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Effects of Light Correlated Color Temperature (CCT) on Sustained Attention and Reading Comprehension: A Study in Albanian Elementary Classrooms

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Abstract

This study examines how differences in the spectral composition of classroom lighting, expressed as Correlated Color Temperature (CCT), influence the sustained attention and reading comprehension of Albanian elementary students. Research indicates that exposure to short-wavelength light can heighten physiological arousal, while Cognitive Load Theory emphasizes that environmental conditions influence working memory allocation. Despite this, both international and Albanian school lighting standards largely address only light intensity. Using a quasi-experimental design, 60 fourth-grade students were assessed on attention and reading comprehension in classrooms equipped with either 5000K or 4000K LED lighting, with illuminance levels held consistent across conditions. Students exposed to 5000K lighting demonstrated significantly higher scores on measures of concentration, attentional performance, and reading achievement. The findings suggest that optimizing the spectral composition of classroom lighting—specifically utilizing cooler CCTs for focused tasks—can be a viable, low-cost intervention to enhance cognitive engagement and academic performance in elementary education.

Keywords: Lighting, Cognitive Load Theory, Sustained Attention, Reading Comprehension, Albania, Elementary Education

1. INTRODUCTION

Classroom environments significantly affect how students regulate and allocate cognitive resources. According to Cognitive Load Theory, working memory capacity is limited and learning is optimized when instructional and environmental conditions minimize extraneous cognitive demands (Sweller 1988). Environmental stressors—such as glare, insufficient contrast, or suboptimal spectral lighting—may impose unnecessary cognitive effort, thereby reducing the resources available for meaningful processing and comprehension.

From a cognitive perspective, working memory functions as a constrained system responsible for temporarily holding and manipulating information during task performance (Baddeley 2000). When environmental factors increase perceptual strain, they may indirectly burden this system, limiting students' ability to sustain attention and integrate textual information.

In parallel, research in developmental neuropsychology highlights the central role of executive functions—particularly attentional control and inhibitory regulation—in academic achievement (Diamond 2013). Since sustained attention constitutes a foundational component of executive functioning, environmental variables that modulate alertness may exert measurable effects on learning outcomes.

1.1. The Albanian Context: Infrastructure Modernization and Policy Gaps

In recent years, Albania has invested heavily in updating educational facilities, guided by national policies and supported by EU programs. Despite improvements in structural safety, digital connectivity, and energy efficiency, aspects of human-centered design, such as the quality of classroom lighting, have received relatively little focus. INSTAT (2020) reports that nearly four-fifths of schools in Albania have undergone renovations over the last ten years, yet few studies have evaluated the spectral characteristics of classroom lighting.

Research by Gjoka (2019) suggests that a significant number of classrooms still use older fluorescent lighting, frequently delivering illuminance below national recommendations and potentially causing discomfort for students. The existing national guidelines (Ministry of Education and Sport 2022) address only light intensity, neglecting spectral qualities such as CCT. This overlap of practical challenges and regulatory gaps makes Albania a particularly suitable context for studying the cognitive effects of classroom lighting.

1.2. Research Aims and Hypotheses

The present study examines how classroom lighting, specifically CCT, influences attention and reading outcomes in fourth-grade students in real-world Albanian school settings. Grounded in a neuroergonomic approach that combines the biology of ipRGCs with Cognitive Load Theory, we propose the following hypotheses:

1. Exposure to cooler lighting (5000K) is expected to decrease unnecessary cognitive effort by enhancing visual clarity and minimizing eye strain.
2. The 5000K lighting condition is anticipated to boost task-relevant cognitive processing by increasing alertness via ipRGC-related mechanisms.

These combined effects are predicted to yield higher scores on standardized measures of sustained attention and reading comprehension relative to the warmer 4000K lighting condition.

2. THEORETICAL FRAMEWORK

This research integrates photobiology, cognitive psychology, and environmental design to explain how the light spectrum affects learning outcomes.

