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# Practical Investigation of the impact of Classroom Lighting on Student Behaviour: A comparison of LED and incandescent Light

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ABSTRACT. The European Union has taken several steps to ban the production and trade of incandescent and halogen lamps in the near future because energy consumption is higher than for light-emitting diodes (LEDs). The potential effects of LEDs on pupils have hardly been investigated. The purpose of the study was a comparison of LEDs and incandescent light on pupils' behaviour under practical conditions in three schools with a total of six classes. While the results on alertness and concentration were heterogeneous, memory and creativity performance were reduced by LED lighting. There is a substantial lack of knowledge of the potential effects of LEDs on pupils' behaviour. With regard to students' behaviour, the planned ban on incandescent and halogen lighting by the EU is untimely and missing a scientific basis.

ZUSAMMENFASSUNG. Die Europäische Union hat mehrere Maßnahmen ergriffen, um die Produktion und den Handel mit Glüh- und Halogenlampen in naher Zukunft zu verbieten, da der Energieverbrauch höher ist als bei Leuchtdioden (LEDs). Die möglichen Auswirkungen von LED auf das Verhalten von Schülern sind kaum untersucht worden. Ziel der Studie war ein Vergleich von LED und Glühlampen- bzw. Halogenlicht über das Verhalten von Schülern unter praktischen Bedingungen in drei Schulen mit insgesamt sechs Klassen. Während die Ergebnisse hinsichtlich Wachsamkeit und Konzentration heterogen waren, wurde die Gedächtnis- und Kreativitätsleistung durch LED-Beleuchtung reduziert. Es besteht ein erhebliches Wissensdefizit über die möglichen Auswirkungen von LEDs auf das Verhalten der Schüler. Im Hinblick auf Verhaltenseffekte von Schulkindern ist das geplante Verbot von Glüh- und Halogenlampen durch die EU verfrüht und ohne wissenschaftliche Grundlage.

*Keywords*: Classroom lighting, halogen, LED, student behaviour

## Introduction

Interior lighting is an important component of the physical learning environment in schools. Currently, possible ways of using artificial light are rapidly changing. So-called light-emitting diodes (LEDs) are increasingly being utilised and are replacing the incandescent light bulbs and fluorescent lights that are currently in use. LEDs are attractive because of their low energy consumption and versatility. The European Commission (EC) has taken several steps to ban the production and trade of incandescent lamps, and it plans to do so with the lighting features in the near future because energy consumption is higher for incandescent lamps than LEDs (EC, 2016).

Different types of light bulbs vary technically; they also produce different kinds of light. LEDs emit a higher proportion of blue light and a lower proportion of red and infrared light than halogen and incandescent bulbs. This difference between LED and halogen/incandescent light does not fundamentally change, even with a warm light colour. Halogen and incandescent bulbs exhibit the most continuous and sun-like spectra. Many classrooms are equipped with fluorescent lighting tubes. The light from these lamps has a discontinuous spectrum, which usually has peaks in the blue, green and yellow wavelength ranges.

The effects of the high-energy shortwave blue light in LEDs are increasingly being debated in connection with the frequent use of monitors and smartphones. They have been medically shown to produce sleep disorders (Gringas et al., 2015; Yang et al., 2018) and retinal damage risk (Behar-Cohen et al., 2013; Ratnayake et al., 2018; Tosini et al., 2016). A number of studies reported performance improvements in night shift workers when working in a brightly lit environment (Boyce et al., 1997; Campbell & Dawson, 1990; Figuerio et al., 2001; Mills et al., 2007). Other studies point to higher achievements of office workers in blue-enriched white light environments (Viola et al., 2008). This is attributed to the effects of the short-wave (blue) light component (Cajochen et al., 2005; Chellappa et al., 2011; Lockley et al., 2006).

Blue-enriched lighting is associated with higher alertness (Alkozei et al., 2017; Viola et al., 2008). For higher alertness, in addition to visual effects, non-visual effects have been found to have an effect on the hormonal system. However, there are also indications that physiological stimulation using blue-enriched lighting does not always lead to greater alertness (Rodriguez-Morilla et al., 2017).

Few studies have investigated the effect of blue-enriched lighting on students (Keis et al., 2014; Pulay & Williamson, 2018). In both studies, fluorescent light was used as the standard. No previous studies have compared LED lighting against incandescent or halogen lighting in school environments.

A series of studies investigated the light conditions on the behaviour of students at constant illuminants, namely fluorescent or incandescent lighting. Baron et al. (1992) simulated office work with students under different lighting conditions. The students' communication skills improved and their performance on tasks that required social skills was better in environments with warmer and darker light (3000 Kelvin (K), 150 lux (lx)). In the study by Fleischer (2001), which simulated a laboratory work situation, communication and social behaviour also improved under warm white light. However, alertness was found to improve in daylight white light. Küller and Lindsten (1992) came to a similar conclusion in their study with primary school pupils; they reported increased alertness and concentration in daylight white light and increased communication in warm white light. Steidle and Werth (2013) conducted a variety of experiments to investigate the effect of lighting conditions on the creativity of students. In a dim room (150 lx), the overall creativity was higher, while in a bright room (1500 lx) analytical thinking was improved.

Shamsul et al. (2013) investigated the effects of the correlated colour temperature (3,000 K, 4,000 K or 6,500 K) on task performance and alertness among students. The authors concluded that 4,000 K or 6,500 K light were more beneficial for alertness level and academic activities for both computer-based and paper-based activities.

Werth et al. (2013) identified a considerable need for research into the influence of light and lighting on perception and behaviour towards other persons. According to Chok and Suk (2016), there is a lack of interior lighting studies in learning environments, especially with a younger population.

The study by Slepian et al. (2010) is the only one that compares incandescent lighting with cold fluorescent light to determine their effect on problem solving. That study reported that insight problems were solved better under incandescent lighting than cold fluorescent lighting. In the experiment by Geier (2016) with adults who were trained in self-observation, a significantly better sense of well-being was found under halogen light than under LED light.

In the two available studies, which examined LED effects on children and adolescents (Keis et al., 2014; Pulay & Williamson, 2018), the focus was on parameters of alertness, concentration and cognitive processing. Social skills or creativity have not been considered.

