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The Effect of Spectrum-Enhanced Artificial Light on Students' Cognitive Activities

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Abstract

Light is a powerful environmental factor with proven effects on human cognitive activity. This study investigated the effects of two types of light—LED with an enhanced long-wavelength spectrum and classic fluorescent—on concentration and attention of undergraduate students. Concentration was assessed through EEG, while attention was evaluated using d2 and TP psychometric tests. The experiment was carried out in a classroom equipped with both lighting systems, with each participant completing two testing sessions under different light conditions, separated by at least seven days to allow for washout. Results showed that during the first administration, LED lighting supported better performance across both EEG and psychometric measures compared to fluorescent light, suggesting enhanced concentration and attention. By the second administration, these differences were less evident, likely due to learning and task familiarization effects. Nonparametric ANOVA-type analyses further indicated that the effect of lighting on performance depended not only on the light type but also on the order of exposure, with students who switched from fluorescent to LED showing improvement, whereas the reverse sequence was associated with a decline. Overall, the findings suggest that LED lighting enriched in warm tones may positively influence attention and concentration, though results should be viewed as exploratory due to the small sample size.

Keywords: light spectrum; LED lamp; fluorescent lamp; concentration; attention; classroom; student; daylight; circadian light

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1. Introduction

Light has important effects on the human mind and body. Many papers available in the literature discuss these effects, for example [1–6]. Summarizing, the most significant effects of lighting could be categorized as follows:

- **Visual effects**, which influence our ability to see clearly. These include aspects such as brightness and contrast, visual acuity, color perception, and adaptation to light and dark. Effective lighting improves visibility, enhances safety and aesthetics, and supports task performance by making environments easier to navigate. It also contributes to setting the mood and atmosphere—ranging from the calming glow of sunset to the sharp illumination of workspaces.
- **Non-visual effects**, which impact the body's physiological and psychological functions. These involve hormonal balance, regulation of circadian rhythms and sleep, mood, well-being, comfort, concentration, alertness, and overall cognitive and work performance. Thoughtfully designed lighting has been shown to enhance productivity, reduce eye strain, and support mental health by lowering stress and fatigue. In contrast, inadequate lighting can cause discomfort, increase the risk of accidents, and contribute to long-term health concerns.

It is also important to mention that the effects of lighting can express directly on individuals, with fast manifestation (first-order effects), over a longer period (second-order effects), or indirect, when an individual affects others around him (third-order effects) [6].

There is a lot of research in the literature on the effects of artificial lighting sources on human cognitive performance, focused on both indoor and outdoor lighting.

Regarding outdoor lighting, a part of the research literature is focused on the impact of lighting on drivers, more specifically, on the detection of driver fatigue. Among these articles, Němcová et al. [7] present a summary of the methods for detecting driver fatigue, among which we mention the following: physiological indicators, such as electroencephalogram (EEG) and cardiogram (ECG) analysis, respiration rate, skin surface temperature, sweating rate, blood pressure, as well as kinesthetic indicators, such as facial expressions, eye blinking, reaction time, and involuntary body movements.

Some of the numerous studies on this topic show that there is a correlation between the lamps' colors and spectrum and the performance of drivers or their fatigue. Chakraborty et al. [8] evaluated drivers' obstacle detection times and EEG responses under two common road lighting sources: metal halide (MH) and high-pressure sodium (HPS) lamps, which differ significantly in color temperature and spectral output. Their findings indicate that MH lighting correlates with enhanced cognitive performance, whereas HPS lighting induces long-term fatigue due to heightened brain engagement, increased cognitive load, and elevated anxiety levels. Liu et al. [9] investigated how road lighting characteristics affect drivers' reaction times and visual performance in long tunnels. The study compared seven lamp types: five LEDs with varying CCTs and spectral distributions, along with metal halide (MH) and high-pressure sodium (HPS) lamps, under different tunnel lighting conditions. By analyzing both visual and non-visual effects, the authors proposed optimal CCT and spectral recommendations for LED lighting in long tunnels, balancing driving safety with energy efficiency.

As people in modern society spend approximately 90% of their time indoors [10], there are many studies focusing on the effects of artificial indoor lighting. Some of them investigate what are the most important characteristics of lighting or the geometry of the room that affect cognitive activities or user perception. For example, Dang et al. [11] studied how light affects the degree of fatigue experienced by students during class. The visual impact of lighting was characterized using 20 parameters including different luminance characteristics and CCT. The results identified an optimal lighting range that reduces visual

fatigue. They also developed a mathematical model for predicting visual fatigue, providing a quantitative tool for assessing and improving classroom lighting quality. Leccese et al. [12] showed that the most important lighting quality factors inside an educational building with respect to visual comfort are, in descending order of relevance, daylight brightness, luminance distribution, glare, daylight availability, lighting scenes, lighting uniformity, flicker effects, luminous flux regulation, surface treatments, overhead glare, illuminance, color rendering, color temperature regulation, circadian effects and color temperature. Nole Fajardo et al. [13] investigated the effects of lighting (CCT and illuminance level), room color, and room geometry (height, width) on students' cognitive functions. Results identified significant differences by gender and that illumination had the greatest influence, followed by color.

Other articles compare various artificial lighting systems, which differ in the position of the luminaires, the average illuminance level, and the characteristics of the sources, e.g., CCT. Barkmann et al. [14] compared seven types of scenarios: "Standard", "Focus on board", "Board only", "Concentrate", "Activate", "Relax", and "Extreme Relax". Findings reveal a considerable effect of these scenarios on both student achievements and attitudes. Between their results, the scenario "Concentration", which is characterized by a very bright, cold light (1060 lx, 5800 K) was correlated with a higher reading speed and reading comprehension. In another study, presented by Sleegers et al. [15], a system for the dynamic lighting of classrooms was designed to support the rhythm of activity in the classroom with four different lighting settings, "Energy", "Focus", "Calm", and "Standard", in succession during daytime. The results indicate a positive influence of the "Focus" lighting system on pupils' concentration performance, although some of the differences were not statistically significant. Some positive findings have been presented by Mott et al. [16], which compared the impact of dynamic lighting with four different lighting settings, "Energy", "Focus", "Calm", and "Standard", on third grade students. "Focus" lighting led to a higher percentage increase in oral reading fluency performance (36%) than did "Standard" lighting (17%), and no lighting effects were found for motivation or concentration. Hsieh et al. [17] investigated how lighting affects concentration during tasks requiring sustained attention. Two lighting conditions were considered: focused (on the worktable only) and general (in the room, without the focused component). By analyzing the electroencephalograms (EEG) and cortisol secretion, they showed that the level of concentration increases in the focused lighting environment for a short (15 min) task, but no significant differences were observed between the two systems in the case of a longer task (30 min).

Starting from the idea that natural light is highly variable during daytime, there are many articles which study the impact of dynamic lighting systems on work or study efficiency. Ru et al. [18] evaluated the effects of a daytime dynamic lighting model with an intensity and spectral variation pattern compared to a static office lighting setup on markers of well-being, cognitive performance, visual experiences, and sleep in a simulated office environment. The results revealed no consistent differences in results, but they suggest that a dynamic lighting approach represents a viable strategy for promoting diurnal well-being and nocturnal sleep, while also highlighting the necessity for further research into parameter and model improvement. Hartstein et al. [19] investigated how rapid, dynamic changes in light CCT can impact cognitive performance and comfort compared to traditional, static indoor light fixtures. They observed that a triangular wave pattern at a frequency of 0.03 Hz had a negative impact on participants' processing speed and reported ability to focus, while semi-random changes at a frequency of 0.03, 0.07, or 0.10 Hz produced no measured effects on participant task performance, alertness, mood, or comfort. De Kort et al. [20] has also used a dynamic setup in which the illumination level and CCT

had two important variations, decreasing from morning until noon, then returning to a high value around 2 p.m. and gradually decreasing until afternoon. The subjects, office workers, reported no significant differences in their need for recovery, vitality, alertness, headache and eyestrain, mental health, sleep quality, or subjective performance. However, the level of satisfaction was higher with the dynamic than the static lighting. Shishegar et al. [21] studied the influence of two lighting systems on the mood and cognitive functions of healthy older adults (older than 65), one with a constant CCT of 2700 K and another one with a dynamic CCT, starting at 6500 K in the morning and gradually decreasing, reaching 2700 K in the evening. Both systems had a gradually decreasing illuminance level, starting from 500 lx in the morning and reaching 100 lx in the evening. Significant improvements in mood and cognitive functions measured after exposure to both lighting conditions were observed, and there were significantly greater improvements for the dynamic CCT condition compared to the constant condition, suggesting that an all-day lighting scheme that follows the natural light/dark cycle could be an effective design solution. Benefits of a dynamic system have also been reported by Hoffmann et al. [22], who compared two scenarios: one with a CCT of 6500 K and a variable illumination level in the range 500–1800 lx and a second one with a constant CCT of 4000 K and a constant lighting level of 500 lx. The mood assessment revealed a benefit of variable light compared to constant light in the dimension ''Activity'', which increases, while ''Deactivation'' and ''Fatigue'' decrease.

