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Research Article

Influence of blue-enriched classroom lighting on students' cognitive performance

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ABSTRACT

Light is a powerful zeitgeber that synchronizes our endogenous circadian pacemaker with the environment and has been previously described as an agent in improving cognitive performance. With that in mind, this study was designed to explore the influence of exposure to blue-enriched white light in the morning on the performance of adolescent students.

58 High school students were recruited from four classes in two schools. In each school, one classroom was equipped with blue-enriched white lighting while the classroom next door served as a control setting. The effects of classroom lighting on cognitive performance were assessed using standardized psychological tests. Results show beneficial effects of blue-enriched white light on students' performance. In comparison to standard lighting conditions, students showed faster cognitive processing speed and better concentration. The blue-enriched white lighting seems to influence very basic information processing primarily, as no effects on short-term encoding and retrieval of memories were found.

1. Introduction

Light is a powerful zeitgeber that synchronizes our endogenous circadian pacemaker with the environment. The retina of the human eye contains, besides the classical photoreceptors (rods and cones), intrinsically photosensitive Retinal Ganglion Cells (ipRGC) that send light information via the retinohypothalamic tract directly to the circadian pacemaker of the brain, the suprachiasmatic nucleus of the hypothalamus [1,24,44]. In this way the ipRGC play a major role in synchronizing circadian rhythms to the 24-hour light/dark cycle. Short-wavelength blue light at around 460–480 nm is most effective in inducing circadian phase shifts [3,13,19,32,34]. Exposure to light late in the evening leads to an increase in sleep latency and a delay in sleep onset [6,8,12,16,30]. Exposure to light in the morning advances the circadian rhythm and the activity onset [8,12,14,40].

Adolescents can have misaligned circadian rhythms as a result of a delayed sleep phase. They stay up late, thereby accumulating a sleep debt during the week [9,20,28] due to the constraints of early school or work schedules. Adolescents therefore suffer from "social jetlag" (the discrepancy between the daily timing of the physiological clock and the social clock, i.e. the realities of daily schedules) while it is known that later sleep onset can result in poor school performance [42].

Timed light exposure promotes circadian entrainment and is therefore a successful countermeasure against circadian misalignment [5,29]. A stable alignment of the circadian sleep–wake rhythm and sufficient sleep are essential for proper cognitive functioning. If sleep and wakefulness occur out of phase with the internal biological time, several cognitive functions such as learning are impaired [43]. Office workers who were exposed to blue-enriched white light for 4 weeks improved, among other things, in subjective measures of alertness, of performance and of concentration and reported less daytime sleepiness [41]. Thus, the beneficial effects of light on circadian entrainment could enhance cognitive performance.

Furthermore, there is evidence that exposure to light acutely enhances alertness and cognitive performance [10,11,18]. Exposure to bright light enhances cortical activity and improves subjective alertness [36,38]. Especially short wavelength light has been found to increase alertness [7,11,22,25,27]. Neuroimaging studies observed that modulation of non-visual brain activity related to complex cognitive tasks is more pronounced for blue light exposure than for red or green [37,39]. Even exposure times as brief as 18 min have already been shown to be effective [37].

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Not only the aforementioned lab studies but also evaluations in real life settings find an acute effect of short wavelength lighting on alertness. A previous study evaluated different lighting scenarios in a classroom environment and found cool white light to increase alertness and performance in students aged 8 to 16 years [2].

Our study pursues two core goals. Firstly, we wish to confirm that blue-enriched white lighting can be utilized in a real-world classroom setting to improve alertness and cognitive performance of students. It is hypothesized that processing speed, concentration and memory are improved with blue-enriched white lighting resembling the properties of natural daylight with respect to wavelength, timing and spatial distribution as opposed to common warm white fluorescent lighting. Secondly, we want to differentiate between short-term acute effects of exposure to blue-enriched white lighting and indirect long-term effects from e.g. circadian entrainment.

2. Study population and methods

2.1. Subjects

A total of 58 high school students declared their willingness to participate in the study and completed the assessments. Subjects were recruited from two year 12 classes of two schools in Ulm (a secondary and a vocational school). Students in the selected classes of each school were of similar age; the classes were of similar size and gender ratio (cf. Table 1). Furthermore, all students had a similar educational background and socioeconomic status as indicated by their teachers.

Prior to the study, written informed consent was obtained from all participants and, if they were under 18 years of age, their parents, too. The study was carried out according to the tenets of the Declaration of Helsinki. Given the experimental conditions, the study contained no danger to the participants' health at any moment and we regarded a statement from the local ethics committee as not necessary.