In three experiments with students in a total of six classes in three schools, we investigated whether the conversion from incandescent or halogen lighting to LED lighting changed the students' behaviours. For all three of the experiments, the colour temperature and light intensity were as similar as possible. The aim was to consider a broad spectrum of abilities of children and adolescents. Based on the literature (Keis et al., 2014; Küller & Lindsten, 1992; Steidle & Werth, 2013), the skills of alertness/concentration, memory and creativity were selected.

The guiding questions of the three sub-studies were: Do the pupils behave differently under LED and incandescent or halogen light (Preparatory Study 1)? Is it possible to repeat the effects of the first study with students in more classes (Preparatory Study 2)? Can the results of both preparatory studies be repeated in an extended experimental design (Study 3)? It was assumed that blue-enriched lighting (LED) promoted alertness and concentration. There were no assumptions regarding memory and creativity skills.

To avoid any teaching disturbances, the testing tasks were designed to be similar to typical class exercises. The exercises and the experimental design were discussed with the teachers involved in the study.

Alertness and concentration were checked via the error rates in dictations and in arithmetic. Memory was tested on memorized content when copying from the blackboard, from text sheets and from teacher narratives. Creativity was measured by the ability to paint pictures. The spectral distribution and design of halogen and incandescent lamps are very similar. In the experiment, therefore, both are considered as one variant.

## Study 1 (preparatory study)

### *Design*

During a two-week period in spring 2016, the lighting regime (nine pendant luminaires) in the classroom was changed in the following order: LED, halogen, and halogen and LED light. Each lighting regime lasted one day. The halogen lighting represented the current situation (Osram Halolux Ceram® 150 W, E 27, 2870 lumens (lm), 2900 K, colour rendering index (CRI/Ra) 100) (Osram 2018a), while the LED lighting represented the future situation (Luxwerke x.course 35 W, 3650 lm, 2700 K, CRI/Ra >90). The influence of sunlight (daylight) was reduced by the use of curtains during the experiments.

### *Participants*

Twenty-seven students in a fifth-grade class (ages 11 and 12) in a private integrated comprehensive school in southwestern Germany participated in Study 1. Only 21 students could be included in the evaluation due to absence on one date.

### *Exercises*

For each of the four exercise sessions, a dictation was carried out. The text length of each dictation ranged between 30 and 50 words. For the first two sessions, an open retelling was conducted (66 or 106 words). During the last two sessions, the students had to copy text that was written on the blackboard (332 or 154 words). The orthographical mistakes were measured for all the exercises. The copied text addressed the students' direct speech. The direct speech portion of the exercises included five to seven verbs, such as reported, said, explained, asked, etc. The correct use of the verbs was examined. The error rate in the dictations was assigned to the alertness and concentration capability, while the error rate when transferring text from the table was associated to the memory capability.

*Results and Discussion*

The dictation was normalised to 100 words. The average word error rate was 4.40 (standard deviation (SD) 4.58) under LED light and 1.95 (SD 3.70) under halogen light. The pairwise t-test showed statistically significant differences between the two types of lighting ($p = 0.002$).

In the open retelling and text copying exercises, more mistakes occurred under LED lighting. For the open retelling normalised to 100 words, 4.61 (SD 2.83) mistakes occurred under LED lighting in comparison to 3.90 (SD 1.94) mistakes under incandescent lighting ($p = 0.319$). In the text copying exercise normalised to 100 words, 3.6 (SD 2.28) mistakes occurred under LED lighting and 0.8 (SD 1.20) mistakes occurred under incandescent lighting ($p < 0.0001$).

In the text copying exercise under LED lighting, 47% of the 21 students applied the seven verbs correctly, while 53% were confused about at least one verb. Under the incandescent light, 100% of the students used the five verbs correctly ($p < 0.0001$).

## Study 2 (preparatory study)

*Design*

In February 2017, the lighting regime (nine pendant luminaires) was altered in three classrooms. The experiments were conducted for one week under the current lighting regime (incandescent light bulbs Osram 100 W, E 27, 2700 K, 1340 lm, CRI/Ra 100) (Osram 2018b). In the second week, comparable LED lighting (Philips warm white 13 W, E 27, 2200-2700 K, 1521 lm, CRI/Ra 80) (Philips 2018a) was used. One classroom started with LED lighting, while two classrooms started with incandescent lighting.

*Participants*

Students of three classes (Class 3, ages 9 and 10: n= 34; Class 5, ages 11 and 12: n=22, Class 7, ages 13 and 14: n=26) in a private integrated comprehensive school in the southern Germany participated in Study 2.

*Exercises*

In Class 3, dictation, mental calculation and drawing of pictures were examined. For the dictation, the teacher recited four short sentences. The mental calculation consisted of eight exercises with monadic or binary numbers. Pictures were drawn twice; in the first case the students were allowed to draw any image they wanted (free-style); in the second case, the theme for the drawing was animals. In Class 5, dictation and text copying were examined. In Class 7 dictation, mental calculation and open retelling were examined.

Mistakes from the text copying, dictation and mental calculation exercises were measured. The text length of the open retelling was counted. The images were assessed and coded by an experienced teacher from the Netherlands using the following parameters: size, colourfulness, harmony, forming capacity, devotion and unity.

The error rate in writing and mental calculation was associated to the alertness and concentration capability. The text length of the open retelling was associated to the memory capability. The ability to draw was related to the skill to be creative.

*Results and Discussion*

**Class 3**

For dictation and mental calculation, no differences were observed between the two types of lighting regimes (dictation: 8.28 mistakes (SD 4.77) [LED] per 100 words; 9.38 mistakes (SD 4.09) [incandescent] per 100 words, p = 0.065; mental calculation: 0.41 mistakes (SD 0.76) [LED], 0.44 mistakes (SD 0.80) [incandescent], p= .879). The students in classroom 3 painted two free-style pictures. In both cases, the pictures created under incandescent lighting were evaluated better, with significant differences in three of the five and five of the five painting capacity criteria (see Table 1). The total value of the single criteria shows significant differences, too. Figures 1 to 3 show examples of the pictures of three students painted under different lighting conditions.