Since the discovery of the intrinsically photosensitive retinal ganglion cells (ipRGCs) [23], a lot of research was dedicated to analyzing the non-visual effects of light. Many of these studies concentrate especially on the effects of the short-wavelength blue light part of the spectrum on the human physical and mental state, as it impacts melatonin secretion. Mills et al. [24] studied the effect of fluorescent light sources with a high CCT (17,000 K) on employees' well-being, functioning, and job performance, compared with a classic system, with 2900 K CCT fluorescent lamps. Individuals in the intervention arm of the study showed significant self-reported improvements in concentration, fatigue, alertness, daytime sleepiness, and work performance. Similar outcomes have been reported by Viola et al. [25] as a result of a similar study, involving a comparison between fluorescent lamps with 17,000 K and 4000 K CCTs. Another study, performed by Rautkylä et al. [26], indicated that exposure of the subjects to a fluorescent 17,000 K light source during afternoon lectures potentially assists students in maintaining higher levels of alertness, as compared with the results of the 4000 K fluorescent light sources. Keis et al. [27] demonstrate that blue-enriched spectrum lamps increase students' school performance (faster cognitive processing speed and better concentration). The systems compared consisted of both LED lamps, one with direct lighting (CCT 4000 K) and the improved one, with additional LED modules (CCT 14,000 K) for indirect lighting. Van de Putte et al. [28] explored the impact of an integrative lighting (IL) scenario in a factory by comparing two setups: a classic one, using LED luminaries (500 lux horizontal illuminance and approximately 50 lux m-EDI at eye level) and an IL one (1034 lux horizontal illuminance and 192 lux m-EDI at eye level). It was shown that IL settings improved sleep and alertness compared to classic lighting conditions. Cajochen et al. [29] compared two LED lighting sources: one that has a spectrum closer to the spectrum of natural daylight, with a higher melanopic strength (called "dayLED"), and one with a conventional LED source ("conLED"—with a typical LED spectrum, having a peak in the "blue" region). The authors found that the intervention led to better visual comfort, increased alertness, and a better mood in the morning and evening under the dayLED condition, while the daytime melatonin profile, psychomotor alertness, and working memory performance were not significantly different.

There are only a few articles that studied the influence of the long-wavelength red light part of the spectrum on humans. Among these, Figueiro et al. [30] demonstrated

that both blue and red light at low illumination levels (10 lux) and applied at night impact the alertness of subjects. Another study, conducted by Sahin et al. [31] demonstrated that exposure to short-wavelength (blue) or long-wavelength (red) light, both at 40 lux, during the afternoon increases alertness. Furthermore, Shahin et al. [32] demonstrated that red light (213 lux at the cornea) can increase short-term alertness, as shown by the significantly reduced response time and higher performance at concentration tests during the daytime, compared to "white light" (2568 K, 361 lux at the cornea). The authors suggest that small amounts of red light delivered by local desk sources could be used as a means of energy economy rather than increasing general ambient light levels.

In the literature, many articles concentrate mainly on the CCT and average horizontal illuminance level as the main parameters influencing circadian health, cognitive performance, and general well-being. The brain activity variation with these two parameters was demonstrated, for example, by Mostafavi et al. [33], who analyzed a matrix of 49 combinations (seven illumination levels and seven CCT levels) by an EEG-based method. Hawes et al. [34] studied the visual perceptual, affective, and cognitive implications of four lighting systems: one fluorescent (3345 K, 218 lux average illuminance) and three LED technologies (4175 K/191 lux, 5448 K/236 lux, and 6029 K/350 lux). The subjects exhibited the highest visual acuity, measured on symbol and color identification, symbol recognition, and symbol recognition tasks with LED lighting compared to fluorescent lighting, and this effect was greatest at the highest color temperature. Similar results were found by Lasauskaite et al. [35], which examined the influence of four LED systems (2800 K, 4000 K, 5000 K, and 6500 K CCTs and around 500 lux average illuminance for all systems) on mental effort. The results indicate that cognitive effort varies with lighting conditions, with warmer light correlating to higher effort and cooler light to lower effort. Mohebian et al. [36] compared the effect of different lighting levels (200, 500, and 1500 lux) of a system with fluorescent lamps (4500 K) and demonstrated that the attention of students increased with higher illumination levels and that the female participants showed a better performance and lower error rate in some tasks compared to men. A study by Yu et al. [37] demonstrates that the impact of the combination between the illuminance level and CCT on comfort and mental fatigue is not always obvious; that is, combinations with the highest values are not always the best performing or preferred. They investigated all combinations between four levels of illumination (300 lx, 500 lx, 750 lx, and 1000 lx) and three levels of CCT (3000 K, 5000 K, and 6500 K). For example, it was shown that a combination of 500 lx and the correlated color temperature of 5000 K resulted in the least fatigue. Also, the participants were more comfortable at 3000 K and 750 lx than at a high correlated color temperature and low illuminance.

As many research articles seem to associate a higher CCT with a higher melanopic quality of light, we must mention here the article of Esposito et al. [38], which demonstrates that CCT is not a reliable metric for predicting the non-visual effects of light in humans. It is shown that there can be significant variations in CS (e.g., Circadian Stimulus [39]) and m-EDI (melanopic equivalent illuminance [40]) at any CCT and fixed photopic illumination, making CCT as an indicator inappropriate for these effects.

Overall, from an evolutionary perspective, human physiology and psychology developed under natural light conditions, making it the optimal lighting source for our physical and mental well-being. The positive effects of daylighting are reported in several synthesis studies. For example, studies like [1–6] all seem to indicate that the presence of daylight has a strong positive influence on the cognitive performances and well-being of people in schools, offices, and homes. Given these benefits of daylight, there is a concern within the scientific community to develop tunable luminaires in order to realize an artificial light that can simultaneously satisfy both visual and non-visual parameters. Zheng et al. [41] present

an optimization approach for a 3-channel (RGB) LED luminaire, which works by adjusting the R,G,B intensities in order to obtain a high color rendering index (CRI) and a better CAF (Circadian Action Factor, defined in [42]). Marín-Doñágueda et al. [43] developed a method for designing four channel (two monochromatic and two white LEDs) lighting sources that can be adapted to different CCTs and circadian performances. Dai et al. [44] proposed a lighting solution based on dimmable LEDs (four channels: RGBW), which allows for tuning at the same time as the Circadian Stimulus, the CCT, and the CRI. Also, Nie et al. [45] implemented an adjustable artificial lighting system based on dimmable LEDs (five channels: RGBWW), which allows for the simultaneous adjustment of CCT and CAF and is also energy efficient.

The present work aims to explore how the artificial lighting spectrum affects cognitive performance in classrooms. For this purpose, we built an experimental setup consisting of an adjustable LED light system with three channels (2700 K, 4000 K, and 6500 K). We chose a fixed, static setting where the spectrum is richer in warm colors, towards the yellow and red part of the spectrum. This system has been compared with a classic cold light fluorescent lighting system (CCT ~= 5600 K), with a spectrum richer in "blue" light.

As an argument in support of our research idea, we should mention that there is a very reduced number of studies which aim to assess the effect of artificial lighting systems on the cognitive activities of students [13–16,19,27] or office workers [18,20,22,24]. Having this in mind, we believe that any work on this topic is positive and represents a gain of knowledge in the field.

Also, it should be emphasized that the quality of light influences the proper functioning of the nervous and endocrine systems and the secretion of hormones, such as melatonin (sleep hormone), adrenaline, cortisol (stress hormone), serotonin, dopamine, oxytocin, testosterone, estrogen, insulin, growth hormone, and other hormones [46–54], which govern the proper functioning of the body. In the modern world in which we live, we are exposed to artificial light much of the time, even during the day, and artificial light, having a different spectrum from natural light, can affect all of the above-mentioned hormones. Considering these complex effects and interactions produced by light in the human body, we think it is too simplistic to consider that only the blue part of the spectrum could play a role in stimulating the cognitive activities of human subjects by inhibiting melatonin production. Therefore, in our opinion, the whole range of spectral wavelengths would be worth investigating. In support of this claim comes a number of studies showing that red light can also stimulate attention [30–32]; these effects appear to be unrelated to melatonin suppression, though the authors do not propose an alternative cause.

In the present study, we have used psychological tests and an EEG analysis as tools to assess the individual attention and concentration ability of some undergraduate university students under two lighting conditions.

We have used the d2 test [55] and the Toulouse–Piéron test [56,57]. The choice of d2 test was motivated by the well-known reliability and validity of this test, demonstrated by its large usage in this research field [14–16,19,27,28] and its ease of use. As for the Toulouse–Piéron (TP) test, it is a classic psychometric tool, widely used internationally, and it has demonstrated its efficacy over the years. Although, as far as we know, it was not frequently used in this research area (we only found one study which employed it [36]), we chose to use a second test in order to have a stronger validation.