2.2. Light exposure

2.2.1. Blue-enriched white lighting

In each of the two schools, the lighting in one classroom was changed to blue-enriched white lighting in order to stimulate the circadian system. An LED lighting system consisting of a pendant luminaire [OSRAM *Siteco Quadrature II LED*, direct lighting, correlated color temperature (CCT) 4000 K] was newly installed and equipped with additional customized LED modules (CCT 14000 K) for indirect lighting (up-lighting bouncing back from the white ceiling). For circadian effects, vertical illuminance levels are supposed to be relevant, while horizontal data is important for good vision. Vertical illuminance levels were measured at eye level in sitting position (120 cm height) oriented in the subjects' main viewing direction during class. The lighting was adjusted such that vertical illuminance averaged about 300 lx. Color temperatures (CCT) were at about 5500 K.

2.2.2. Standard lighting

In each of the two schools, a classroom located next door to the classroom with blue-enriched white lighting served as a control setting. As the windows of both rooms faced in the same direction influences from weather and daytime on classroom illumination did therefore not differ between the classrooms.

In the classrooms with standard lighting common T8/T5 grid fluorescent luminaires (not optimized for circadian effects; correlated color temperatures: vocational school 3000 K, secondary school 4000 K) were installed prior to the study and kept to serve as typical baseline. Average vertical illuminance levels were about 300 lx, comparable to the intervention-setting. Correlated color temperatures vertically at eye level were about 3000 K (vocational school) and 3500 K (secondary school).

The key differences between the lighting in both rooms exposure are thus, firstly, the high (5500 K) vs. lower (3000 K, 3500 K) color temperatures as well as, secondly, the luminance distribution (indirect lighting bounced back from white ceiling creating large area lighting source vs. purely direct lighting). Light originating over a large area and from above, similar to the lighting situation in nature under the blue sky, is supposedly more effective in creating non-visual effects than bundled spots (direct lighting) [2].

2.3. Study design

The study was designed as a controlled trial with pre/post measurements and four different lighting conditions (Fig. 1). In the 'standard' condition students had their lessons and their testing in the standard light classroom. In the 'acute' condition students had their lessons in the standard light classroom but their post-tests took place in the classroom with blue-enriched white light. In the

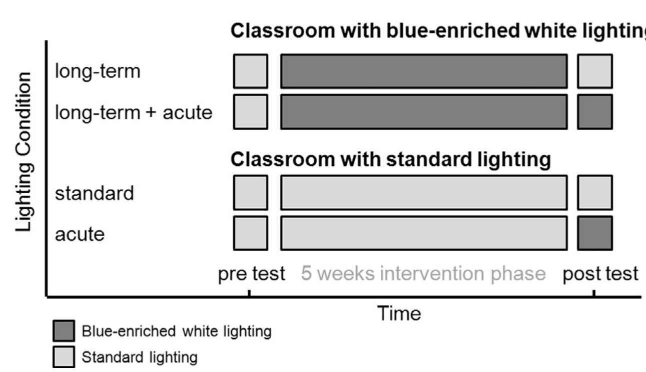

Fig. 1. Study design and lighting conditions.

Table 1
Descriptive summary of study population and inferential statistics (Chi-squared test, *t*-test).

	Secondary school Daily start: 8:15 am			**Vocational school** Daily start: 7:20 am		
	Classroom with			**Classroom with**		
	Blue-enriched white lighting	**Standard lighting**	***p***	**Blue-enriched white lighting**	**Standard lighting**	***p***
Number of students	21	17		11	9	
Percentage male	86	88	.819	82	89	.660
Age						
Mean	17.6	17.6	.947	20.6	21.6	.355
Min–Max	16–19	17–20		19–22	18–29	

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'long-term' condition students had their lessons in the classroom with blue-enriched white light but their post-tests took place under standard lighting. In the 'long-term+acute' condition students had their lessons and their post-tests in the classroom with blue-enriched white light. The lighting during the pre-test consisted for all subjects of the standard light. All testing was conducted by qualified experimenters and took place in the first lesson during the school day (vocational school: 7:20–8:05 am; secondary school: 8:15–9.00 am).

During the intervention phase of five weeks in November and December, the intervention group was exposed to blue-enriched white lighting every weekday. During the first two lessons (7:20–8:55 am) when artificial lighting was required, the students of the vocational school spent every weekday apart from Thursday in the assigned classroom. During the weekday they spent at least 4 lessons and at most 6 lessons (mean: 5) there. The students of the secondary school were in the assigned rooms every weekday for 6 lessons (including the first two (8:15–9.45 am).

The classes from each school were randomly assigned to the 'long-term' conditions ('long-term', 'long-term+acute') and the other conditions ('standard', 'acute'). Thus, students were randomized on class level but not on an individual level to the lighting in their classroom. Randomization on an individual level would have required an unwelcomed rearrangement of class composition. However, students were randomized on an individual level to the lighting condition 'long-term' vs. 'long-term+acute' and to lighting condition 'standard' vs. 'acute'.

