), getting up after 11 a.m. ($n = 1$)). Thus, data analyses of sleep parameters assessed by actigraphy were based on 22 participants (19 of these 22 participants participated on school days). Results of the actigraphy measures of sleep, including statistical results, are depicted in Table 2.

We did not observe differential effects of our light conditions (factor LIGHT) on total sleep time (F(1,20) = 0.00, n.s.), sleep onset latency (F (1,20) = 1.47, n.s.), sleep efficiency (F(1,20) = 0.33, n.s.) or WASO (F (1,20) = 0.15); however, all of these parameters (see Table 2) were in the range as reported by a recent meta-analysis [44]. For the number of phases with movement activity after sleep onset (see Fig. 4) a trend was obtained for LIGHT (F(1,20) = 2.97, $p = .10$, part. $\eta^2 = 0.13$), related to a lower number of phases with movement activity after sleep onset in the night after the red- compared to blue-enriched light condition in the evening.

The subgroup analysis of our pilot study (see Fig. 4), including only the subjects that conducted evening sessions after 7 p.m. ($n = 15$), yielded a trend for LIGHT for the sleep onset latency (F(1,13) = 3.82, $p < .10$, part. $\eta^2 = 0.23$). This was related to shorter sleep onset latencies after the red- compared to blue- enriched light condition in the evening. For the subgroup analysis, no significant effect of LIGHT was observed for the number of phases with movement activity after sleep onset, while the effect size remained the same (medium effect) as for the trend obtained for the total sample (F(1,13) = 1.95, $\eta_p^2 = 0.13$).

4. Discussion

In our study assessing typically developing adolescents, blue-

Table 1
Results of the attention tasks.

Task	Red-enriched light in the morning	Blue-enriched light in the morning	Statistics	*P* value
Arithmetic tasks:			L: F(1,22) = 4.54, η_p^2 = 0.17	p < .05
			L*O: F(1,22) = 56.44, η_p^2 = 0.72	*p* < .001
Addition task:	12.42 ± 1.17	13.58 ± 4.85		
NC task:	26.00 ± 4.93	26.71 ± 4.94		
Reading test:	63.64 ± 10.99	64.00 ± 9.42	L: F(1,26) = 0.09	n.s.
			L*O: F(1,26) = 15.16, η_p^2 = 0.37	p = .001
ANT: hits (of 108 trials)	101.73 ± 3.40	103.15 ± 4.16	L: F(1,24) = 3.06, η_p^2 = 0.11	p < .10
			L*O: F(1,24) = 0.14	n.s.
ANT: mean RT (ms)	436.92 ± 41.57	442.85 ± 56.00	L: F(1,24) = 1.26	n.s.
			L*O: F(1,24) = 15.37, η_p^2 = 0.39	*p* = .001
ANT: variability of RT (ms)	89.46 ± 17.44	80.46 ± 14.24	L: F(1,24) = 6.25, η_p^2 = 0.21	p < .05
			L*O: F(1,24) = 2.72	n.s.

Note. The table lists the mean value and standard deviation of each attention measure (number of correct responses, unless stated otherwise), which were assessed during morning sessions. Results of the repeated-measure ANOVAs including the effect size measure, partial eta square (η_p^2), are depicted in the right-hand columns. The two arithmetic tasks (addition task and number comparison task) were analyzed in one statistical analysis based on z-transformed values. NC: number comparison, ANT: attention network test, RT: reaction time, ms: milliseconds, L: within-subject factor LIGHT, O: between-subject factor ORDER, n.s.: not significant.

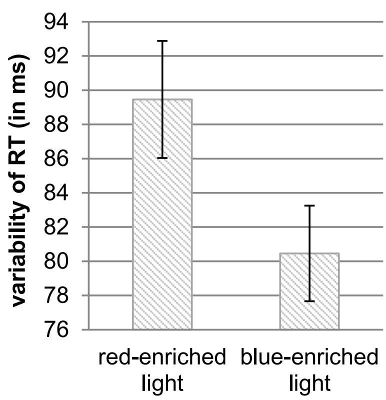

Fig. 3. Variability of reaction time (RT). The variability of RT (ms: milliseconds) is depicted for the red- and blue-enriched light conditions (with error bars).

enriched (compared to red-enriched) light was associated with improved performance on two of three attention demanding tasks: significantly more correct responses (large effect) in mathematical tasks; tendency for a higher number of correct responses (medium effect) and significantly reduced variability of reaction time (large effect) in the attention network test. Regarding our pilot study on sleep parameters assessed by actigraphy, during the night after the red-enriched evening light condition (compared to the blue-enriched) a reduced number of awakening responses for the whole group (trend toward significance) were observed. Additionally, there was a reduced sleep onset latency for the subgroup analysis with later light exposition times (trend toward significance), which were in the range of medium to large effect sizes.