**Table 1: Evaluation of the students' drawing capacity. Descriptive statistics. Type of criteria (mean value %) and p-values (bold type means significant results); n=34 students in classroom 3 (INC = incandescent or halogen light).**

| **Pictures with a free-style theme** | | | | | | |
|---|---|---|---|---|---|---|
| | Size | colour-fulness | harmony | forming capacity | unity /integration | Total value all criteria |
| LED | 72.0 (41.6) | 30.2 (43.4) | 50.7 (44.6) | 30.9 (39.9) | 33.8 (40.8) | 43.5 (41.3) |
| INC | 90.4 (26.8) | 76.5 (40.3) | 62.5 (43.6) | 64.7 (42.2) | 52.9 (43,4) | 69.4 (44.9) |
| p-value | **0.039** | **<0.0001** | 0.307 | **0.001** | 0.058 | **<0.0001** |

| **Pictures with the animal theme** | | | | | | |
|---|---|---|---|---|---|---|
| | devotion | unity | forming capacity | firmness | fullness | Total value all criteria |
| LED | 23.5 (43.1) | 35.3 (48.5) | 38.2 (49.3) | 26.5 (44.8) | 23.5 (43.1) | 29.4 (45.7) |
| INC | 55.9 (50.0) | 58.8 (50.0) | 64.7 (48.5) | 61.8 (49.3) | 64.7 (48.5) | 61.2 (48.9) |
| p-value | **0.009** | **0.030** | **0.048** | **0.005** | **<0.0001** | **<0.0001** |

*Class 5*

In class 5, the mistakes under LED lighting were 172% (copy text: 5.16 mistakes/100 words (SD 3.45) [LED], 2.84 mistakes/100 words (SD 2.59) [incandescent], p=.01) and 114% (dictation: 17.18 mistakes/100 words (11.24) [LED], 15.14 mistakes/100 words (SD 11.30) [incandescent], p= .26) in comparison to incandescent lighting (100%).

*Class 7*

While the students from class 7 performed *better* under LED lighting in terms of dictation mistakes (12.21 mistakes (SD 11.95) [LED], 26.13 mistakes (SD 20.58) [incandescent], p= .0003), there were no differences in the errors in mental calculation (2.46 mistakes (SD 2.67) [LED], 2.64 mistakes (SD 2.26) [incandescent], p= .67). The text length of the open retelling was longer under incandescent lighting (10.54 (SD 3.75) [LED], 17.04 (SD 7.99) [incandescent], p= .0004).

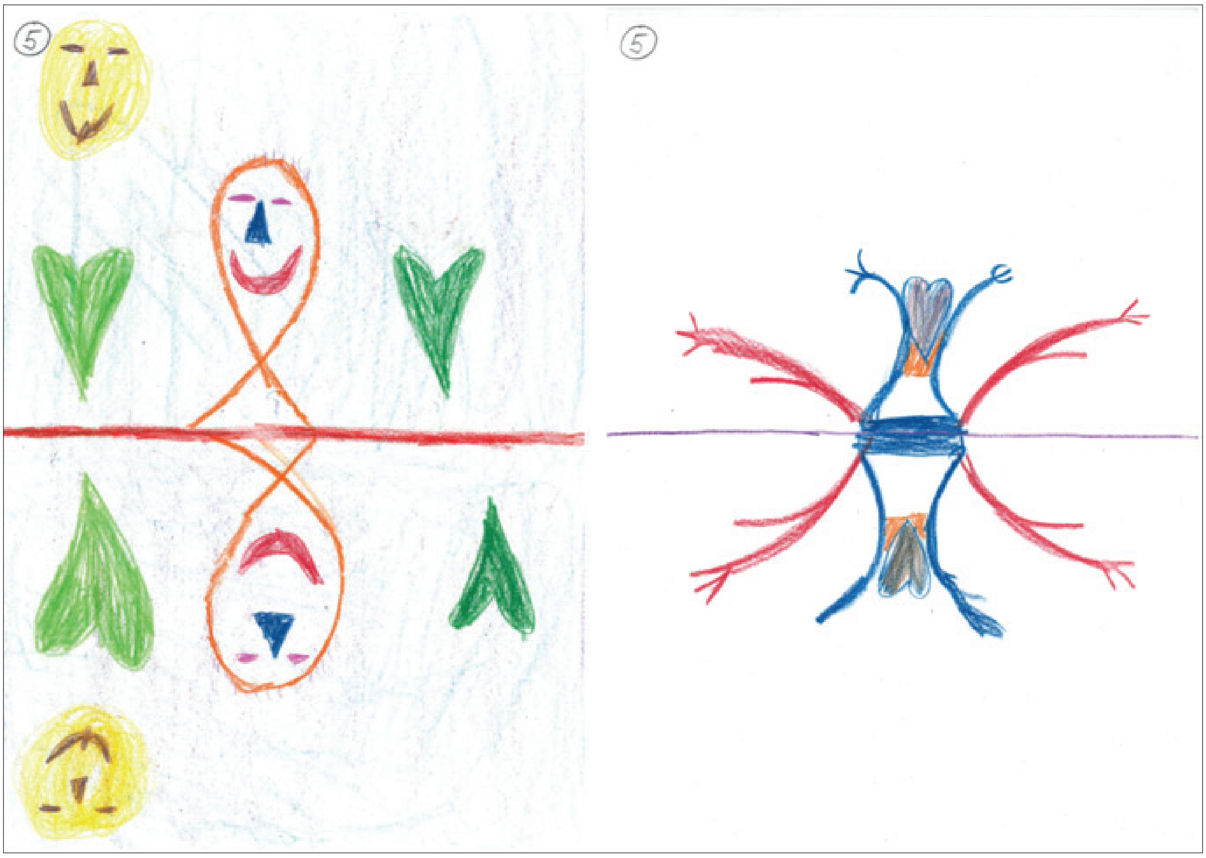


Figure 1: Example of one pupil of Class 3 painting under incandescent (left) and LED (right) light.