The different experimental conditions were introduced to test not only for effects from blue-enriched white lighting on cognitive performance in general, but also to be able to differentiate indirect effects mediated through circadian entrainment from direct acute effects. The study design was setup to uncover differences between the 'standard' and 'long-term' condition that would be attributed to the exposure to blue-enriched white light during morning classes, i.e. circadian alignment. Differences between the 'standard' and 'acute' condition would be attributed to an acute stimulating effect by blue-enriched white lighting. A comparison between the 'long-term' and 'acute' conditions shows which of the two effects is bigger. Finally, differences between the 'long-term' and 'long-term+acute' condition show whether the effects can be combined.

2.4. Measures

The outcome measures were operationalized using standardized, psychometrically validated and normed tests. Speed of cognitive processing was assessed with the German Zahlen-Verbindungs-Test (ZVT) [26]. Subjects are instructed to connect a set of numbers in ascending order as fast as possible while maintaining accuracy. The ZVT provides one indicator that stands for speed of processing.

Concentration was assessed by the d2 test [4]. The test items consist of the letters d and p with one to four dashes, arranged either individually or in pairs above and below the letter. The subject must scan across each line to identify and cross out each *d* with two dashes. Two indicators of the d2 test are analyzed: the concentration performance, which is calculated by subtracting errors of commission from the number of correctly processed items, and the quality of performance, which is measured by percentage of errors, i.e. the proportion of errors made within the area of all items processed.

Memory retention was measured by the Visual and Verbal Memory test [31]. The test determines the short-term memory of visuospatial and verbal materials and is divided into two subtests. The visuospatial subtest consists of a map that students have to memorize and then reproduce. The verbal subtest examines the memory of facts by providing a text that includes names, numbers, and terms. Again, students had to memorize and then reproduce the information, which was summed up as correctly remembered items. Both indicators for the visuospatial and verbal memory were analyzed. The test exists in two versions that were both deployed.

In addition to these standardized tests, a questionnaire was developed to assess students' attitude towards the respective classroom lighting, which had to be filled out after three weeks of intervention. Students were asked to evaluate their classroom lighting on 5-point-Likert-scales in terms of general liking (1=very pleasant, … 3=neutral, … 5=unpleasant), brightness (1=much too bright,… 3=just right,… 5=much too dark) and light color (1=very pleasant,… 3=neutral,… 5=unpleasant).

2.5. Statistics

Data analysis was carried out in SPSS (PASW Statistics 18) using a two-way (repeated measures) ANOVA with the within-subjects factor Time (pre vs. post) and the between-subjects factor Lighting Condition (standard, acute, long-term, long-term+acute). Our main focus is on the interaction, i.e. the differences in development of the subjects in the conditions over time. As repeated presentations of tests on cognitive functions very often result in learning we expect significant main effects of time and display graphics with gain scores. Gain scores show the improvement in a particular test and are computed by subtracting pre-test scores from post-test scores. After finding a significant interaction, Bonferroni corrected *t*-tests were calculated to resolve whether the gains (post minus pre) of two lighting conditions differ from each other. Subjects whose gain scores deviated more than 2.5 standard deviations from the mean were excluded as outliers. Through this procedure in total 7 data points from 5 subjects were excluded. One subject from the long-term+acute condition produced three outliers in both of the d2 scores (being better than all others) and the verbal memory (being worse than all others). Another subject of the long-term condition was excluded from the data of the ZVT (being better than all others). A further subject from the long-term+acute condition was excluded from the data of the d2 inaccuracy (being worse than all others). One subject of the standard condition was excluded from the data of the visuospatial memory test (being worse than all others). A last subject of the long-term+acute condition was excluded from the data of the verbal memory test (being worse than all others except the other outlier). In sum, 2.4% of data points were excluded due to outliers.

Chi-squared test and *t*-tests were used to look for differences in the study population. Also the questionnaire assessing students' attitude towards the respective classroom lighting was analyzed by using *t*-tests. Two-sided testing was used and the level of significance was set to .05 for all analyses in this study.

3. Results

3.1. Summary of study population

Participants of the standard and long-term condition were of similar age and were part of classes of similar size and gender ratio (cf. Table 1).

3.2. Speed of cognitive processing (ZVT)

Subjects increased their performance on the test from pre to post: a main effect of *Time* [$F(1,53)=76.8$; $p<.001$] but not of group (*Lighting Condition*) [$F(3,53)<1$] was found. The main interest was to find out if the performance of subjects in the four groups developed differently to another. It did: data analysis revealed a significant interaction between *Lighting Condition* * *Time* for the four conditions (Table 2, Fig. 2). Subjects under the

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Table 2
Summary of descriptive and inferential statistics (repeated measures ANOVA) for outcome measures.