We also have used an EEG analysis, as it is one of the most used methods based on physiological indicators. This tool has been employed in many other studies and for various purposes, among which we mention the following: ref. [8]—performance of drivers in two street lighting conditions, ref. [9]—recognition of mental fatigue of drivers, ref. [17]—effects of different indoor lighting environments on concentration levels, ref. [29]—effects of the

light spectrum on visual comfort, mood, waking performance, and sleep, ref. [30]—effects of blue and red light on night alertness, ref. [33]—effects of illuminance and CCT on brain activity, ref. [58]—the effect of the medium on which the information is displayed (screen or paper) and the brightness of the medium on memory performance, ref. [59]—identification of mental fatigue of construction workers, ref. [60]—effects of evening light exposure on subjective and objective alertness and sleep, and ref. [61]—establishment of comfortable indoor lighting conditions. In our research, the EEG analysis was utilized in order to assess the concentration and fatigue level of participants under the two lighting conditions.

2. Materials and Methods

2.1. Classroom and Lighting Systems

In order to perform the experiment, a classroom in our department building was used. The dimensions of this classroom (in cm) are illustrated in Figure 1. The total area of this room is around 70 square meters. Only the central area, enclosed by the dotted line, was used for the experiment; that is, students were seated in benches only in that area, as this was the zone with best illumination uniformity.

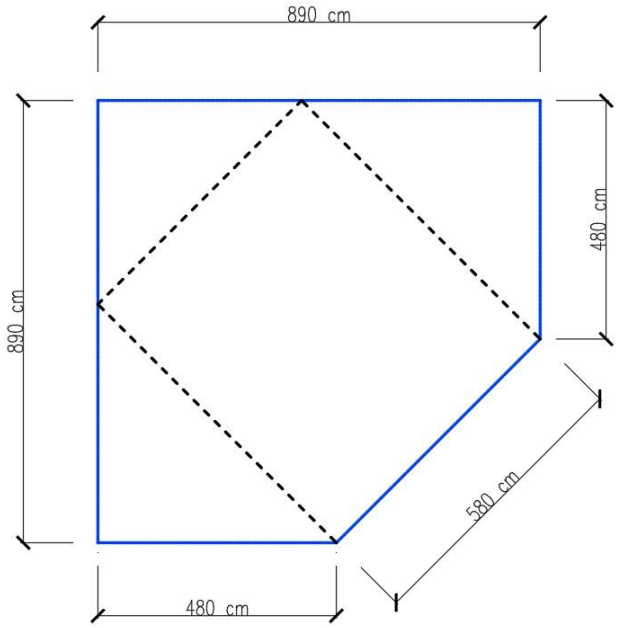

Figure 1. Sketch of the classroom used for the experiment (with blue—perimeter of the room, with dotted line—experimental work zone).

The original classroom lighting system was a fluorescent one, with each luminary equipped with 2 tubular fluorescent lamps of 120 cm with an approximate electrical power of 36 W. In order to perform the study, we have equipped the room with a system containing 14 luminaires, each formed by 3 linear LED strips, mounted inside rails. Each of these 3 LED strips constitutes a separate channel (Ch1, Ch2, and Ch3), and the luminous flux of similar channels of all luminaries can be controlled simultaneously, i.e., Ch1 of all luminaires and so on. Luminaires are powered by a controller, which in turn receives the control signals from three 0. . .10 V.d.c. signal sources, one for each channel (see Figure 2).

Each channel of the adjustable LED system had different correlated color temperatures and spectral distributions: Ch1—2700 K, Ch2—6500 K, and Ch3—4000 K. We have used high-quality LED strips, LumiFlex3098+ Toshiba-SSC LED Strip Sunlike CRI98 for Ch1 and Ch3 and LumiFlex3080 Seoul LED Strip for CH2. The first 2, i.e., Ch1 and Ch3, have a reduced part of the "blue" spectrum and an enhanced part of the warm colors, towards the yellow and red part of the spectrum. Adjustment of the light intensity could be performed

from the 3 rotary knobs that the signal sources were equipped with, mounted on the control panel, as can be observed in Figure 3.

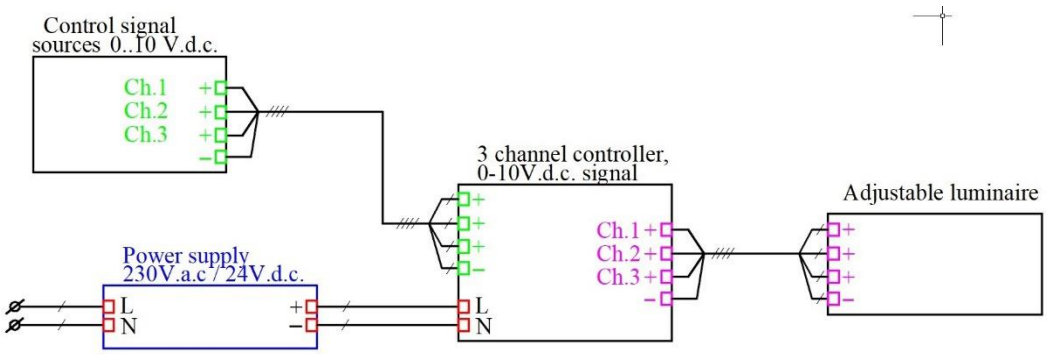

Figure 2. Schematic of the lighting control system.

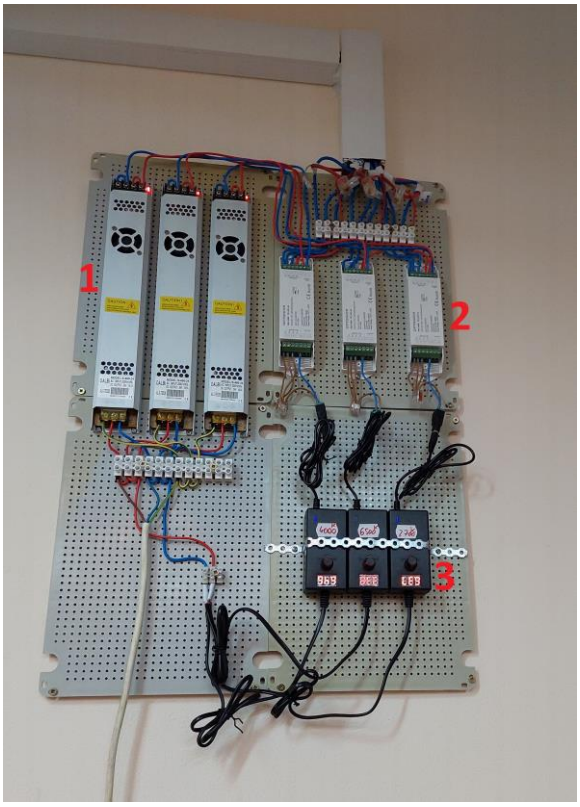

Figure 3. The control panel of the LED lighting system (1—power supplies; 2—controllers; and 3—control signal sources).

Figure 4 illustrates the classroom before and after implementation of the tunable LED lighting system. To ensure controlled testing conditions, all natural light sources were eliminated through complete window occlusion using opaque aluminum foil. The original fluorescent fixtures were ceiling-mounted at 3.4 m height, while the new LED luminaires were suspended from structural beams at 3.0 m elevation (measured from the floor up to fixture underside).

The absolute spectral power distributions of the two systems are presented in Figure 5. In order to measure the photometric quantities, we have used a LISUN LMS-6000 handheld spectroradiometer (typical measurement accuracy: ±1.0%, Spectral Range: 380–780 nm, and Spectral Resolution: 1 nm).



(**a**) (**b**)

Figure 4. The classroom before (**a**) and after (**b**) the installation of the adjustable LED lighting system. In Figure (**b**), both the fluorescent and LED systems are on, the fluorescent lamps are mounted on the ceiling, and the LED lamps are suspended.

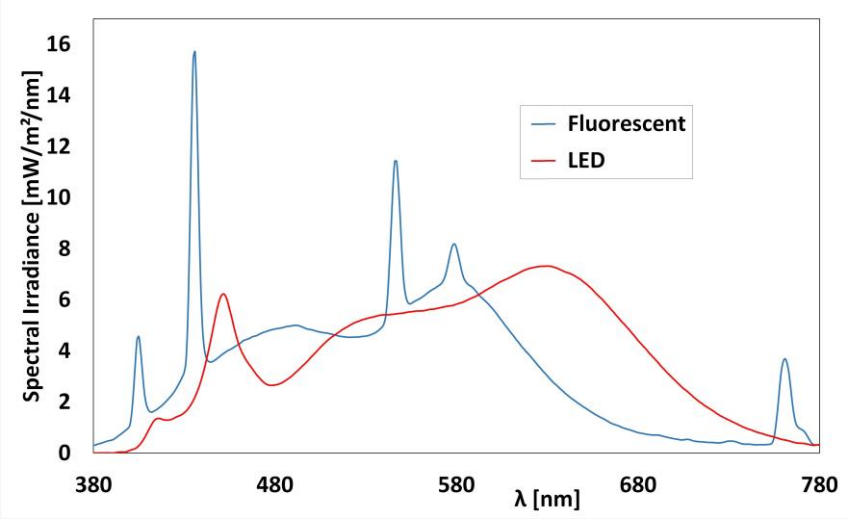

Figure 5. The absolute spectral power distribution (SPD) of the lighting systems.