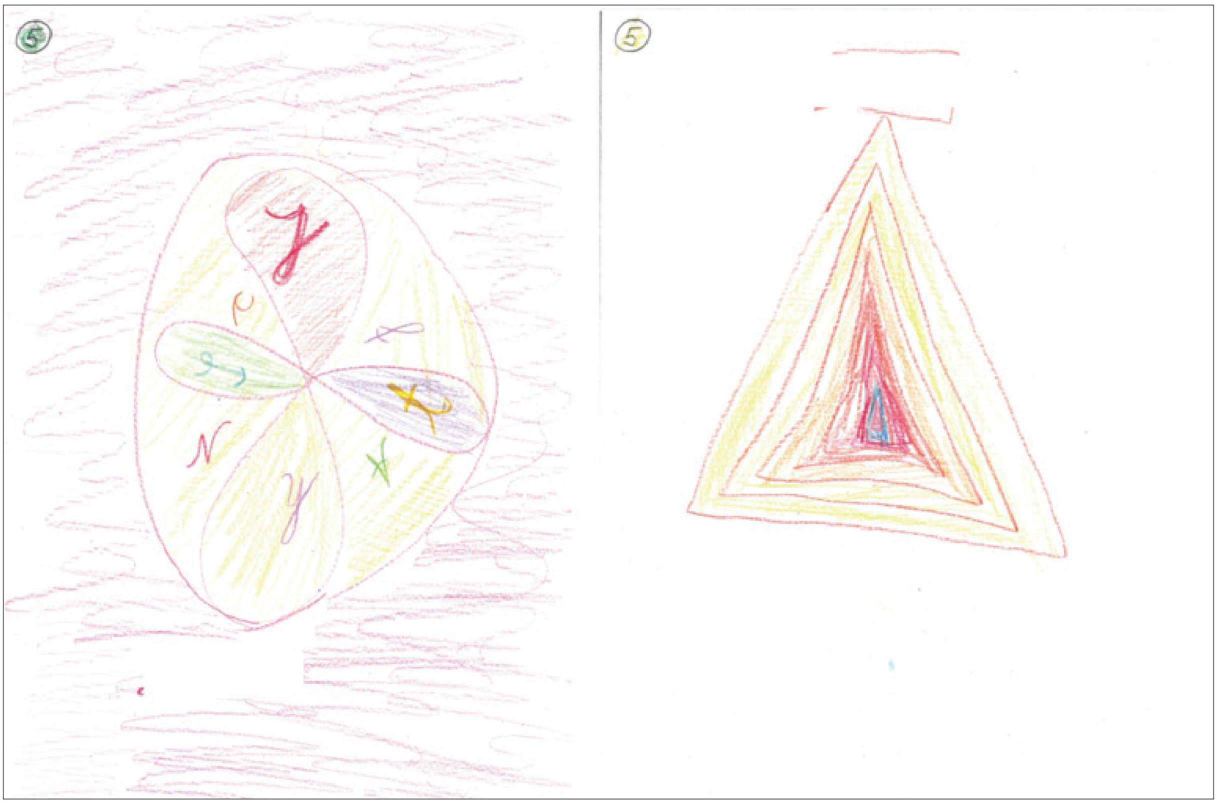


Figure 2: Example of one pupil of Class 3 painting under incandescent (left) and LED (right) light.

Figure 3: Example of one pupil of Class 3 painting under incandescent (left) and LED (right) light.

## Study 3

### *Design*

The experiments in study 3 were conducted over a four-week period in February and March 2018. For every week, the lighting regime in the classroom (six pendant luminaires) was altered in the following order: LED, halogen, LED and halogen (Classroom 4) and halogen, LED, halogen and LED (Classroom 6).

Class 4 used the same lighting that was used in Study 1: Osram Halolux Ceram® (150 W, E 27, 2870 lm, 2900 K, CRI Ra 100) (Osram 2018a) for halogen and Luxwerke x.course (35 W, 3650 lm, 2700 K, CRI Ra >90) for LED. In Classroom 6 Osram halogen light bulbs (77 W, E 27, 2800 K, 1320 lm, CRI Ra 100) (Osram 2018c) and Philips LED light bulbs (warm white 11.5 W, E 27, 2700 K, 1521 lm, CRI Ra 80) (Philips 2018b) were used.

### *Participants*

Students in two classrooms (Class 4, ages 10 and 11: n= 26; Class 6, ages 12 and 13: n=21) in a private integrated comprehensive school in the middle of Germany participated in Study 3. Only the results from students that were in attendance all four weeks were considered. Thus, the number of students was reduced from 26 to 21 (Classroom 4) and from 21 to 13 (Classroom 6).

### *Exercises*

The exercises were conducted each week over the course of four weeks. The students in both classes had to describe a photo of a child. The following questions were asked: What do you see in the picture? How do the children feel? Because most of the students did not answer the second question, only the answers to the first question were evaluated. The aim was to measure the students' visual recognition. In both classrooms, visual discrimination was examined using a image search test (with photos of a boat or a train).

Drawing capacity was evaluated by asking the students in both classrooms to create free-style paintings. An open retelling exercise was conducted in Class 4. The text length was counted and the most important topics were identified to measure the students' memory capacity. A text-copying exercise was carried out in Class 6. The students had to read three short stories, each containing four or five sentences, within five minutes. After receiving an acoustic signal from the teacher, the students had to turn the sheet around and write down the information they remembered within five minutes. Text length and mistakes were measured.

As in the preliminary studies, the results of the error rate in writing and arithmetic were assigned to alertness and concentration skills. The length of the text and the content of retellings and transcriptions were assigned to the skill of memory. The ability to draw was related to the skill creativity. Only in this study was the ability of visual recognition tested by describing a photo and a image search test.

### *Lighting conditions*

The lighting conditions in both classrooms were very similar; therefore, only Classroom 4 is described in more detail.

The lighting conditions were impacted during the day by daylight from the windows on the northwest side of the room. Since the position of each student was essential, the measurement took place at desks with a height of 0.75 m, which were arranged in four rows in the classroom from the windows to the side wall. Additionally, the light density was measured at the blackboard in front of the classroom. Figure 4 presents the light intensity respectively illuminance of artificial light in Classroom 4.