		Lighting conditions				Interaction time × lighting condition		
		Condition	***M***	**SD**	***N***	***F***	***p***	**Post-hoc tests**[a]
ZVT speed of cognitive processing (arbitrary units)	Pre	Standard	2.88	.62	16	5.43	.002	Standard < l.t. acute (p=.018; d=1.26 [1.38/1.06][b])
		Acute	3.04	.27	10			acute < l.t. acute (p=.004; d=1.77 [2.03/1.24])
		Long-term	2.75	.44	14			
		Long-term+acute	2.69	.35	17			
	Post	Standard	3.04	.52	16			
		Acute	3.14	.32	10			
		Long-term	2.96	.41	14			
		Long-term+acute	3.03	.33	17			
d2 Concentration performance (correctly processed items minus commission errors)	Pre	Standard	190.5	36.50	16	7.35	.000	Standard < l.t. acute (p=.004; d=1.35 [.91/2.67])
		Acute	181.7	28.14	10			standard < long-term (p < .001; d=1.81 [1.67/2.34])
		Long-term	174.2	34.49	15			standard < acute (p=.024; d=1.35 [.73/3.94])
		Long-term+acute	181.9	30.12	16			
	Post	Standard	207.8	35.49	16			
		Acute	215.1	31.11	10			
		Long-term	211.9	35.22	15			
		Long-term+acute	216.3	35.86	16			
d2 Error % (percentage of errors)	Pre	Standard	24.10	11.44	16	4.09	.011	Standard > l.t.acute (p=.039; d=.99 [.84/1.30])
		Acute	25.95	8.25	10			standard > long-term (p=.016; d=1.20 [1.24/1.29])
		Long-term	27.75	10.38	15			
		Long-term+acute	24.93	8.85	15			
	Post	Standard	18.30	9.43	16			
		Acute	16.83	7.79	10			
		Long-term	17.26	8.92	15			
		Long-term+acute	14.90	6.63	15			
VVM visuospatial memory (correctly remembered items)	Pre	Standard	24.47	5.50	15	3.02	.038	l.t. Acute < long-term (p=.051; d=1.00 [1.17/.74])
		Acute	25.00	3.43	10			
		Long-term	23.53	4.93	15			
		Long-term+acute	27.12	3.35	17			
	Post	Standard	28.27	3.06	15			
		Acute	27.20	3.71	10			
		Long-term	27.93	4.04	15			
		Long-term+acute	27.94	4.42	17			
VVM verbal memory (correctly remembered items)	Pre	Standard	13.69	4.92	16	2.51	.069	
		Acute	13.80	3.05	10			
		Long-term	13.53	4.14	15			
		Long-term+acute	15.93	3.77	15			
	Post	Standard	15.69	5.68	16			
		Acute	16.90	3.96	10			
		Long-term	17.93	4.06	15			
		Long-term+acute	16.86	4.16	15			

[a] Bonferroni corrected post-hoc tests on gain scores (post minus pre).
[b] Effect size Cohen's d in total [secondary school/vocational school].

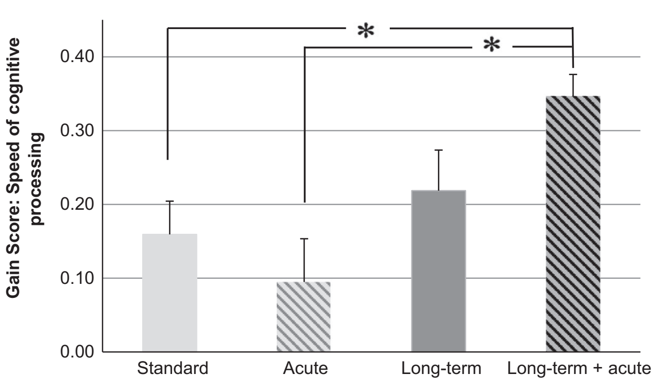

Fig. 2. Gain scores for speed of cognitive processing (ZVT).

'long-term+acute' condition showed significantly more improvement in speed of cognitive processing than subjects in the acute and standard conditions.

3.3. Concentration performance (d2)

Subjects increased their performance on the test from pre to post: A main effect of *Time* [F(1,53)=291.6; p < .001] but not of group (*Lighting Condition*) [F(3,53) < 1] was found. Furthermore, data analysis revealed a significant interaction between *Lighting Condition* ∗ *Time* for the four conditions (Table 2, Fig. 3). Subjects in the standard conditions showed less improvement on concentration performance than subjects in the other lighting conditions.

3.4. Inaccuracy/error% (d2)

The amount of errors made by subjects in the test decreased from pre to post: a main effect of *Time* [F(1,52)=248.1; p < .001] but not of group (*Lighting Condition*) [F(3,52) < 1] was found. Furthermore, data analysis for the four conditions revealed a significant interaction between *Lighting Condition* × *Time* (Table 2, Fig. 4). Subjects in the standard lighting condition showed less improvement on accuracy than subjects in the long-term+acute and the long-term conditions.