2.1. Neurobiological Foundations

Light influences human physiology not only visually but also through ipRGCs, which are particularly responsive to blue-rich wavelengths. These cells transmit signals to brain areas involved in arousal, circadian regulation, and hormone release. Consequently, light with higher short-wavelength content can promote alertness and cognitive readiness. LED fixtures with higher CCTs typically provide more blue light, enhancing engagement of these pathways and supporting tasks requiring sustained attention.

2.2. Cognitive Mechanism: Cognitive Load Theory and Environmental Design

Cognitive Load Theory posits that instructional effectiveness depends on the optimal allocation of limited working memory resources (Sweller 1988). Extraneous load—cognitive effort unrelated to learning objectives—reduces the capacity available for schema construction and comprehension. Environmental inefficiencies, including inappropriate lighting spectra, may subtly increase perceptual processing demands. By improving visual clarity and reducing strain, optimized lighting conditions may therefore decrease extraneous load and enhance attentional stability.

Working memory models further suggest that environmental clarity influences the efficiency of information encoding and integration (Baddeley 2000). In sustained reading tasks, even minor perceptual disruptions may accumulate, affecting both fluency and inferential comprehension.

2.3 Neurocognitive Integration

Executive functions, including sustained attention and cognitive flexibility, are strongly associated with academic performance in childhood (Diamond 2013). Light exposure that enhances physiological alertness may support executive regulation by facilitating attentional engagement. Within this framework, spectral composition becomes not merely a technical feature of architectural design but a variable with potential neurocognitive implications.

Table 1 summarizes how different ranges of CCT typically influence classroom experiences and cognitive performance, based on previous research.

CCT Range	Descriptor	Effects	Classroom Implication
3000K–3500K	Warm White	Creates a relaxed and calm atmosphere; may support creative or reflective tasks	Suitable for low-intensity or discussion-based activities
4000K–4500K	Neutral White	Perceived as visually balanced; supports general cognitive performance	Good for extended instructional periods
5000K–6500K	Cool White	Associated with greater alertness and sharper focus	Ideal for demanding, high-focus academic tasks

Recent studies underscore this nuance. Research with primary school students (Li et al. 2025) identified 4000K as optimal for overall comfort and cognitive performance, while a study with university students (Lan et al. 2025) found 6000K most effective for focused learning. This evidence advocates not for a single static CCT, but for adaptive lighting systems capable of modulating spectral output to align with specific pedagogical activities and circadian timing.

2.4. The Albanian Imperative: A Convergence of Opportunities

Albania's simultaneous objectives of modernizing education and promoting sustainable development create an opportunity to improve classroom lighting. Retrofitting older fluorescent systems supports national energy efficiency goals while enhancing learning environments. Implementing high-quality, tunable LED lighting can simultaneously reduce operational energy costs and foster better cognitive outcomes for students.

3. METHODOLOGY

3.1. Research Design and Participants

This study utilized a between-subjects, quasi-experimental design. 60 fourth-grade students (ages 9–10; 28 boys, 32 girls) were recruited from two private schools in Tirana with similar demographic profiles. The age group was chosen because it represents a critical period for consolidating foundational literacy skills. Students with uncorrected vision problems were excluded, and informed consent was obtained from both parents and school administrators.

3.2. Experimental Setting and Lighting Conditions

Testing took place in a single standard classroom at each school, with environmental factors other than lighting kept consistent. To create the two lighting conditions:

- **School A (Experimental Condition: High CCT):** The experimental classroom was fitted with four LED panel fixtures (60×60 cm), each containing four 9W chips, emitting cool-white light at 5000K with a CRI above 80. Vertical illuminance at desk height was maintained around 350 ± 20 lux.
- **School B (Control Condition: Moderate CCT):** The control classroom was equipped with four pendant lamps, each housing three 9W LED Edison bulbs (4000K, CRI >80). To ensure the primary experimental variable was CCT, vertical illuminance at desk height was matched to the experimental condition (350 ± 30 lux). Classroom layouts, wall colors (beige/white), and access to natural light were comparable. Blinds were adjusted to control sunlight, and all other factors—including teacher, schedule, and curriculum—were kept consistent with national standards.