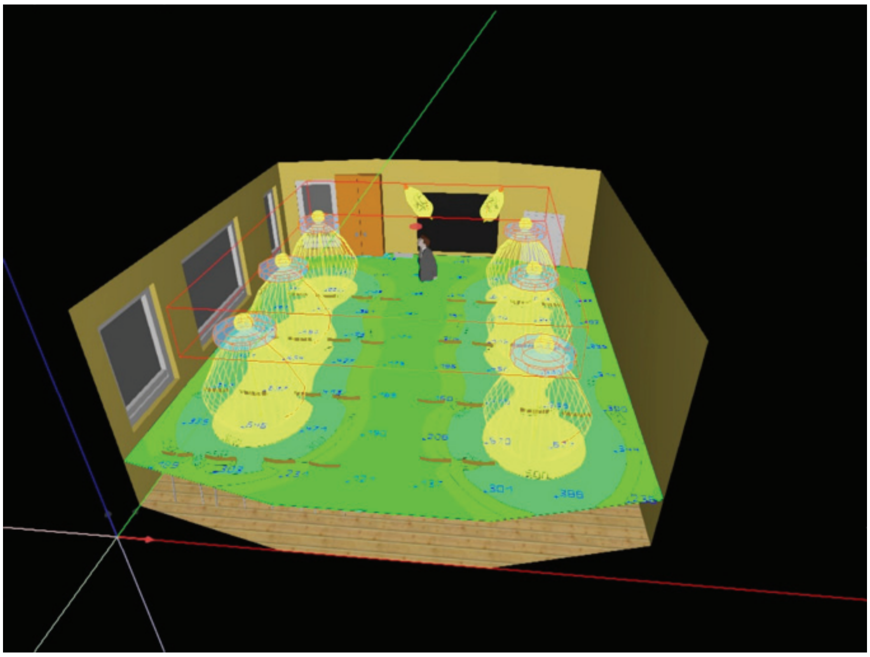
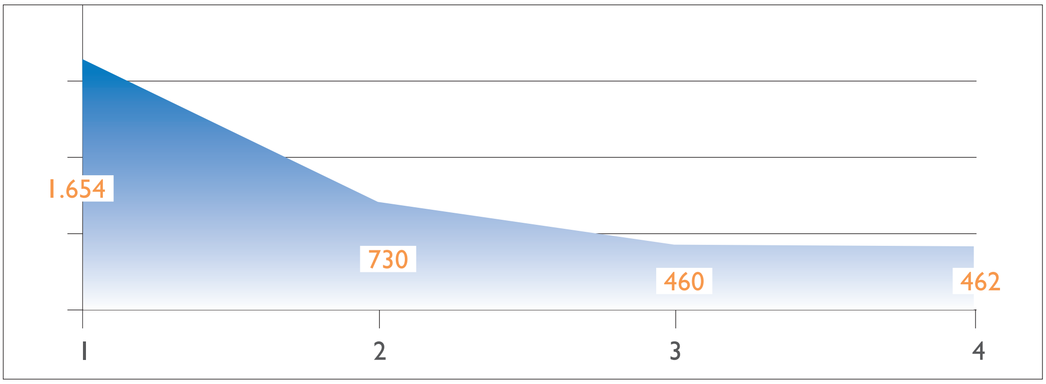


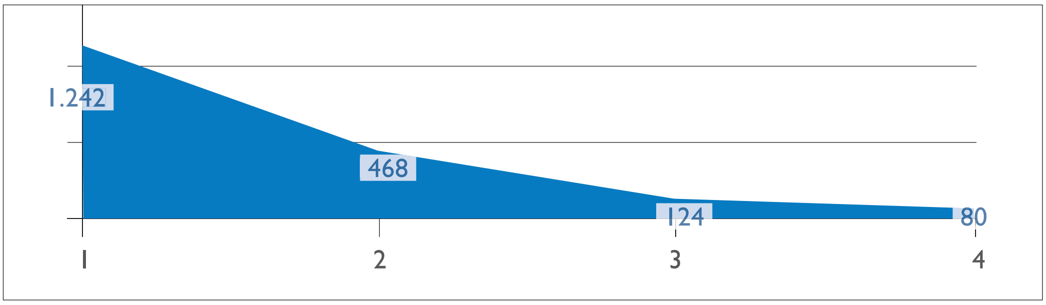
Figure 4: Illuminance at desk height of the artificial light in Classroom 4.

Figure 5 shows the average illuminances in the cross-direction for daylight and artificial light at 1 p.m. and 3 p.m., respectively. On a bright day at 3 p.m. the intensity of the daylight on the desks increases from 1242 lux at the window side of the room to 80 lux at the wall side. The total average illuminance of the daylight was 505 lux. At 1 p.m. the average values were 1099 lux at the window side of the room to 116 lux at the wall side, respectively with a mean value of 490.

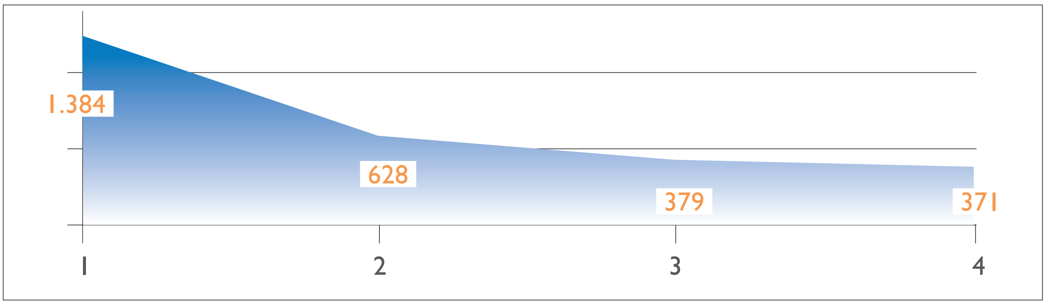
Class 4: LED + daylight at 3 p.m. Lighting intensity (Lux). Left (1) values from the desks near the windows, right (4) values from the desks near the wall.