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3.5. Visual and Verbal Memory (VVM)

Subjects increased their performance on the test from pre to post: Main effects of *Time* for the visuospatial subtest [$F(1,53)=31.6$; $p<.001$] and the verbal subtest [$F(1,52)=30.8$; $p<.001$] but not of group (*Lighting Condition*) [$F(3,53)<1$; $F(3,52)<1$] were found. Furthermore, data analysis for the visuospatial subtest revealed a significant interaction between *Lighting Condition* × *Time*. However, Bonferroni post-hoc tests show only a strong tendency for an advantage of the long-term condition in comparison to the long-term+acute condition. No significant interaction between *Lighting Condition* × *Time* could be found for the verbal subtest (Table 2).

3.6. Opinions about classroom lighting

Students rated the standard classroom lighting better in terms of pleasantness, brightness and light color (Table 3). But, when asked whether to keep or remove the blue-enriched white classroom lighting, 50% of the students in the classroom with blue-enriched white lighting expressed their wish to keep the new lighting, adding comments like 'The new light makes me feel more awake'.

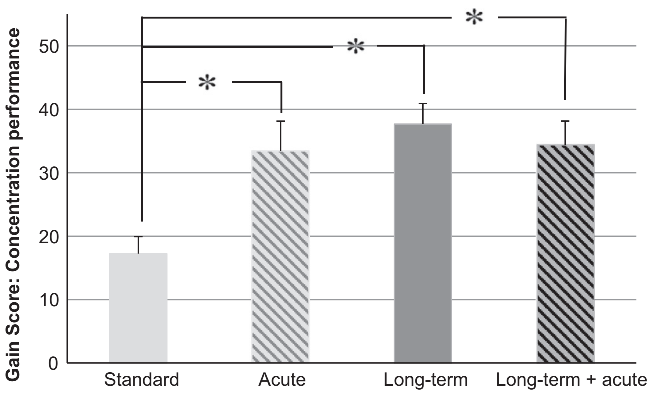

Fig. 3. Gain scores for concentration performance (d2).

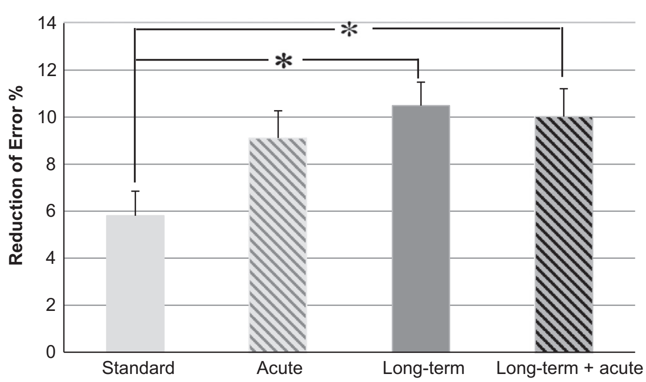

Fig. 4. Reduction of error % (d2).

4. Discussion

The performance of subjects in our study increased on average from pre to post-tests: main effects of *Time* were found on all repeated measures. Most likely, these effects are due to learning what to expect from and how to cope with a particular test. No main effects of *Lighting Condition* were found for any of the repeated measures showing that the groups did not differ from each other systematically in terms of performance. Of interest for this study were the interaction effects in order to establish whether or not subjects' performance develops differently according to the lighting conditions they were exposed to. Four significant interaction effects were found. Only for the verbal memory the interaction effect failed to reach significance. Bonferroni corrected post hoc tests dismissed the effect for visuospatial memory but revealed altogether seven differences of pairwise comparisons between lighting conditions (cf. Table 4). All of these differences show that subjects benefited from lighting conditions with more blue-enriched white lighting either at testing or in the classroom the previous weeks.

One of the seven effects, the difference between standard and acute conditions for concentration performance indicates that there is an acute stimulating effect of blue-enriched white lighting. The subjects who took their tests under blue-enriched white lighting showed more improvement in their concentration performance than the subjects under standard lighting. The acute effect is pronounced in the vocational school ($d=3.94$) that starts an hour earlier than the secondary school ($d=.73$) and has students who are on average 3 years older (cf. Table 1). Evidence for an acute beneficial effect of blue-enriched white lighting has been found before. One study has proposed doing exams under high color temperature lighting to improve concentration performance [2].

Two of the seven differences presented in Table 4 suggest a mechanism of entrainment: Subjects exposed to blue-enriched white lighting during morning classes show higher test score gains in all measurements than subjects under the standard lighting condition, even though the differences are only significant for the d2 test (concentration performance and error %). As all subjects in these groups were tested under the same standard light, the differences cannot be attributed to acute effects of blue-enriched white lighting. A third significant difference, the one between the acute and the long-term+acute condition concerning the speed of cognitive processing, also hints at this mechanism. Subjects in these groups were tested under the same blue-enriched white lighting. These groups differed only in the classroom lighting during the previous 5 weeks, not in the light during testing.