The horizontal average values of photometric quantities (at desk level) are presented in Table 1. Also, the vertical average values of photometric quantities (at eye level) are presented in Table 2. These quantities are calculated as an average of 16 points, with each point corresponding to a desk in the central area of the classroom, where measurements were taken. During tests, students were placed only in that area.

Table 1. Horizontal average values of photometric quantities (at desk level).

	Average CCT [K]	Std. Dev. (CCT)	Average Illumination [lux]	Std. Dev. (Illumination)
Fluorescent	5642	46	405	27
LED	3624	16	400	26

Table 2. Vertical average values of photometric quantities (at eye level).

	Average CCT [K]	Std. Dev. (CCT)	Average Illumination [lux]	Std. Dev. (Illumination)
Fluorescent	5331	69	209	24
LED	3446	68	193	23

In Table 3, we present the calculated average melanopic quantities for our systems (vertical plane, at the level of the eye, and 1.20 m height). In order to assess these values, we have used the CS Calculator (2.0) available online [62]. We can notice that these values do not meet the recommended values [63] of 0.3 for CS, 250 for m-EDI, or 300 for CLA. We chose to keep these values because the aim of this research was to compare the two systems under the assumption of an approximately equal horizontal illuminance of about 400 lux, with this value being imposed by the existing fluorescent system. The value of minimum horizontal illuminance is the main factor by which lighting systems are currently dimensioned.

Table 3. Average values of melanopic quantities at eye level (CS—Circadian Stimulus; m-EDI—melanopic Equivalent Daylight Iluminance; and CLA—Circadian Light).

	CS	m-EDI	CLA 2.0
Fluorescent	0.26	152	221
LED	0.20	114	154

2.2. Experiments and Participants

Participants were all undergraduate students at Technical University of Iasi, Romania, and all Caucasian. The total duration of all experiments was 2 months (April–May 2025). As the experiments were paired, the two sessions were at least 7 days apart in order to keep a washout interval. Participants sat in the same location for each of the two testing sessions. All experiments took place between 10 a.m. and 2 p.m.

The project was approved by the Ethics Committee of the Technical University of Iasi, and, after being briefed on the study procedures, all participants read and signed an informed consent document before the experiments began. All students reported having no visual problems and receiving a sufficient amount of sleep (at least 7 h) on the night before the experiment. Researchers framed the study as an exploration of indoor environmental effects on cognitive performance and comfort without disclosing the specific focus on lighting changes.

Participants completed two experiments: Experiment 1 with paper tests (d2 and Toulouse–Piéron tests) and Experiment 2 with EEG recordings. Both experiments were completed across two sessions in a balanced crossover design, whose design is outlined in Table 4: the students were split into two equal groups, G1 and G2. In Phase 1, each group was tested under one type of lighting, and in Phase 2, they were tested under the other.

Table 4. Summary of experiments.

	Group	
Phase	**G1**	**G2**
Phase 1	LED	Fluorescent
Phase 2	Fluorescent	LED

Experiments 1 and 2 were performed on different groups of students, with characteristics synthetized in Table 5. All sessions were carried out in small groups of 5–7 persons for Experiment 1 and with only 1 person for Experiment 2.

Table 5. Characteristics of groups of participants in the experiments.

	Ages Between	Average Age	Number of Students by Gender [1]
Experiment 1	19–51	23.6	10/44 (F/M)
Experiment 2	19–25	21.8	0/16 (F/M)

[1] F—female/M—male.

Participants were not informed that the study was about changes in lighting; rather, they were told that researchers were exploring how features of an indoor environment impact cognitive performance and comfort. Before any experiment, students spent around 10. . .15 min in the room to acclimatize to the environment, while the researchers prepared the test papers or EEG montages.

2.3. Description of Psychological Tests

All subjects had to perform, in the following order, two attention tests: the Toulouse–Piéron (TP) test, a short break of 5 min, and then a d2 test. The results of both tests are proportional with the attention and concentration levels of the participants.

2.3.1. The TP Test

The subject was presented with a large matrix of symbols arranged in rows and columns (23 lines and 20 columns in our version [57]), typically very similar in appearance (a fragment is presented in Figure 6). They must identify and mark some specific target symbols, presented at the top of the worksheet, among a large field of distractors. For our version, the test was limited to exactly 4 min, after which a stop signal was given, and the subjects must mark the last analyzed symbol. After this, the score was calculated:

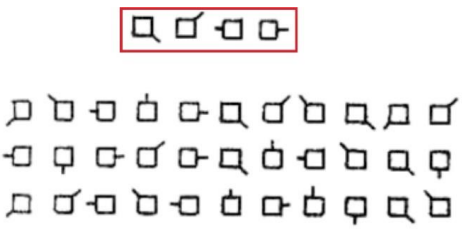

Figure 6. A fragment of the Toulouse–Pieron attention test (the symbols which should be identified are framed in the red rectangle).

TP_Score = T − (E + O)—indicating the quality of identifications (T is the total number of identifications (marked symbols); E is the number of errors, i.e., wrongly identified symbols; and O is the number of omissions).

2.3.2. The d2 Test

The subject is given a paper with 14 lines of characters (letters) — a fragment is presented in Figure 7. Each character is either a “d” or a “p”, accompanied by one to four small dashes above or below it. The subjects must scan each row and mark only the letters “d” with two dashes (either above, below, or one on each side) among a large field of distractors, which include the letter “p”, with or without dashes, and letter “d”, with 1, 3, or 4 dashes. The students are allowed exactly 20 s to complete a line, encouraging both speed and accuracy.

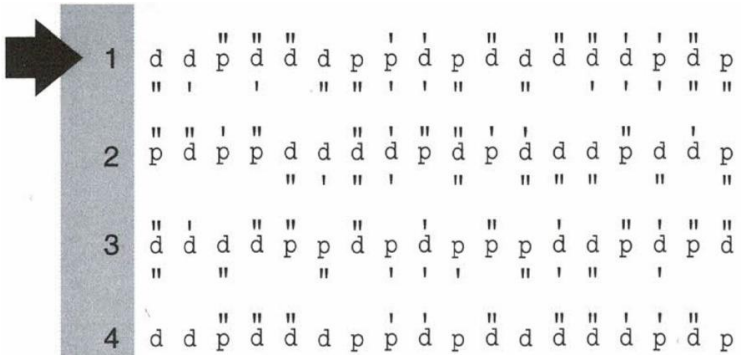

Figure 7. A fragment of the d2 attention test.

The performance indicators for this test are NT—the total number of symbols traversed, E1—the number of omission errors, and E2—the number of substitution errors. Attention performance score was calculated as the sum of the total number of marked symbols minus the number of errors, both omission and substitution:

$$D2_Score = (NT - E1 - E2).$$

2.3.3. The EEG Setup

For the EEG analysis, we have used a Contec KT88 electroencephalograph with 16 channels, which uses Ag/AgCl wet electrodes that can be placed on a mesh cap. The electrodes were measured relative to a reference electrode attached to the ear lobe. The EEG signal sampling frequency was 100 Hz. The typical setup of the EEG experiment in the classroom used for the study is illustrated in Figure 8.

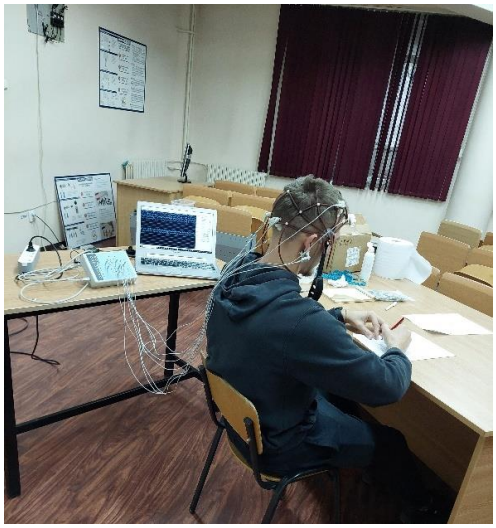

Figure 8. EEG setup (photo taken during preliminary tests, before the experiments).

As reported in the literature [17,59,64], in order to detect the changes in concentration or fatigue, the waves from Fp1 and Fp2 locations (10–20 international system) were recorded.

For each participant, EEG recordings were taken while the student was performing the TP test described in the previous paragraph. The same procedure was conducted twice, for each type of lighting setup: fluorescent and LED. Each recording lasted 4 min, from which the first 15 s were cut out, and the final analysis was performed on the remaining approximately 3 min and 45 s. It should be mentioned here that we did not use these TP test

results in the present paper, this was only used at this stage to induce subjects to perform an activity that required them to concentrate.

We have exported the data in the EDF format, then we used the EEGLAB tool to process the recordings. We used the Cleanline algorithm to remove 50 Hz power-line noise and then applied a band-pass filter between 0.5 and 49 Hz using pop_eegfiltnew function in EEGLAB. Then, the data was resampled at 200 Hz. The artifacts were removed by applying Clean Rawdata and ASR automatic procedure, followed by a visual inspection and manual removal of the remaining artifacts. Finally, we have re-referenced the data to the average between the two ear lobe electrodes.