Class 4: Daylight at 3 p.m. Lighting intensity (Lux). Left (1) values from the desks near the windows, right (4) values from the desks near the wall.




Class 4: Halogen + daylight at 1 p.m. Lighting intensity (Lux). Left (1) values from the desks near the windows, right (4) values from the desks near the wall.




Class 4: Daylight at 1 p.m. Lighting intensity (Lux). Left (1) values from the desks near the windows, right (4) values from the desks near the wall.

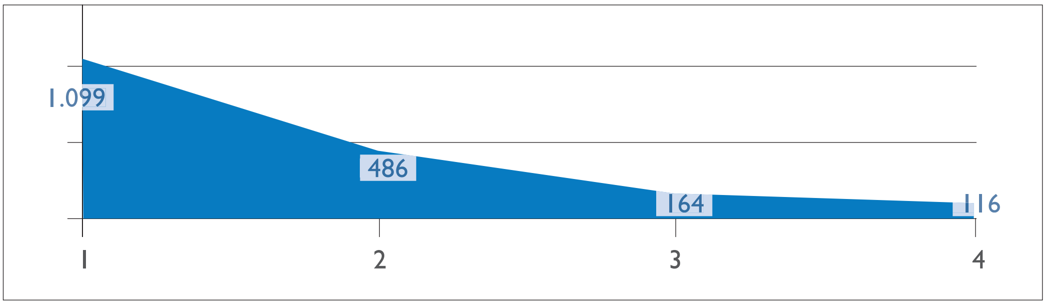



**Figure 5: Mean illuminance in the cross direction for daylight and artificial light.**

The largest difference between maximum and minimum illuminance was 1:14 and 1:20 in the cross-direction at 1 p.m. and 3 p.m., respectively. At 3 p.m. the illuminance of LED lighting and daylight together was 1654 lux for the window side of the room and 462 lux for the wall side. The total average illuminance of the daylight and LED lighting was 851 lux. At 1 p.m. the average values were 1384 lux, 371 lux and 712 lux, respectively. When artificial light was used, the largest difference between maximum and minimum light intensity improved up to 1:5 at 3 p.m. and 1 p.m.

The yield of artificial lighting results from the reduction of the mean illuminance of daylight and artificial light and the mean of the daylight. The illuminance value for the LED light component is 346 lux, which represents 41% of the total light. For the halogen light component, the illumination value is 222 lux, which is 31% of the total light.

The luminance of the front wall at the teacher's desk was measured at four points at a height of approximately 1.60 m in daylight as well as in artificial lighting. The blackboard in the middle of this wall creates the contrast. Two parabolic reflector (PAR) halogen spotlights (Radium PAR 38 FL, 100 W, 900 lm, E 27, 2900 K, CRI/Ra 100) directed at the wall, as well as the daylight, further determine the contrast values that were found. At 1 p.m., the mean luminance increased by 29% using all halogen lighting to a mean value of 53 candela/m2; at 3 p.m. the approximately 37% lower daylight component increased by 87% with both the LED and PAR halogen lighting to a mean value of 48 candela/m2.

The light measurement reveals the large differences of illuminance in the classroom. Obviously, the measurement of the potential effects of artificial light was impacted by daylight. However, the classrooms did not offer the possibility of dimming the artificial lighting or obscuring the amount of daylight that entered the room.

In Classroom 6, the position of each student changed during the experiment; however, the seating positions of the students in Classroom 4 did not change. In order to test the impact of daylight on all the exercises, the students in Classroom 4 sitting near the windows and far from the windows were considered separately.

### *Statistical Analysis*

The results of the exercises were evaluated using analysis of variance (ANOVA) and Tukey's honest significant difference (HSD) to determine if there were statistically significant differences between the variables. All data analyses were carried out using XLStat statistical software.

## Results and Discussion

### *Class 4*

### *Visual recognition*

The number of observations was counted. No significant differences were found between both lighting regimes (mean values: 5.38 (SD 2.19) [halogen], LED 5.76 (SD 2.06) [LED], $p = .223$). However, the students sitting far from the windows (n=8) performed better under LED lighting (mean values: 5.16 (SD 2.12) [halogen], 6.38 (SD 1.90) [LED], $p = .002$), while no significant differences were observed for the students sitting near the windows (mean values: 5.62 (SD 2.39) [halogen], 5.06 (SD 2.11) [LED], $p = .12$). This indicates that LED lighting had a positive effect on visual recognition and provided better visual discrimination for the students sitting far from the windows than the halogen lighting regime.

### *Visual discrimination*

The number of observed meanderings between the two photos was measured. The type of lighting regime had no effect on visual discrimination for the entire classroom (mean values: 7.86 (SD 0.80) [halogen], 7.60 (SD 1.58) [LED], $p = .49$) or for the students sitting near the windows or far from the windows.

### *Open retelling*

No significant differences were found between the halogen and LED lighting regimes. Text length (mean values: 103 (SD 12.11) words [halogen], 97 words (SD 12.11) [LED], p = .237) and the main topics (mean values: 10.0 (SD 3.83) [halogen], 9.4 (SD 3.46) [LED], p = .167 were measured. Moreover, no differences were observed for the students sitting near the windows and the students sitting far from the windows.

### *Drawing capacity*

Four drawing capacity criteria were determined: strength, harmony, colourfulness and fullness. Additionally, the total value of all four criteria was calculated.

Of the four criteria, no differences between the lighting regimes were observed for strength (mean values: 45.1% [halogen], LED 48.0% [LED], p = .379), harmony (mean values: 49.5 % [halogen], LED 45.1 % [LED], p = .180) and colourfulness (mean values: 48.0% [halogen], 42.0% [LED], p = .201). However, significant differences between the lighting regimes were found for fullness. Pictures drawn under halogen light had greater fullness (mean values: 57.9% [halogen], 46.1% [LED], p = .007). In half of the students sitting far from the windows, the difference was greater (mean values: 66.0% (SD 12.64) [halogen], 47.7 % (SD 15.41) [LED], p = .002).