4.1. Attention

Overall, the significant interaction effects of LIGHT and ORDER observed for different measures were mainly related to the cross-over design of our study and reflected a better task performance when the task was performed for the second time, i.e. independent of the light condition. Increased task performance due to repeated measurement is an expected finding [54,55].

For two out of three school-like attention tasks we observed increased task performance in the blue- compared to the red-enriched light condition in the morning, which was in the range of medium to large effect sizes. These results in typically developing adolescents are similar to previous findings with adults for whom performance improvements in various attention demanding tasks, at various times of the day, have been described for short-wavelength light conditions (e.g. [8,10,11,12,14,15]) and for bright cold light [18]. Comparable effects

Table 2
Results of the actigraphy measures of sleep.

Actigraphy measure	Red-enriched light in the evening	Blue-enriched light in the evening	Statistics	P value
TST (h:m:s):	07:28:33 ± 00:56:49	07:27:57 ± 01:07:41	L: F(1,20) = 0.00	n.s.
			L*O: F(1,20) = 0.32	n.s.
SOL (min)				
Total group (n = 22):	8.78 ± 10.90	12.81 ± 10.79	L: F(1,20) = 1.47	n.s.
			L*O: F(1,20) = 0.13	n.s.
Subgroup (*n* = 15):	6.42 ± 7.77	12.92 ± 9.83	L: F(1,13) = 3.82, η_p^2 = .0.23	p < .10
			L*O: F(1,13) = 2.70	n.s.
SE (%):	88.75 ± 5.17	87.85 ± 5.39	L: F(1,20) = 0.33	n.s.
			L*O: F(1,20) = 0.36	n.s.
WASO (min):	32.84 ± 16.53	34.52 ± 14.86	L: F(1,20) = 0.15	n.s.
			L*O: F(1,20) = 0.67	n.s.
NMA				
Total group (n = 22):	41.00 ± 17.29	46.59 ± 17.27	L: F(1,20) = 2.97, η_p^2 = 0.13	p = .10
			L*O: F(1,20) = 0.51	n.s.
Subgroup (n = 13):	43.00 ± 17.50	50.13 ± 14.33	L: F(1,13) = 1.95, η_p^2 = .0.13	n.s.
			L*O: F(1,13) = 0.03	n.s.

Note. The table lists the mean value and standard deviation of each actigraphy measure assessed in the night after the light expositions in the lab. Results of the repeated-measure ANOVAs including the effect size measure partial eta square (η_p^2) are depicted in the right-hand columns. L: within-subject factor LIGHT; O: between-subject factor ORDER; n.s.: not significant; TST: total sleep time (in h: hours, m: minutes, s: seconds); SOL: sleep onset latency (in minutes); SE: sleep efficiency (in percent); WASO: wake-after-sleep onset (in minutes); NMA: number of phases with movement activity after sleep onset.

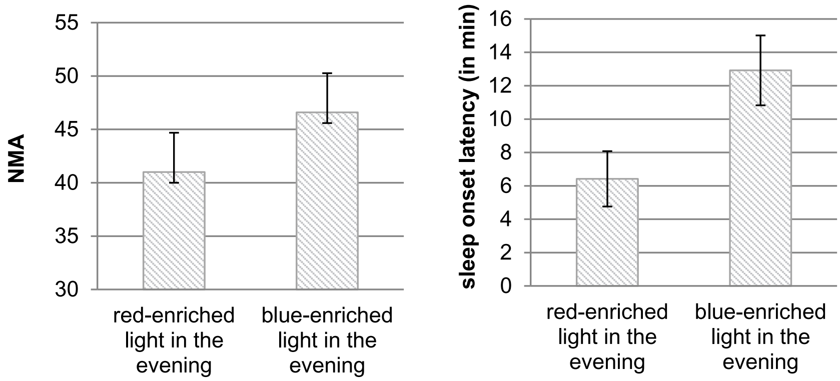

Fig. 4. Actigraphy results (pilot study). Left: number of phases with movement activity after sleep onset (NMA), total group ($n = 22$). Right: Sleep onset latency, subgroup analysis ($n = 13$). Error bars depict the standard error of each measure. Red-enriched light in the evening (i.e. light condition corresponding to the circadian rhythm); blue-enriched light in the evening (i.e. light condition contrary to the circadian rhythm).

have also been described in a study combining adolescents and young adults [56], in adolescents [13], and for bright cold light in adolescents [17]. Thus, our findings add to the limited literature concerning the adolescent demographic group. Our results are best comparable to Münch and colleagues [15], who also described positive effects of blue-enriched light in the morning (similar study design, but in adults) on attentional performance. While a review by Xu and Lang [57] concluded that alerting effects of blue-light were only observed at night, not during daytime, this does not seem to be valid for attentional performance assessed via cognitive performance (which were excluded from their review due to varying task difficulty).