3.3. Instruments and Measures

3.3.1. d2 Test of Attention (Brickenkamp and Zillmer 1998): A validated paper-and-pencil cancellation task was used to assess selective and sustained attention. Outcomes measured included total items processed (Processing Speed, TN), focused accuracy (Concentration Performance, CP), and error rate (E%)

A. **Processing Speed (TN):** Total number of items processed.

B. **Concentration Performance (CP):** TN minus errors of commission and omission, considered the purest measure of focused attention and accuracy.

C. **Error Percentage (E%):** Ratio of errors to total items processed.

3.3.2. Researcher-Created EFL Reading Comprehension Test: To assess task-specific comprehension, a custom test was developed using an authentic A1-level English text aligned with the national fourth-grade curriculum. The test assessed both reading fluency—through time-on-task and word recognition accuracy—and comprehension via multiple-choice and short-answer items. To ensure validity and reliability, the test instrument was reviewed by two EFL specialists and piloted with a separate group of 15 fourth-grade students from a non-participating school. Based on pilot feedback, minor adjustments were made to question clarity. The final test showed good internal consistency (Cronbach's $\alpha = .78$).

3.4. Procedure

3.4.1. Scheduling and Circadian Control

All experimental sessions were conducted over five consecutive school days during a fixed morning time block (10:00 AM – 12:00 PM). This schedule was chosen to align with the students' peak circadian alertness and their standard EFL class period, thereby minimizing the confounding influence of time-of-day effects on cognitive performance.

3.4.2. Testing Protocol

During their scheduled sessions, students completed the d2 test and the reading comprehension assessment. The sequence of the two tests was counterbalanced across participants to control for order and fatigue effects. All testing occurred exclusively under the pre-set, monitored lighting condition (5000K or 4000K) for their respective classroom.

3.5. Data Analysis

Statistical analyses were conducted in SPSS v.26. Descriptive statistics were calculated for all variables, and assumptions of normality and equal variance were checked with Shapiro-Wilk and Levene's tests. Independent samples t-tests were used to compare the 5000K and 4000K groups on mean d2 CP scores and reading comprehension outcomes, with effect sizes reported using Cohen's d. Significance was set at $\alpha = 0.05$. Exploratory correlations between d2 sub-scores and reading performance were also examined.

4. RESULTS

4.1. Attentional Performance

Independent samples t-tests indicated a significant difference in d2 Concentration Performance between the groups, $t(58) = 2.87$, $p = .006$. Students in the 5000K condition (M = 185.4, SD = 21.3) scored higher than those in the 4000K group (M = 168.1, SD = 24.7), with a moderate effect size (Cohen's $d = 0.75$). Additionally, the 5000K group had a lower percentage of errors ($p = .01$)

4.2. Reading Comprehension Performance

Analysis of reading comprehension scores showed a significant difference between the groups, $t(58) = 2.42$, $p = .019$. Participants under 5000K lighting achieved higher mean scores (M = 82.5%, SD = 9.1) compared to the 4000K group (M = 76.2%, SD = 11.4), corresponding to a small-to-moderate effect size (Cohen's $d = 0.62$). The improvement was particularly notable for inferential questions relative to literal ones.

4.3. Correlation Analysis

Across all participants, d2 Concentration Performance scores were positively correlated with reading comprehension outcomes, $r(58) = .54$, $p < .001$. This strong positive correlation suggests that a student's capacity for focused attention is closely linked to their reading comprehension performance under the study conditions.

5. DISCUSSION

The findings suggest that exposure to cooler-spectrum classroom lighting (5000K) is associated with improved performance on tasks requiring sustained attention and reading comprehension. Compared with students in the 4000K condition, those exposed to 5000K lighting showed higher levels of concentration and comprehension, lending support to the proposed role of spectral lighting characteristics in shaping cognitive engagement.

Two interacting mechanisms may explain these outcomes. On one hand, cooler-spectrum lighting may decrease visual effort by enhancing contrast and clarity, thereby reducing extraneous cognitive demands. On the other hand, blue-enriched light may elevate physiological alertness via ipRGC-related pathways, supporting sustained focus during extended academic tasks.