The summary of all five drawing capacity criteria demonstrates the significant effects of the lighting regime (mean values: 50.1% [halogen], 45.3% [LED], p = .014). Again, the effect is enhanced in the group of students sitting far from the windows (mean values: 53.3% (SD 15.80) [halogen], 45.3% (SD 13.31) [LED], p = .003). No significant effect was found for the students sitting near the windows (mean values: 47.3% (SD 14.06) [halogen], 45.3% (SD 15.04) [LED], p = .430). This indicates that halogen lighting has a positive effect on drawing capacity and this lighting regime provides better discrimination for the students sitting far from the windows.

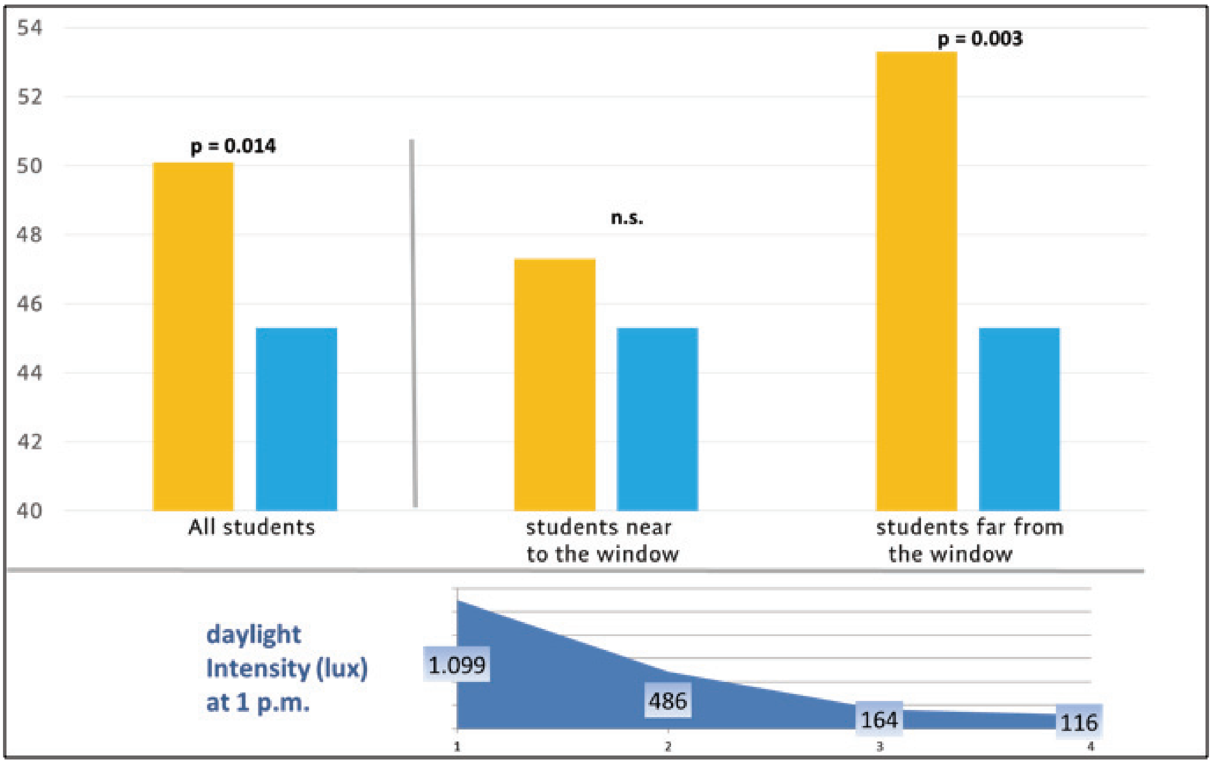



Figure 6: Effect of artificial light on the ability of children in 4th grade to paint. Total value of all criteria (characteristic value in percent). Influence of daylight. Lower part of the figure: Mean light intensities in the cross-direction for daylight.

**Table 2: Evaluation of drawing capacity. Descriptive statistic. Type of criteria (mean value %, SD in brackets) and p-values (bold type means significant results), (INC = incandescent or halogen light).**

| **Classroom 4 (n=21)** | | | | | |
|---|---|---|---|---|---|
| | strength | harmony | colourfulness | fullness | Total value of all criteria |
| LED | 48.1 (14.16) | 45.1 (9.83) | 42.0 (17.49) | 46.1 (14.45) | 45.3 (14.15) |
| INC | 45.0 (13.43) | 49.5 (14.04) | 48.0 (15.76) | 57.9 (16.14) | 50.1 (15.39) |
| p-value | 0.379 | 0.180 | 0.201 | **0.007** | **0.014** |
| **Classroom 6 (n=13)** | | | | | |
| | strength | harmony | colourfulness | fullness | Total value of all criteria |
| LED | 48.8 | 49.1 | 50.0 | 68.0 | 53.5 |
| INC | 48.4 | 55.0 | 50.7 | 73.6 | 56.9 |
| p-value | 0.737 | 0.358 | 0.891 | 0.214 | 0.167 |

*Classr 6*

*Visual recognition*

No significant differences between the lighting regimes were found (mean values: 5.79 incandescent], 5.58 [LED], p = .586).

*Text copying*

The length of the text, rate of mistakes and main topics were measured. Under incandescent lighting the students wrote significantly longer texts (mean value: 82.5 words [incandescent], 66.1 words [LED], p = .002). The rate of mistakes did not differ between the two lighting regimes (mean value of mistakes/100 words: 9.54 [incandescent], 9.95 [LED], p = .563). For the criterion, main topics, the students were tended to perform better under incandescent light (mean value: 16.9 [incandescent], 14.9 [LED], p = .052).

*Drawing capacity*

Four drawing capacity criteria were determined: strength, harmony, colourfulness and fullness. Additionally, the total value of the five criteria was calculated. No significant differences in drawing capacity were found for the four criteria or the total value of the five criteria (see Table 2), even if the rating under halogen lighting is slightly higher (e.g. total value of the five criteria 6.4%).