In contrast to our findings, Chellappa, Gordijn and colleagues [6] did not observe beneficial effects of blue light on an addition task. However, their study was performed with adults, in the evening and with a light intensity of only 40 lx. In our study, light intensity was about 1000 lx which is rather high compared to many other studies [e.g. 10: 40 lx, 12: 190 lx, 16: 250 lx, 58: 250 lx]. Additionally, the attention tasks in our study were performed after 20–55 min of light exposition. Thus, the morning blue-enriched light with a rather high intensity, which corresponded to the circadian rhythm, impacted task performance in typically developing adolescents even after a short time. Quick effects of light applications are of special relevance when discussing their application in schools, where immediate benefits are desirable compared to effects which require several hours of exposure.

In line with Barkmann and colleagues [17] in school students and Wessolowski [18] in adults, we did not find beneficial effects of light on reading comprehension in school students.

To our knowledge, our study in typically developing adolescents was the first study where a significantly reduced variability of reaction time was observed under blue-enriched light. Since increased variability of reaction time is assumed to reflect occasional lapses in attention [59], our findings reflect a more stable attentional performance (in the range of a large effect) under blue-enriched light. This finding suggests that light could possibly be used therapeutically for conditions in which attention is affected [60]. Inattention is one of the core symptoms of attention deficit/hyperactivity disorder (ADHD) [61]. A meta-analytic review has reported increased variability of reaction time in children, adolescents and adults with ADHD compared to typically developing controls [60] and increased reaction time variability is considered one neuropsychological endopenotype for ADHD [60,62]. Additionally, circadian disturbances have been described in ADHD [63]. Thus, it would be interesting to apply our study design to individuals with ADHD and examine in how far blue-enriched light in the morning may lead to improved performance, in this case reduced variability of reaction time, in a group with known impairments in this performance parameter.

Overall, our study is one of few studies which have examined the effects of light on attention in adolescents. We consistently observed beneficial effects of blue-enriched light in the morning (a light condition corresponding to the circadian rhythm) on attentional performance, which stresses the importance of studying such light effects in this demographic group. According to a recent review by Fisk and colleagues [64], effects of light on cognitive processes are mediated via increased alertness. Further studies should examine the application of specific light in school settings, comparable to the initial study by Barkmann and colleagues [17].

4.2. Sleep

Generally viewed, the direction of the sleep effects observed in our pilot study in typically developing adolescents was in accordance with our hypothesis of the beneficial effects of the red-enriched compared to the blue-enriched light condition in the evening (i.e. for the light condition corresponding to the circadian rhythm) on sleep. These observations are also in line with previous findings of effects of light on sleep in adults [14,15,33,35–37,39,65].

More specifically, we observed a tendency for reduced sleep onset latencies after the red-enriched compared to the blue-enriched light condition in the evening (1 h of light exposition in the morning, 1 h in the evening, high light intensities of about 1000 lx). This effect was only present in the subgroup with later light exposition times in the evening, i.e. effects of light exposition on sleep onset latency were more prominent when light exposition occurred closer to bedtime. Besides light exposition close to bedtime, light intensity and duration may play an important role for light effects on sleep onset latency. In adults, reduced sleep onset latencies have been reported after reading a printed compared to an e-book for 4 h (i.e. long duration) before bedtime [36]. In contrast, other studies have found no differential effects of light on sleep onset latency (assessed by polysomnography) in adults [65] or in adolescents [26], despite light exposition occurring close to bedtime, possibly related to the low light intensities (58 or 80 lx) combined with short exposition times (30 or 60 min). A further difference to our study design was that we combined light expositions in the evening with light expositions in the morning resulting in light conditions corresponding or contrary to the circadian rhythm. Reduced sleep onset latencies have been reported in adults after higher levels of circadian sensitive light in the morning [39], however our study design did not allow for differentiation of effects regarding morning vs. evening exposition on sleep onset latency. Overall, sleep onset latencies seem to be affected by light exposition of longer duration and higher light intensities (when exposition times are close enough to bed time) and may also possibly be affected by expositions in the morning.