Evidence for such a long-term effect has been found before: Our results correspond to similar findings on effects of blue-enriched white lighting [23,41]. Additionally, a mechanism has been proposed that bases the beneficial effect of blue-enriched

Table 3
Students' opinions about classroom lighting, descriptive and inferential statistics (t-test).

	Classroom lighting	*N*	*M*	SD	*p*
Pleasantness 1=very pleasant	Standard lighting	23	2.22	.67	.004
	Blue-enriched white lighting	30	2.83	.79	
Brightness 3=just right	Standard lighting	23	3.04	.21	.000
	Blue-enriched white lighting	30	2.53	.63	
Light color 1=very pleasant	Standard lighting	23	2.22	.67	.001
	Blue-enriched white lighting	30	3.00	.83	

Note: Different *N* due to missing data (e.g. illness of students) at the time of rating the classroom lighting.

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Table 4
Significant post hoc differences between lighting conditions.

	Acute	Long-term	Long-term + acute
Standard	d2 concentration[a]	d2 concentration d2 error[b]	ZVT d2 concentration d2 error[c]
Acute	n/a	none	ZVT[b]

[a] Acute effect of lighting.
[b] Non-acute long-term effects possibly due to entrainment.
[c] Effects that can be either acute or long-term or a combination of both.

white lighting on entrainment: Light not only has an acute visual effect, but also an important non-visual biological effect on the human body, positively influencing alertness [35]. Artificial blue-enriched white lighting acts as a zeitgeber and entrains the human circadian clock [21,33,41]. Correspondingly, missing short-wavelength light in the morning postpones entrainment and leads to a delay of circadian cycle of high school students [15,17]. These results suggest that the long-term effects found in this study may be due to entrainment through blue-enriched white lighting in classrooms.

Three of the seven differences presented in Table 4, the differences between the standard and the long-term + acute condition, could be due to either acute or long-term effects or a combination of both. No differences were found between the 'long-term' and 'acute' conditions that would have shown which of the two effects (acute vs. long-term) is bigger.

Even though the blue-enriched white lighting improved students' performance, subjects preferred the standard lighting in terms of pleasantness, brightness and light color. The new lighting was considered, for instance, too bright. At the end of the intervention, only half of the subjects wanted to keep the new light in their classroom despite the fact that indirect light is regarded as more comfortable to the eye than direct light.

This study has explored the influence of blue-enriched white light on the performance of students in a school setting. Generally, beneficial effects of blue-enriched white lighting were found on student performance. The first goal of our study was achieved: blue-enriched white lighting can be utilized in a real-world classroom setting to improve alertness and cognitive performance of students. The second goal was to clarify the underlying mechanisms of this improvement by untangling the contributing acute and non-acute effects. Our results suggest both mechanisms at work: one of the seven found pairwise differences can only be explained in terms of acute effects (cf. Table 4(a)) while three can only be explained in terms of long-term effects (cf. Table 4(b)). The other three differences hint at an additive effect of acute and long-term mechanisms (cf. Table 4(c)).

Any long-term effect that can be attributed to entrainment would have been accompanied by changes in sleeping pattern. However, there is no valid information available about sleep onset and wake-up times of the subjects. We had asked the subjects to keep a sleep diary. But even with an elaborated incentive system it was hard to get the subjects to comply throughout the weeks of the study. Besides, the teachers informed us that subjects filled in their diary in the morning at school guessing the entries shortly before handing in the form. Only 22 subjects continually handed in their diaries. No differences could be found between the conditions in the small self-selected subpopulation.

The difficulties with obtaining the sleep data show just one of the limits of a quasi-experimental design. A study in a real-world classroom means also that subjects cannot be recruited freely and randomized at will. Distribution of age, gender and socioeconomic status is given by the sample, as is the number of students in one classroom. Since the first goal of the study was to see if blue-enriched white lighting can be utilized in a real-world classroom setting, there was no alternative to a quasi-experiment.

The beneficial effects of blue-enriched white light on student performance were obtained from a sample of youth with light exposure during mornings in winter. The result from the present study cannot necessarily be generalized to older or younger people. Furthermore, the study involved classroom lighting exposure during morning classes, so a generalization to other times of the day is not possible. Blue-enriched white lighting as it was applied in the current study during the early morning hours should actually be avoided in the evening and during the night to prevent impaired sleep quality or delayed sleep onset, as even the evening daylight may cause adolescents to sleep less in spring than in winter [16]. Note that the present lighting installation includes light management systems. Hence, it is possible to provide an adaptive lighting system that fits the human requirements during the day: continuously lower color temperatures, lower illuminance levels and reduced indirect lighting towards the evening.