5.1. Interpretation and Contextualization

The advantage of 5000K lighting for attention-demanding tasks is consistent with prior findings on the relationship between light spectrum and executive functioning. The two mechanisms proposed---reduced visual strain and increased physiological alertness---likely operated in concert. Critically, the strong positive correlation observed between attentional performance and reading comprehension ($r = .54$) supports the interpretation that the lighting condition facilitated gains in focused attention, which in turn translated directly into improved academic performance on the reading task. However, evidence indicating that 4000K lighting supports overall comfort across the school day (Li et al. 2025) suggests that a single fixed CCT may not be optimal for all classroom activities.

5.2. Implications for Albanian Educational Policy

The present findings provide an empirical basis for informing educational policy and infrastructure planning in Albania. One implication is that the Ministry of Education and Sports could expand its school infrastructure guidelines to incorporate spectral lighting criteria, such as CCT and CRI, thereby encouraging lighting designs that better support cognitive functioning. Second, tunable LED retrofits represent a dual benefit: advancing energy efficiency and sustainability goals while simultaneously enhancing student learning outcomes. Establishing human-centered lighting standards may also advance educational equity by helping ensure that students in rural or under-resourced schools benefit from learning environments that support attention and cognitive engagement to a degree comparable with urban settings.

5.3. Limitations and Future Research

Several limitations should be acknowledged, including the quasi-experimental design, which limits control over inter-school differences, and the focus on a single age group of fourth-grade students. Moreover, while illuminance levels were matched, a practical constraint of the real-world setting introduced a confounding variable**.** In the control classroom (4000K), the use of pendant lamps with Edison bulbs, compared to the panel lights in the experimental room, resulted in a different luminous distribution and potential for minor glare. Although this reflects the diversity of existing lighting infrastructure in schools, it limits our ability to attribute outcomes solely to CCT with absolute certainty. Future laboratory-style studies should utilize identical fixture types to isolate the effect of spectral composition. Nonetheless, by strictly controlling for illuminance and CCT—the core variables of interest—this study provides ecologically valid evidence for the cognitive impact of lighting spectrum in authentic classroom environments. Future research could employ within-subject crossover designs using tunable lighting in a single classroom, as well as longitudinal studies across multiple regions, to examine the stability of cognitive and academic effects over time. Investigating the interplay between spectral quality, duration of exposure, and other classroom factors (e.g., noise, temperature) could further refine recommendations for optimal educational environments.

6. CONCLUSION AND RECOMMENDATION

The present study provides evidence that the spectral characteristics of classroom lighting, particularly cooler CCTs, are associated with differences in elementary students' sustained attention and reading comprehension. In the Albanian context, where efforts to modernize educational infrastructure are ongoing, incorporating lighting systems that address both spectral quality and energy efficiency represents a timely opportunity. Human-centered and adaptive lighting systems may serve not only functional purposes but also support students' cognitive engagement, with potential benefits for learning outcomes and educational equity.

For educational policymakers and architects in Albania and similar contexts:

1. Prioritizing spectral quality should be a key consideration in school lighting specifications. New constructions and retrofits could benefit from LED systems with tunable CCT, with higher CCT ranges (approximately 5000K–6500K) used during core instructional periods requiring sustained focus.
2. Lighting design may be more effective when treated as an integral component of the pedagogical environment rather than as a purely technical feature. Dynamic lighting systems could support warmer CCT ranges (3000K–4000K) during collaborative or creative activities to foster a calmer atmosphere, while cooler CCTs could be employed for individual reading, assessment, or detail-oriented tasks.
3. Professional development initiatives could increase educators' awareness of how environmental factors, including lighting conditions, influence students' readiness to learn

In summary, aligning classroom lighting environments with the neurobiological mechanisms underlying attention and cognition may enable the design of learning spaces that actively support, rather than simply accommodate, educational processes. The findings presented here suggest that optimizing classroom lighting is an important component in the development of more effective and equitable educational environments.

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