The frequency bands examined were as follows: theta (θ) 4–8 Hz and beta (β) 12–33 Hz. The power spectral density (PSD) was estimated using Thomson's multitaper method, as implemented in the MNE-Python package, then the integration of the PSD over the θ and β frequency bands using the Simpson method, as implemented in the ScyPy-Python package, was performed in order to extract the total power for theta and beta bands.

A simplified diagram of the EEG data processing workflow is shown in Figure 9.

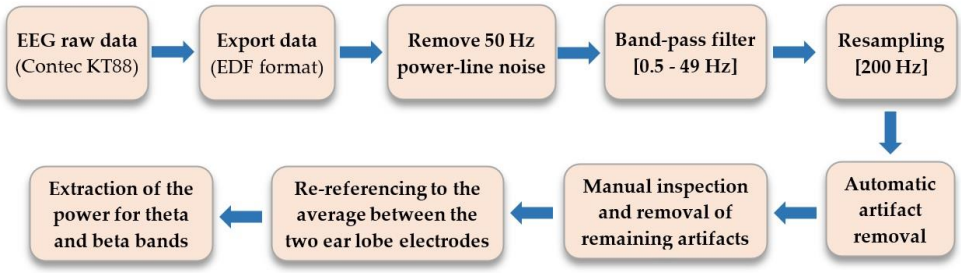

Figure 9. Processing steps for EEG analysis.

As a metric for concentration, we used the ratio between beta and theta waves, a numerical value which we will call the concentration score C_Score and which is calculated with the following formula:

$$C_Score = \frac{P_\theta}{P_\beta} \quad (1)$$

where P_θ is the total power for the theta band [μV^2] and P_β is the total power for the beta band [μV^2]. The interpretation of this result is straightforward: the smaller the ratio, the higher the level of concentration and vice versa [64–66]. As the Fp1 and Fp2 electrode locations are associated with cognitive processes such as logical attention, decision-making, task completion, and working memory [17,59], we chose to use the average value of total power for these locations.

3. Results and Discussion

3.1. Preparation and Processing of Experimental Data

The statistical analysis was performed using SPSS Version 26.0 and R version 3.5.0 (employing RStudio Version 2025.05.0) statistic software packages.

We analyzed the data using multiple statistical methods to account for the design of the study and to validate the robustness of the findings. Specifically, we compared the performance between groups where observations were independent (e.g., between different exposure orders), examined within-subject changes across lighting conditions (LED vs. fluorescent), and simultaneously tested within-subject effects of the lighting condition, between-subject effects of the exposure order, and their potential interaction. This multi-method approach ensured that both simple pairwise comparisons and more comprehensive factorial effects were evaluated.

Before performing any analysis, we checked the normality of the data. This assessment is essential, as parametric tests rely on the assumption that the data are approximately normally distributed, which ensures the validity of the resulting significance tests. For independent *t*-tests, this assumption concerns the raw scores within each group; for paired *t*-tests, it applies to the distribution of the difference scores between conditions; and for mixed ANOVA, it relates to the residuals of the statistical model across groups and conditions. When these normality assumptions are not met, non-parametric alternatives are more appropriate, as they do not rely on the data being normally distributed.

In our study, sample sizes were relatively small (27 subjects for the TP and d2 tests and 8 subjects for the EEG tests). For small samples like these, the Shapiro–Wilk test is considered the most robust method for assessing normality. Normality checks for all analyses (EEG, TP, and d2 results) indicated deviations from a normal distribution ($p < 0.05$), prompting, therefore, the use of non-parametric statistical methods. As a non-parametric alternative to the independent *t*-test, we applied the Mann–Whitney U test, which is particularly suitable for small sample sizes. For paired comparisons, we used the Wilcoxon signed-rank test, which evaluates the ranks of differences between paired observations without assuming normality. For mixed-design analyses, we employed the f1.ld.f1 test from the nparLD R package, a rank-based non-parametric alternative to mixed ANOVA, robust to non-normal distributions, and capable of evaluating both the main effects and interactions.

3.2. EEG Analysis

3.2.1. Mann–Whitney U Test

The results of the Mann–Whitney tests are presented in Figure 10 for Phase 1 and in Figure 11 for Phase 2. In Phase 1, the test indicated a significant difference between C_Scores depending on the type of light: U = 12.00, Z = −2.10, $p = 0.038$ (<0.05, significant), and the effect size r = 0.53. Participants exposed to LED light had significantly lower C_Score scores (mean rank = 6.00) than those exposed to fluorescent light (mean rank = 11.00), suggesting a better level of concentration (inverse of C_Score) when performing the task under the influence of LED light. In Phase 2, the test no longer indicated a significant difference between the two groups of subjects who performed the task under the two lighting conditions ($p = 0.834$), the mean ranks being very close: 8.75 for fluorescent and 8.25 for LED light.

Total N	16
Mann-Whitney U	12.00
Wilcoxon W	48.00
Test Statistic	12.00
Standard Error	9.52
Standardized Test Statistic	−2.10
Asymptotic Sig. (2-sided test)	**0.036**
Exact Sig.(2-sided test)	**0.038**

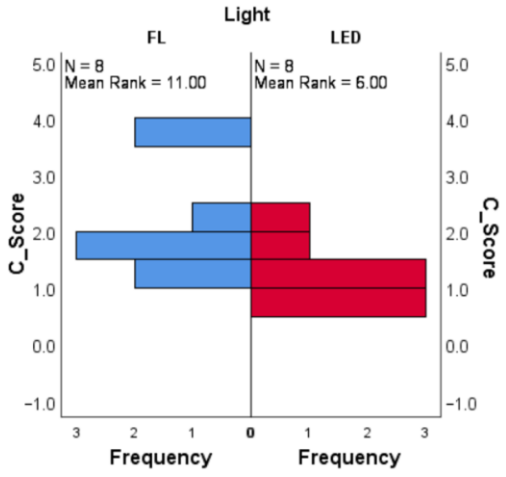

Figure 10. Results of the Mann–Whitney tests for Phase 1 of the EEG analysis.

Total N	16
Mann-Whitney U	30.00
Wilcoxon W	66.00
Test Statistic	30.00
Standard Error	9.52
Standardized Test Statistic	−0.21
Asymptotic Sig. (2-sided test)	0.834
Exact Sig.(2-sided test)	0.878

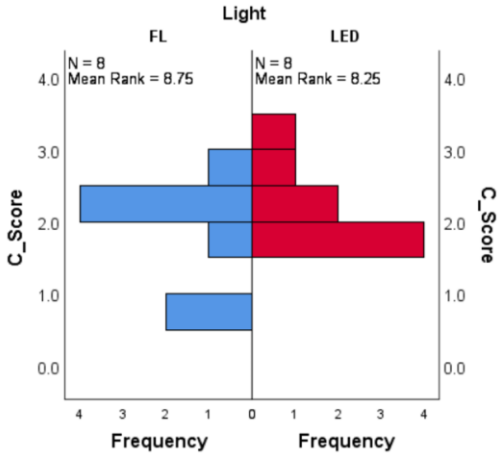

Figure 11. Results of the Mann–Whitney tests for Phase 2 of the EEG analysis.

3.2.2. Wilcoxon Signed-Rank Analysis

Analyzing the results of the crossover experimental design, using the Wilcoxon test for paired samples (Table 6 and Figure 12), we found that the average scores were lower under LED light (mean = 1.70, Std. Dev. = 0.69) than under fluorescent light (mean = 2.07, Std. Dev. = 0.92), indicating higher concentration (inverse of C_Score) under the influence of LED light. The Wilcoxon test for paired samples showed a marginally statistically insignificant difference (Z = 1.913, $p = 0.056$). However, the effect size r is moderate to large (r = 0.478), suggesting a trend in favor of LED light. Although the conventional significance threshold ($p < 0.05$) was not reached, the direction of the difference is clear: exposure to LED light was associated with lower scores, which corresponds to a higher concentration compared to fluorescent light.

Table 6. Results of the Wilcoxon signed-rank test for the EEG analysis.

Total N	16
Test Statistic	105.0
Standard Error	19.3
Standardized Test Statistic	1.91
Asymptotic Sig. (2-sided test)	0.056
Effect size, r	0.478
Average/Std. Dev., LED_light	1.70/0.69
Average/Std. Dev., Fluorescent_light	2.07/0.92

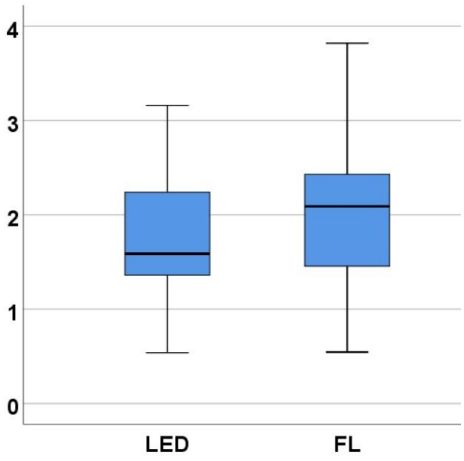

Figure 12. Boxplots of C_Scores for the EEG analysis.