To summarize this study, blue-enriched white lighting in the early morning hours can improve the speed of cognitive processing and concentration. But further research is needed to clarify the contributions of acute effects and long-term effects of regular morning exposure respectively. This study showed both mechanisms at work.

Authors' contributions to the study

OK: acquisition of data, analysis, interpretation of data, drafting the article.
HH: conception and design, drafting the article.
JS: acquisition of data, analysis, interpretation of data, revising the article.
KH: conception and design, acquisition of data, analysis, interpretation of data, drafting the article.

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References

[1] Aston-Jones G, Chen S, Zhu Y, Oshinsky ML. A neural circuit for circadian regulation of arousal. Nat Neurosci 2001;4(7):732–8.
[2] Barkmann C, Wessolowski N, Schulte-Markwort M. Applicability and efficacy of variable light in schools. Physiol Behav 2012;105(3):621–7.

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[3] Brainard GC, Hanifin JP, Greeson JM, Byrne B, Glickman G, Gerner E, et al. Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. J Neurosci 2001;21(16):6405–12.
[4] Brickenkamp R. Test d2: Aufmerksamkeits-Belastungs-Test (9 ed.). Göttingen: Hogrefe; 2002.
[5] Burgess HJ, Sharkey KM, Eastman CI. Bright light, dark and melatonin can promote circadian adaptation in night shift workers. Sleep Med Rev 2002;6(5):407–20.
[6] Cajochen C, Dijk D, Borbély A. Dynamics of EEG slow-wave activity and core body temperature in human sleep after exposure to bright light. Sleep 1992;15(4):337.
[7] Cajochen C, Münch M, Kobialka S, Kräuchi K, Steiner R, Oelhafen P, et al. High sensitivity of human melatonin, alertness, thermoregulation and heart rate to short wavelength light. J Clin Endocrinol Metab 2005;90(3):1311–6.
[8] Carrier J, Dumont M. Sleep propensity and sleep architecture after bright light exposure at three different times of day. J Sleep Res 1995;4(4):202–11.
[9] Carskadon MA, Acebo C, Seifer R. Extended nights, sleep loss, and recovery sleep in adolescents. Arch Ital de Biol 2001;139:301–12.
[10] Chellappa SL, Gordijn MC, Cajochen C. Can light make us bright? Effects of light on cognition and sleep In: Kerkhof G, Van Dongen HPA, editors. Progress in brain research, vol. 190. The Netherlands, UK, USA: Elsevier; 2011. p. 119–33.
[11] Chellappa SL, Steiner R, Blattner P, Oelhafen P, Götz T, Cajochen C. Non-visual effects of light on melatonin, alertness and cognitive performance: can blue-enriched light keep us alert? PLoS One 2011;6(1) (Retrieved from doi:e16429).
[12] Czeisler C, Gooley J. Sleep and circadian rhythms in humans. In: Proceedings of the paper presented at the cold spring habor symposia on quantitative biology; 2007.
[13] Dacey DM, Liao H-W, Peterson BB, Robinson FR, Smith VC, Pokorny J, et al. Melanopsin-expressing ganglion cells in primate retina signal colour and irradiance and project to the LGN. Nature 2005;433(7027):749–54.
[14] Dijk DJ, Beersma D, Daan S, Lewy AJ. Bright morning light advances the human circadian system without affecting NREM sleep homeostasis. Am J Physiol Regul Integr Comp Physiol 1989;256(1):R106–11.
[15] Figueiro MG, Brons J, Plitnick B, Donlan B, Leslie R, Rea M. Measuring circadian light and its impact on adolescents. Light Res Technol 2011;43(2):201–15.
[16] Figueiro MG, Rea MS. Evening daylight may cause adolescents to sleep less in spring than in winter. Chronobiol Int 2010;27(6):1242–58.
[17] Figueiro MG, Rea MS. Lack of short-wavelength light during the school day delays dim light melatonin onset (DLMO) in middle school students. Neuroendocrinol Lett 2010;31(1):92–6.
[18] Gabel V, Maire M, Reichert CF, Chellappa SL, Schmidt C, Hommes V, et al. Effects of artificial dawn and morning blue light on daytime cognitive performance, well-being, cortisol and melatonin levels. Chronobiol Int 2013;30(8):988–97.
[19] Hattar S, Liao H-W, Takao M, Berson DM, Yau K-W. Melanopsin-containing retinal ganglion cells: architecture, projections, and intrinsic photosensitivity. Science 2002;295(5557):1065–70.