## General Discussion

Our study aimed to measure the effects of LED lighting and incandescent respectively halogen lighting on different students' skills under practical conditions. The illuminance and colour temperature of the lighting were similar in each case. The LED illuminance was slightly higher than the incandescent brightness (see Figure 1). LED light has more blue light and less red and infrared light in its spectrum than incandescent or halogen light. Furthermore, halogen and incandescent light have no radio frequency, less flicker and a different source temperature than LED.

In many cases, lighting has an influence on students' performance. Table 3 presents a summary of the results of the study's experiments.

**Table 3: Effect of lighting on students' behaviour. Which lighting regime performed better? Summary of the results of the three studies.**

| **Skills** | ***Alertness, concentration*** | ***Memory*** | ***Creativity*** | ***Visual recognition*** |
|---|---|---|---|---|
| **Exercises** | Mistakes in writing and calculation | Text copying and open retelling (completeness, text length) | Drawing of pictures | Written scene description, picture search |
| Study 1<br>class 5 | INC, INC, n.s. | INC | x | x |
| Study 2<br>class 3 | n.s., n.s. | x | INC | x |
| class 5 | INC, n.s. | x | x | x |
| class 7 | LED, n.s. | INC | x | x |
| Study 3<br>class 4 | x | n.s., n.s. | INC* | LED**, n.s. |
| class 6 | n.s. | INC, n.s.*** | n.s. | n.s. |

x = not detected, n.s. = not significant, INC = incandescent or halogen light significantly better, LED = LED light significantly better. Each item represents the results of one exercise.
*Enhanced differences in the student group with low daylight influence
**Significant differences only in the student group with low daylight influence
***Trends towards better INC results (p=0.052)

In those exercises that require more alertness and concentration, the results were heterogeneous. The type of lighting was found to have no significant effect for half of the exercises. In one case, in Class 7 (students ages 13 and 14), and for one exercise (mistakes in dictation), students made fewer mistakes under LED light. In the two cases with students in Class 5 (ages 11 and 12) (mistakes in dictation and copy text), the performance was improved under incandescent light.

The outcome is different with the tasks that are associated with memory. In three out of four classes, the students' memory was better under incandescent or halogen lighting. There were no differences in one class (Class 4, Study 3).

This result is similar to the finding observed for creativity, which was evaluated by having the students paint pictures. In two of the three classes, the pictures painted under incandescent or halogen lighting were better than the pictures painted under LED lighting. In one class (Class 6, Study 3), the differences were not significant.

The classification of the exercises into the skills of memory or creativity is not always unambiguous. For example, it is also possible to classify the text length of an open retelling under creativity instead of under memory. However, the impact of the type of lighting would change little because the results were found to be similar for both skills.

Visual recognition was only measured in two classes (Classes 4 and 6, Study 3). In Class 4, the students' visual recognition was better under LED lighting than halogen lighting; in Class 6, no difference was found.

Looking at the overall results, both types of lighting seem to address children's abilities differently. LED light shows limited advantages in tasks that are more related to concentration and alertness. Tasks that rather require memory and creativity skills were mostly better solved under incandescent or halogen light. Two studies were identified comparing LEDs with another light source under school conditions (Keis et al., 2014; Pulay & Williamson, 2018). In both studies, concentration and alertness were improved by LED light.

Keis et al. (2014) studied 17 to 21-year-old, mostly male secondary and vocational school students during winter to determine whether very bright white LED light in the early morning improves cognitive performance. The comparison lighting was fluorescent light. That study found that cognitive processing and concentration improved under LEDs. The blue-enriched lighting had no effect on short-term encoding and retrieval of memories. The students preferred the standard lighting, namely fluorescent light. However, Keis et al. (2014) concluded that the results could not be generalised to older or younger people.

In the study by Pulay and Williamson (2018), the influence of LED and fluorescent light with similar colour temperature on the behaviour of 23 students, aged 3–4 years, was compared. The childrens's involvement was measured using a snapshot observational method as an expression of alertness. The LED light increased the engagement of the children.

The results of Keis et al. (2014) correspond with results on the office environment (Viola et al., 2008). However, Werth and Steidle (2013) pointed out with regard to the factors of brightness and colour temperature that at high brightness and low colour temperature, not all cognitive tasks are optimally solved, but for learning and creativity tasks warmer light at lower brightness is more advantageous. Baron et al. (1992) and Fleischer (2001) came to similar conclusions.

The literature review shows that lighting intensity affects human capabilities in different ways. This supports the assumption that LED light improves only some skills.

Some of the findings reported in the literature indicate that LED light has the same effect as cold bright light, namely that it enhances alertness and concentration. In both of the other studies on the influence of LEDs on students' behaviour (Keis et al., 2014; Pulay & Williamson, 2018), there is no testing of creativity, social competence or communication. Our own results point to disadvantages of LED light on memory and creativity.

The introduction of LED lighting in classrooms leads to a higher (short-wave) blue light component and a lower red light component, and often the brightness is increased. On the basis of the findings reported in the current body of literature and the present study's results, it can be assumed that LED light will lead to an increase in alertness and concentration, and a reduction in memory, creativity, social competence and related tasks. Depending on the brightness and colour temperature, the effect would be stronger or weaker.

The literature search shows a widespread lack of studies on the effects of LED lighting on students. Apart from our study, the influence of LED light on students between the ages of 6 and 16 has not yet been tested. Moreover, no study has compared up to now the impact of LED lighting and halogen (and incandescent) lighting on children.

The limitations of our study are the tests applied and the test design. The tests we used were not standardized. The children should not be faced with unfamiliar questionnaires. Instead, together with the teachers involved, tasks were developed that corresponded to the usual tasks, or tasks were applied that were used in class anyway. In this way, the tests should not lead to a disruption of teaching. The overall study consists of three individual studies with their own test design. Therefore, a statistical comparison of the results of all partial studies is not possible. The first two studies are preliminary studies, while in the last all tests were replicated. However, the results of the three sub-studies are confirmatory.

For a complete assessment of the effects of blue-enriched lighting and other features of LEDs on children, factors such as social behaviour and creativity should be evaluated, not just cognitive performance. Until those studies are available, there is no scientific impact assessment justifying a ban on using lamps other than LEDs. This ban is imminent; therefore, there is an urgent need to discuss this topic.

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