3.2.3. f1.Ld.f1 Analysis

The nonparametric analysis for repeated measures, performed with the f1.ld.f1 test (Tables 7 and 8), revealed several significant effects. The main effect of the group was not significant (p = 0.132), indicating no reliable overall difference between G1 and G2. By contrast, the main effect of the light was significant (p = 0.014): RTE values differed between LED (0.430) and fluorescent (0.570), suggesting better concentration under LED light compared with fluorescent light. A significant phase effect (p = 0.001) was also observed, with higher scores (lower concentration) in Phase 2 (RTE = 0.594) than in Phase 1 (RTE = 0.406), regardless of lighting condition.

Table 7. ANOVA-type results for f1.ld.f1 test.

	Statistic	**df**	***p*-Value**
Group [1]	2.263	1	0.132
Light [2]	6.016	1	0.014
Phase [3]	10.694	1	0.001
Group × Light [4]	10.695	1	0.001
Group × Phase [5]	6.015	1	0.014

[1] Group: G1/G2 (see Table 4); [2] Light: Fluorescent or LED; [3] Phase: 1/2 (see Table 4); [4] Group × Light interactions; and [5] Group × Phase interactions.

Table 8. RTE [1]-type results for f1.ld.f1 test.

	Rank Means	**Nobs**	**RTE**
Group G1	13.625	16	0.410
Group G2	19.375	16	0.589
Light_LED	14.25	16	0.429
Light_Fluorescent	18.75	16	0.570
Phase 1	13.50	16	0.406
Phase 2	19.50	16	0.593
G1 × Light_LED/G1 × Phase1	8.375	8	0.246
G1 × Light_ Fluorescent/G1 × Phase2	18.875	8	0.574
G2 × Light_LED/G2 × Phase2	20.125	8	0.613
G2 × Light_ Fluorescent/G2 × Phase1	18.625	8	0.566

[1] RTE (Relative Treatment Effect).

Both interaction effects were significant. The Group × Light interaction (p = 0.001) indicates that the effect of lighting differed by group. Similarly, the Group × Phase interaction (p = 0.014) suggests that the change from Phase 1 to Phase 2 was not the same in both groups. Because of the crossover design, the values for these two interactions are identical in Table 8.

Examining the RTEs more closely, G1 showed a higher concentration (inverse of C_Score) under LED (0.246) compared with fluorescent light (0.574). In contrast, G2 showed a slightly higher concentration under fluorescent (0.566) than LED (0.613) light, though this difference was small. Thus, group differences were substantial under LED but minimal under fluorescent light. Regarding phase effects within the groups, G1—who received LED in Phase 1—displayed a high concentration initially, which declined in Phase 2 under fluorescent light. Conversely, G2—who received fluorescent in Phase 1—showed a lower concentration at baseline, with little improvement in Phase 2 under LED. This pattern highlights that performance changes across phases were influenced by the treatment sequence.

3.3. TP Test

3.3.1. Mann–Whitney U Analysis

The results of the Mann–Whitney tests are presented in Figure 13 for Phase 1 and in Figure 14 for Phase 2. In Phase 1, the test indicated a significant difference between TP_Scores depending on the type of light: U = 514.5, Z = 2.596, and $p = 0.009$. Participants exposed to LED light had significantly higher TP_Score scores (mean rank = 33.06) than those exposed to fluorescent light (mean rank = 21.94), suggesting a better level of concentration when performing the task under the influence of LED light. In Phase 2, the test no longer indicated a significant difference between the two groups of subjects who performed the task under the two lighting conditions ($p = 0.616$), the mean ranks being close: 28.57 for fluorescent and 26.43 for LED light.

Total N	54
Mann-Whitney U	514.50
Wilcoxon W	892.50
Test Statistic	514.50
Standard Error	57.78
Standardized Test Statistic	2.59
Asymptotic Sig. (2-sided test)	**0.009**

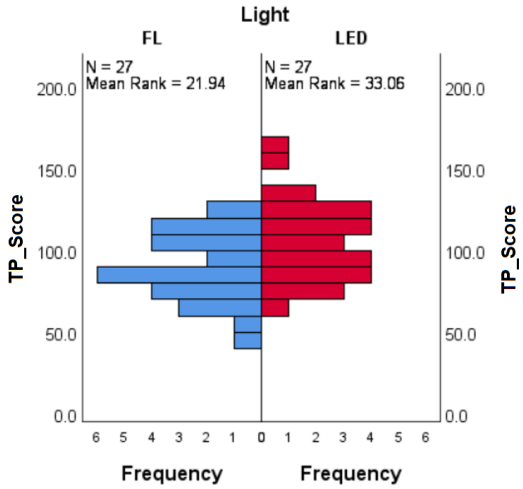

Figure 13. Results of the Mann–Whitney analysis for Phase 1 of the TP test.

Total N	54
Mann-Whitney U	335.50
Wilcoxon W	713.50
Test Statistic	335.50
Standard Error	57.78
Standardized Test Statistic	**−0.502**
Asymptotic Sig. (2-sided test)	**0.616**

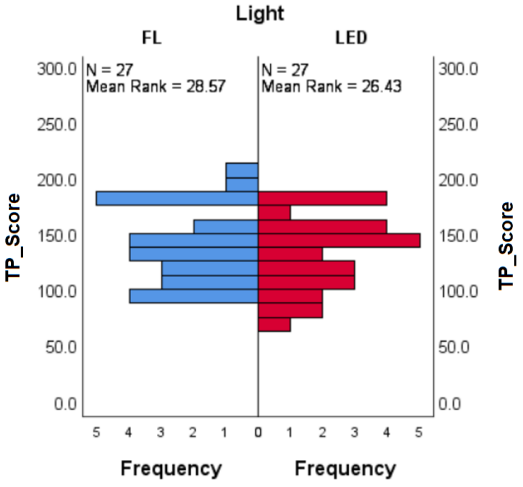

Figure 14. Results of the Mann–Whitney analysis for Phase 2 of the TP test.

3.3.2. Wilcoxon Signed-Rank Analysis

The Wilcoxon test for paired samples (Table 9 and Figure 15) showed a statistically insignificant difference (Z = −0.969, $p = 0.333$). Although the conventional significance threshold ($p < 0.05$) was not reached, analyzing the average values, we found that the scores were higher under LED light (mean = 119.6, Std. Dev. = 31.1) than under fluorescent light (mean = 114.2, Std. Dev. = 37.7), indicating a slightly higher concentration under the influence of LED light.

Table 9. Results of the Wilcoxon signed-rank test for the TP analysis.

Total N	54
Test Statistic	630.0
Standard Error	116.1
Standardized Test Statistic	−0.969
Asymptotic Sig. (2-sided test)	0.333
Average/Std. Dev., LED_light	119.6/31.1
Average/Std. Dev., Fluorescent_light	114.2/37.7

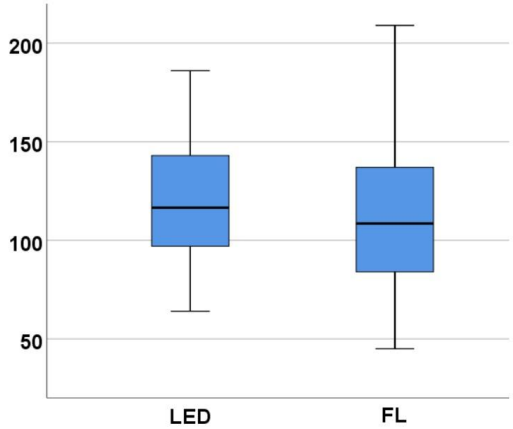

Figure 15. Boxplots of TP_Scores for the TP analysis.

3.3.3. f1.Ld.f1 Analysis

The results of the nonparametric f1.ld.f1 analysis for the Toulouse–Piéron test, presented in Tables 10 and 11, reveal several interesting aspects. One can notice that there are no significant overall differences between the groups.

Table 10. ANOVA-type results for f1.ld.f1 test.

	Statistic	**df**	***p*-Value**
Group [1]	3.168	1	0.075
Light [2]	4.964	1	0.025
Phase [3]	142.537	1	0.000
Group × Light [4]	142.537	1	0.000
Group × Phase [5]	4.964	1	0.025

[1] Group: G1/G2 (see Table 4); [2] Light: Fluorescent or LED; [3] Phase: 1/2 (see Table 4); [4] Group × Light interactions; and [5] Group × Phase interactions.

There are clear differences between light conditions (p = 0.025), with the LED light performing better than the fluorescent light (RTE values are 0.5297 and 0.4703, respectively).

The effect of the phase is also significant (p = 0.000); as in the case of the EEG analysis, the subjects performed better in the second phase, regardless of the type of light they were exposed to (the RTE values are 0.3410 for Phase 1 and 0.6589 for Phase 2).

The interactions Group × Light and Group × Phase are both significant (p = 0.000 and p = 0.025, respectively). It can be noticed that both groups perform better in Phase 2 compared to Phase 1, group G1 from RTE = 0.423 in Phase 1 to RTE = 0.681 in Phase 2, and group G2 from RTE = 0.258 in Phase 1 to RTE = 0.636 in Phase 2. Analyzing the Group × Light interaction, it can be observed that group G1 performed better under fluorescent light (RTE = 0.681) than LED (RTE = 0.423), whereas group G2 performed better under LED (RTE = 0.636) than fluorescent (RTE = 0.258). There is a substantial difference in groups' scores under fluorescent light but a smaller one under LED light. Also, we can

notice that the differences in scores between Phases 1 and 2 are higher for group G2 than for group 2.