[20] Klerman E, Dijk D-J. Age-related reduction in the maximal capacity for sleep—implications for insomnia. Curr Biol 2008;18(15):1118–23.
[21] Lang D, Dehoff P, Lorenz D, Sust CA. Positive effects of biological effective light on residents in nursing homes suffering from dementia. In: Proceedings of the paper presented at the ies symposium light+seniors, Washington, DC; 2012.
[22] Lockley SW, Evans EE, Scheer F, Brainard GC, Czeisler CA, Aeschbach D. Short-wavelength sensitivity for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans. Sleep 2006;29(2):161.
[23] Mills PR, Tomkins SC, Schlangen LJM. The effect of high correlated colour temperature office lighting on employee wellbeing and work performance. J Circadian Rhythms 2007;5(1):2.
[24] Münch M, Kawasaki A. Intrinsically photosensitive retinal ganglion cells: classification, function and clinical implications. Curr Opin Neurol 2013;26(1):45–51.
[25] Noguchi H, Sakaguchi T. Effect of illuminance and color temperature on lowering of physiological activity. Appl Hum Sci 1999;18:117–23.
[26] Oswald WD, Roth E. ZVT Der Zahlen-Verbindungs-Test. Göttingen: Hogrefe; 1987.
[27] Revell VL, Arendt J, Fogg LF, Skene DJ. Alerting effects of light are sensitive to very short wavelengths. Neurosci Lett 2006;399:96–100.
[28] Roenneberg T, Kuehnle T, Pramstaller PP, Ricken J, Havel M, Guth A, et al. A marker for the end of adolescence. Curr Biol 2004;14(24):R1038–1039. http://dx.doi.org/10.1016/j.cub.2004.11.039.
[29] Santhi N, Aeschbach D, Horowitz TS, Czeisler CA. The impact of sleep timing and bright light exposure on attentional impairment during night work. J Biol Rhythms 2008;23(4):341–52.
[30] Santhi N, Thorne HC, van der Veen DR, Johnsen S, Mills SL, Hommes V, et al. The spectral composition of evening light and individual differences in the suppression of melatonin and delay of sleep in humans. J Pineal Res 2012;53(1):47–59.
[31] Schellig D, Schächtele B. Visueller und Verbaler Merkfähigkeitstest (VVM). Frankfurt: Main: Swets Test Services; 2001.
[32] Smith MR, Eastman CI. Phase delaying the human circadian clock with blue-enriched polychromatic light. Chronobiol Int 2009;26(4):709–25.
[33] Sust CA, Dehoff P, Lang D, Lorenz D. Improved quality of life for resident dementia patients: St. Katharina research project in Vienna. Zumtobel Research; 2012.
[34] Thapan K, Arendt J, Skene DJ. An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans. J Physiol 2001;535(1):261–7.
[35] Van Bommel WJM. Non-visual biological effect of lighting and the practical meaning for lighting for work. Appl Ergonomics 2006;37(4):461–6.
[36] Vandewalle G, Balteau E, Phillips C, Degueldre C, Moreau V, Sterpenich V, et al. Daytime light exposure dynamically enhances brain responses. Curr Biol 2006;16(16):1616–21. http://dx.doi.org/10.1016/j.cub.2006.06.031.
[37] Vandewalle G, Gais S, Schabus M, Balteau E, Carrier J, Darsaud A, et al. Wavelength-dependent modulation of brain responses to a working memory task by daytime light exposure. Cereb Cortex 2007;17:2788–95.
[38] Vandewalle G, Maquet P, Dijk D-J. Light as a modulator of cognitive brain function. Trends Cogn Sci 2009;13(10):429–38.
[39] Vandewalle G, Schmidt C, Albouy G, Sterpenich V, Darsaud A, Rauchs G, et al. Brain responses to violet, blue, and green monochromatic light exposures in humans: prominent role of blue light and the brainstem. PLoS One 2007;2(11):e1247.
[40] Vetter C, Juda M, Lang D, Wojtysiak A, Roenneberg T. Blue-enriched office light competes with natural light as a zeitgeber. Scand J Work Environ Health 2011;37(5):437–45.
[41] Viola AU, James LM, Schlangen LJ, Dijk DJ. Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality. Scand J Work Environ Health 2008;34(4):297–306.
[42] Wittmann M, Dinich J, Merrow M, Roenneberg T. Social jetlag: misalignment of biological and social time. Chronobiol Int 2006;23:497–509.
[43] Wright KP, Hull JT, Hughes RJ, Ronda JM, Czeisler CA. Sleep and wakefulness out of phase with internal biological time impairs learning in humans. J Cogn Neurosci 2006;18(4):508–21.
[44] Zaidi FH, Hull JT, Peirson SN, Wulff K, Aeschbach D, Gooley JJ, et al. Short-wavelength light sensitivity of circadian, pupillary, and visual awareness in humans lacking an outer retina. Curr Biol 2007;17(24):2122–8.