We observed a trend toward significance regarding a reduced number of phases with movement activity after sleep onset following the red-enriched compared to the blue-enriched light condition in the evening (i.e. after the light condition corresponding to the circadian rhythm). Thus, our finding fits to observations of increased activity during sleep in elderly people after blue-enriched light exposure [37].

In our study, no differential effects of our light conditions were observed for total sleep time, sleep efficiency, or WASO. In this respect, our findings are in line with Rahman and colleagues [12] in adults and with van der Lely [13] in adolescents which used rather long exposition times (8 and 3 h) but only low light intensities of 50 and about 100 lx, respectively. However, our findings are in contrast to several other studies [15,33,42,66] which also used higher light intensities (between 350 and 1000 lx) and which did report effects on these sleep measures. Their findings could be due to the following reasons: 1. Light expositions were performed near bedtime; 2. Light exposition and sleep assessment were performed in the lab. Moreover, since on school days wake-up times were not necessarily based on the internal rhythm but may have been determined by the ringing of the alarm clock, the measures 'total sleep time' and 'sleep efficiency' are of limited validity in our study.

A difficulty in the setting of our pilot study regarding sleep was that the light exposition was not administered at the same location where participants slept. The transfer from the lab back home, non-controlled home lighting conditions/media use before bedtime as well as the larger time delay between light exposition and bedtime may have reduced the effects. The initially earlier starting times of evening sessions (6 p.m. vs. between 7 and 8 p.m.), which resulted in a small group size for participants with later exposition times, and not reporting sleep data of the night before the intervention (baseline assessment) were further limiting factors. In future studies, it may be of interest to examine both the effects of light on sleep in typically developing adolescents and the application of comparable light conditions in adolescents with impaired sleep. It has been reported that adults with insomnia had improved sleep after wearing blue light-blocking lenses before bedtime [67]. Moreover, while adults with the PER3$^{5/5}$ polymorphism have been reported to be more sensitive to effects of light on sleep [41], this aspect has not yet been examined in adolescents and would be of interest to study in a larger sample.

To our knowledge, our pilot study was the first study where, based on actigraphy measures, a light condition corresponding to the circadian rhythm (blue-enriched light in the morning combined with red-enriched light in the evening) has been associated with improved sleep quality in typically developing adolescents.

4.3. Advantages and limitations of our light conditions

An advantage of our study design was that the duration of light exposition was shorter than in most previous studies (1 h compared to ca. 2–3 h). This was possible because we used higher light intensities (ca. 1000 lx compared to previous studies, ca. 40 to 500 lx (e.g. [10,12,15,33])). The use of shorter exposition times is a design more practical for studies in adolescents.

However, the high light intensity (ca. 1000 lx) used in both light conditions may have interfered with our intention of the red-enriched light condition serving as a neutral condition (i.e. may have reduced differential effects between the two light conditions) since increased alertness has been reported after high light intensities in the majority of studies [23]. Yet, regarding sleep, Green and colleagues concluded that "light wavelength seems to have a greater influence than light intensity on sleep" [33].

While most light studies have examined effects of light at only one time during the day, we have implemented a more comprehensive design with light expositions both in the morning and in the evening. A comparable design had been applied in adults by Münch and colleagues [15], but our study was the first to do so with adolescents. We chose this design in order to establish light conditions both corresponding to and contrary to the circadian rhythm.

5. Conclusion

Overall, in our study with typically developing adolescents, we consistently observed beneficial medium to large effects of blue-enriched light on attentional performance in two out of three tasks. Effects were observed after a short duration of light exposition (< 1 h) with higher light intensities (about 1000 lx). These settings could be favorable for applications at school.

Our attention-related findings in the blue- compared to the red-enriched light condition (increases in performance and reduced variability of reaction time) may be of special relevance for children with ADHD, i.e. in a group with known impairments in this performance parameter. Further research is needed to evaluate this hypothesis.

Regarding sleep, our pilot study was the first to indicate improved sleep quality in typically developing adolescents after light exposition with light corresponding to the circadian rhythm (blue-enriched light in the morning, red-enriched light in the evening).

In addition to the developmental aspects of both attention and sleep, our findings stress the importance of considering light effects on attention and sleep in adolescents. Well-designed studies including larger samples of adolescents are needed to shed more light on the impact of light on attention and sleep in this demographic group.

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Declarations of interest

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