Table 11. RTE [1]-type results for f1.ld.f1 test.

	Rank Means	Nobs	RTE
Group G1	60.167	54	0.552
Group G2	48.833	54	0.447
Light_LED	57.704	54	0.529
Light_Fluorescent	51.296	54	0.470
Phase 1	37.333	54	0.341
Phase 2	71.666	54	0.658
G1 × Light_LED/G1 × Phase1	46.204	27	0.423
G1 × Light_ Fluorescent/G1 × Phase2	74.130	27	0.681
G2 × Light_LED/G2 × Phase2	69.204	27	0.636
G2 × Light_ Fluorescent/G2 × Phase1	28.463	27	0.258

[1] RTE (Relative Treatment Effect).

3.4. D2 Test

3.4.1. Mann–Whitney U Analysis

The results of the Mann–Whitney tests are presented in Figures 16 and 17. In Phase 1, the test indicated a significant difference between D2_Scores depending on the type of light: U = 500.5, Z = 2.353, and p = 0.019. Participants exposed to LED light had significantly higher D2_Score scores (mean rank = 32.54) than those exposed to fluorescent light (mean rank = 22.46), suggesting a better level of concentration when performing the task under the influence of LED light. In Phase 2, the test no longer indicated a significant difference between the two groups of subjects who performed the task under the two lighting conditions (p = 0.081); this time, the mean rank is higher for fluorescent light (31.24) than for the LED light (23.76).

Total N	54
Mann-Whitney U	500.50
Wilcoxon W	878.50
Test Statistic	500.50
Standard Error	57.79
Standardized Test Statistic	2.35
Asymptotic Sig. (2-sided test)	**0.019**

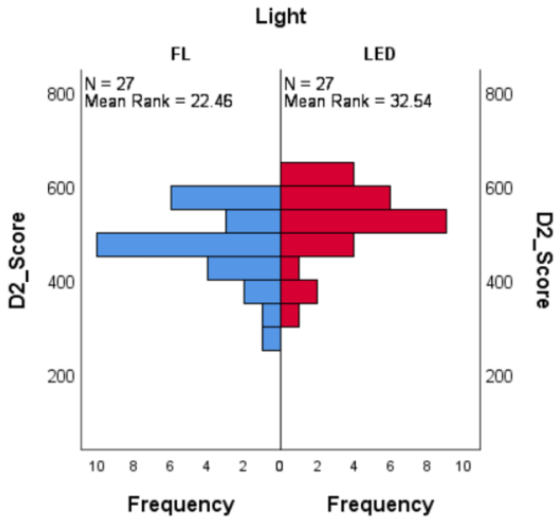

Figure 16. Results of the Mann–Whitney analysis for Phase 1 of the d2 test.

Total N	54
Mann-Whitney U	263.500
Wilcoxon W	641.500
Test Statistic	263.500
Standard Error	57.794
Standardized Test Statistic	−1.748
Asymptotic Sig. (2-sided test)	**0.081**

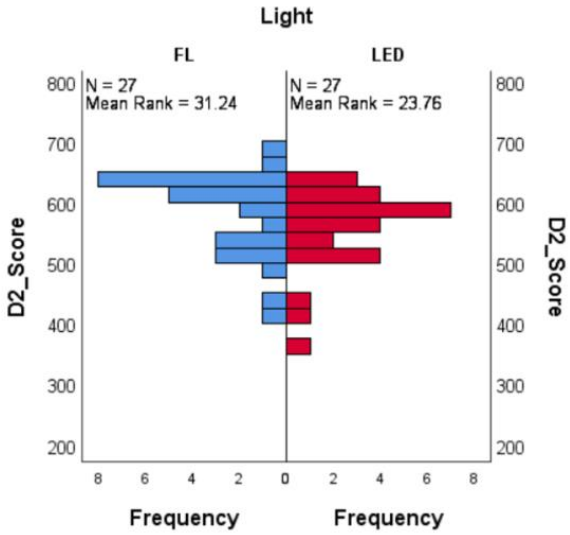

Figure 17. Results of the Mann–Whitney analysis for Phase 2 of the d2 test.

3.4.2. Wilcoxon Signed-Rank Analysis

The Wilcoxon test results (Table 12 and Figure 18) showed a statistically insignificant difference ($Z = -0.939$, $p = 0.348$). Although the conventional significance threshold ($p < 0.05$) was not reached, analyzing the average values, we found that the scores were higher under LED light (mean = 538.5, Std. Dev. = 71.9) than under fluorescent light (mean = 528.9, Std. Dev. = 90.1), indicating a slightly higher concentration under the influence of LED light.

Table 12. Results of the Wilcoxon signed-rank test for the d2 analysis.

Total N	54
Test Statistic	633.5
Standard Error	116.1
Standardized Test Statistic	−0.939
Asymptotic Sig. (2-sided test)	0.348
Average/Std. Dev., LED_light	538.5/71.9
Average/Std. Dev., Fluorescent_light	528.9/90.1

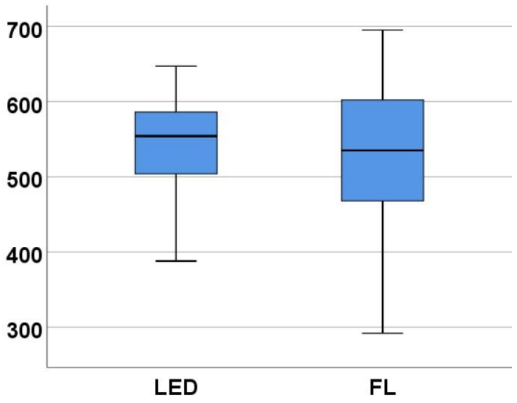

Figure 18. Boxplots of D2_Scores for the d2 analysis.

3.4.3. f1.Ld.f1 Analysis

The nonparametric f1.ld.f1 analysis for the d2 test (Tables 13 and 14) revealed a significant difference between the groups ($p = 0.03$), with G1 performing better overall (RTE = 0.567) than G2 (RTE = 0.433). Although the main effect of the light was not signifi-

cant, Table 14 shows moderate RTE differences, with a slightly better performance under LED (0.515) compared to fluorescent (0.485) light. The main effect of the phase was highly significant ($p < 0.001$), with participants performing better in Phase 2 (RTE = 0.635) than in Phase 1 (RTE = 0.365), regardless of the light condition—an effect also observed for the TP test. As shown in the interaction section of Table 14, G1 performed better under fluorescent light (RTE = 0.686) than under LED (RTE = 0.447), whereas G2 performed better under LED (RTE = 0.584) than under fluorescent (RTE = 0.283) light. The significant Group × Light interaction ($p < 0.001$) indicates, similar to the TP test, a pronounced group difference under fluorescent light but only a minor difference under LED. By contrast, the Group × Phase interaction was not significant ($p = 0.257$), indicating that the Phase 1–Phase 2 improvement was comparable across groups.

Table 13. ANOVA-type results for d2 test.

	Statistic	df	*p*-Value
Group [1]	4.550	1	0.032
Light [2]	1.287	1	0.256
Phase [3]	98.125	1	0.000
Group × Light [4]	98.125	1	0.000
Group × Phase [5]	1.286	1	0.256

[1] Group: G1/G2 (see Table 4); [2] Light: Fluorescent or LED; [3] Phase: 1/2 (see Table 4); [4] Group × Light interactions; and [5] Group × Phase interactions.

Table 14. RTE [1]-type results for d2 test.

	Rank Means	Nobs	RTE
Group G1	61.703	54	0.566
Group G2	47.296	54	0.433
Light_LED	56.166	54	0.515
Light_Fluorescent	52.833	54	0.484
Phase 1	39.944	54	0.365
Phase 2	69.055	54	0.634
G1 × Light_LED/G1 × Phase1	48.814	27	0.447
G1 × Light_ Fluorescent/G1 × Phase2	74.592	27	0.686
G2 × Light_LED/G2 × Phase2	63.518	27	0.583
G2 × Light_ Fluorescent/G2 × Phase1	31.074	27	0.283

[1] RTE (Relative Treatment Effect).

4. Discussion

A global examination of the data highlights the partial convergence of results across the three statistical approaches (Mann–Whitney, Wilcoxon signed-rank, and f1.ld.f1) applied to the EEG, TP, and d2 tests. It should be noted once again that, in the following, when we refer to test performance, we are talking about concentration ability, in the case of the EEG analysis, and attention level, in the case of the TP and d2 tests. In the case of the EEG analysis, the concentration level is the inverse of the C_Score result, and in the case of the TP and d2 tests, the scores are directly proportional to the performance.

The Mann–Whitney tests revealed a significant difference in participants' Phase 1 scores: those exposed to LED light demonstrated higher performances compared to those exposed to fluorescent light. The difference was no longer significant in Phase 2. This behavior is consistent for all three analyses, EEG, TP, and d2.

The Wilcoxon analysis revealed, across all three measures, a slight performance advantage for LED light, although this difference did not reach statistical significance.

The results of the f1.ld.f1 analysis are not as consistent as those of the other two analyses. Thus, for the EEG and TP tests, there were no significant differences between the

performances of groups G1 and G2, while the d2 test showed that group G1 performed better overall. A significant effect of the lighting type was found in both the EEG and TP tests: participants tested under LED light showed a higher performance compared to those tested under fluorescent light. For the d2 test, although the comparison of performance by light type was not significant, the RTE results show that the performance of students was slightly better under LED light.

In our view, the divergent d2 test results may reflect the differential sensitivity of this specific attention task to spectral variations, possibly due to its emphasis on sustained visual discrimination and speed of processing, engaging different neural mechanisms compared to the TP test. It is also possible that, with a larger sample size, such random influences would have been attenuated, and the group differences would no longer be apparent.

For all three tests, the effect of the phase was significant. In the EEG test, performance decreased in the second phase for both groups (G1 and G2), whereas in the TP and d2 tests, performance increased. We interpret this as evidence of a learning effect: participants became familiar with the structure of the tasks and responded more efficiently on the second application regardless of lighting condition, although the manifestation of this effect differed across measures. In the EEG test, where performance reflects concentration, familiarity with the task may have reduced the need for sustained focus in the second phase. By contrast, in the TP and d2 tests, which assess attention, the learning effect likely enhanced recognition speed and accuracy, leading to improved scores in the second phase. Based on these observations, a larger parallel-groups design may be a more appropriate approach for this type of research than the crossover design employed in the present study.

Across all three measures—EEG, TP, and d2—the lighting type and phase influenced performance, but the patterns differed. The effect of lighting showed a consistent interaction with the group: each group tended to perform better under one type of light but which light was optimal differed between groups. The magnitude of group differences varied with the lighting condition, generally being more pronounced under fluorescent light and smaller under LED. The Group $\times$ Phase interaction was significant for EEG and TP, indicating that changes across phases depended on group and treatment order, but it was not significant for d2, suggesting more uniform phase-related improvements. Overall, the study of interactions did not reveal any coherent or generalizable trends. Nevertheless, the interaction results indicate that the type of light has a real effect on performance and that this effect depends not only on the light itself but also on the order in which it is applied. A detailed investigation of these interactions is beyond the scope of this article and would require a study specifically designed to address this question.

Globally, our research seems to suggest that, although fluorescent lighting had higher melanopic values (Table 3), LED lighting with an enhanced warm spectrum was more effective at promoting student attention and concentration. As noted in the introduction section, previous research on the cognitive effects of artificial lighting is limited, with only a small number of studies focusing on students [13–16,19,27] or office workers [18,20,22,24]. The conclusion of most of these articles is that artificial lighting enriched with short wavelengths has positive effects on cognition. However, there are significant differences between our study and these studies which could influence the conclusions. In [13], the authors used a limiting environment created with the help of VR, which, although very useful for research, cannot completely replace immersion in the real environment of a classroom. Articles [14–16] focus on specific lighting, with very high illumination values (for example, the "Concentration" setup in [14] and the "Focus" scenario in [15,16] are all above 1000 lx horizontal illumination). The research in [19] focuses on the effect of rapid CCT changes on subjects, and articles [18,20,22] also study the effect of dynamic lighting, both in illumination and CCT. Unlike the studies mentioned here, our research investigated the case of

artificial, static lighting in a classroom, with an average lighting level typical for this type of room, in order to explore the effects on cognitive activities. Research closer to what we propose would be [24] and [27], both concluding that blue-enriched spectrum lighting can improve cognitive activities. The differences we obtained compared to these articles could be due to various factors, such as

- The type of lighting: In [24], the authors used mixed lighting, artificial supplemented with natural (for their circadian-enhanced artificial lighting system, the contribution of natural lighting was 40%), while our research explored the case of purely artificial lighting.
- The lighting mode: In our case, direct lighting was used, which is the most common in classrooms, while in [27], indirect lighting was used (up-lighting bouncing back from the white ceiling). As the authors state, diffused, overhead light—like natural daylight from the sky—is believed to be more effective at triggering non-visual biological responses than direct, focused light from luminaries.
- The duration spent in the respective environment was 14 weeks for [24] and 5 weeks for [27]. In our case, exposure to the studied lighting was only on the day of the tests for a relatively short period, aiming for short-term effects. In this case, the differences could be due to first-order effects in our case and second-order effects (see [6]) in the case of studies [24,27].
- The time of testing was between 8 a.m. and 8 p.m. and between 7:20 and 9:00 a.m. in [24] and [27], respectively, while we conducted testing between 10 a.m. and 2 p.m. It is possible that the time of testing also affects cognitive activities differently, although, to our knowledge, this has not been studied in depth in the literature.
- The testing method: In our case, we used several quantitative tests, while in [24], the effects were determined through self-assessment. We consider quantitative tests to be more effective for objectively evaluating attention and concentration, whereas self-assessments primarily capture the subjective experience of these processes.

5. Limitations of the Study

One of the limitations of this research is the relatively small number of participants. The EEG study was especially difficult to implement due to the complexity of the procedure and the resources required. We must mention here that during the research we encountered some difficulties due to the variable availability of the subjects; because of this, our research comprised several testing sessions and spanned over a longer period of time. The small sample size, particularly for the EEG study, limits the statistical power and generalizability of the conclusions to larger populations. Although the crossover design allowed each participant to be compared with themselves, individual variability remains a factor that may influence the reproducibility of results in larger samples. Future studies should use a larger number of subjects and a stricter control of subject availability and experiment duration.

Another limitation was the learning effect, familiarization with the task, and adaptation. Subjects performed better on the second application, which meant that they had already familiarized themselves with the task. Learning ability also varies greatly from one individual to another and depends on many personal factors. This may increase performance regardless of lighting conditions, affecting both the magnitude of the observed effects and the reproducibility of results across studies. In future studies, the learning effect may be mitigated by longer breaks between sessions or the use of alternative test variants, such as a parallel-groups design.

We also consider that future research should assess the effects of temporal light modulation (flicker), using accurate measurement methods or, where feasible, testing under flicker-free conditions, as flicker may influence both visual comfort and cognitive

performance. The lack of such precise control poses a risk to the reproducibility of results, as variations in flicker characteristics can affect findings across studies.

Recognizing these limitations, it should be noted that the results provide preliminary insights into the effects of lighting on attention and concentration but should be interpreted with caution. Future studies, with the improvements outlined above, will contribute to increasing the generalizability and reproducibility of the conclusions.

6. Conclusions

This study investigated the effects of two types of light—LED with an enhanced long-wavelength spectrum (warm tones) and classic fluorescent—on concentration, assessed through neurophysiological recordings (EEG), and on attention, evaluated using psychometric tests (d2 and Toulouse–Piéron).

The analysis of the tests showed that, during the first administration, LED light supported a better performance compared to fluorescent light. The statistically significant differences observed in Phase 1 for both EEG and psychometric tests indicate enhanced concentration and attention under LED exposure. In the second administration, the effects of light type were less clear, likely due to learning effects and task familiarization. Non-parametric ANOVA-type analyses indicated that the effect of lighting on performance is influenced not only by the type of light but also by the order of its application.

Overall, this research indicates that LED lighting with a spectrum richer in warm colors can support students' attention and concentration, even though the melanopic values reported in Table 3 are higher for fluorescent lighting. The consequence of this fact is that there must be other mechanisms, besides the inhibition of melatonin secretion, by which cognitive activities are supported. The complex interaction between daylight dynamics and individual human responses remains difficult to quantify and is an important topic for future research. As highlighted in [67], although many features of daylight can be replicated by artificial lighting, it has not yet been demonstrated that the wide range of holistic benefits associated with daylight can be reproduced. Given these limitations, and the fact that an artificial source identical to sunlight is unlikely to be developed in the near term, we believe it is still worthwhile to investigate the effects of lighting sources that approximate sunlight more closely. The findings of the present study, which appear to contradict some previous reports, underscore the need for further research into the mechanisms by which light influences cognition and human physiology. Considering the modest sample size and procedural complexity, the present results should be viewed as exploratory; nevertheless, it provides a valuable foundation for future studies with larger samples, more robust experimental designs, and a deeper integration of EEG data with psychometric performance measures.

Lighting is a major component of energy consumption in educational and office buildings, and the transition from fluorescent to LED systems is central to sustainable building strategies. Beyond efficiency, our study emphasizes that the choice of lighting also impacts human well-being and cognitive functioning, which are key aspects of sustainable learning and working environments. Our findings contribute to the broader understanding of how lighting design can simultaneously meet energy-saving goals and support human performance, addressing sustainability in its environmental, economic, and social dimensions.

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Abbreviations

The following abbreviations are used in this manuscript:

CAF	Circadian action factor
CCT	Correlated color temperature of light
CRI	Color rendering index
CS	Circadian stimulus
D2/d2	D2 attention and concentration test
ECG	Electrocardiogram
EEG	Electroencephalogram
m-EDI	Melanopic equivalent illuminance
TP	Toulouse-Piéron attention and concentration test

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