Smart Lighting and Student Performance: A Novel System Design, Implementation, and Effects in Classrooms

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contribution

Contents from the following articles have been compiled into Chapter 2, Chapter 3, and Chapter 4 of this research:

- Sun, B. S., Cao, S., & Li, Z. C. (2018). The Impact of Classroom Lighting on Student Performance: A Literature Review. *Chinese Journal of Applied Psychology*, *24*(4), 29.

Contributor	Statement of Contribution
Sun, B. S. (Candidate)	Design (85%) Writing and editing (85%)
Cao, S.	Design (10%) Writing and editing (15%)
Li, Z. C.	Design (5%)

- Sun, B., Zhang, Q., & Cao, S. (2020). Development and Implementation of a Self-Optimizable Smart Lighting System Based on Learning Context in Classroom. *International Journal of Environmental Research and Public Health, 17(4)*, 1217.

Contributor	Statement of Contribution
Sun, B. S. (Candidate)	Design (85%) Writing and editing (70%)
Cao, S.	Design (5%) Writing and editing (20%)
Zhang, Q. L.	Design (10%) Writing and editing (10%)

The smart lighting system described in the thesis was developed and implemented by Data Tellit Inc. Data Tellit Inc. owns the intellectual properties of the system. Sun, B. S. (Candidate) was the architect of the system (100% system design) and contributed major part of the core software (70%), while other software (30%) and all hardware (100%) were contributed by engineers from Data Tellit Inc.

The field study described in the thesis was designed by Sun, B. S. (Candidate). Then, Data Tellit Inc. executed the field study, collected, and submitted the data. Sun, B. S. (Candidate) (75%) and engineers from Data Tellit Inc. (25%) together finished the data analysis.

Abstract

As one of the most essential factors of learning environment, lighting in classroom has been found to have significant impact on student performance. Moreover, brightness level and correlated color temperature (CCT) are the two key luminous properties that have been examined in many relevant studies. And researchers were increasingly focusing on the diversity of luminous requirements under different learning context. However, knowledge regarding the optimum lighting configuration (the combination of brightness and CCT) for some specific learning context is still insufficient due to the complexity of reality, including learning context, classroom environment, demographic characteristics of students and user preferences.

To enrich the pertinent knowledge of both engineering and academia, three major works were conducted in this study. Firstly, a context-based smart lighting system was designed and implemented. This system has been tested in more than one hundred classrooms from about ten schools. It turned out to be an advanced and practical solution. Secondly, the data of a field study for examining the effect of different lighting settings on student academic performance were collected and analyzed. The field study involved twelve classrooms, 568 students of grade one and grade two from one elementary school in China. The results showed that students in context-based lighting environment significantly improved more on both Language and Mathematics than those in standard lighting environment. Interestingly, although no significant effect of gender was reported via MANOVA (multivariate analysis of variance), the separated t-tests indicated that the lighting environment had significant effect on female, but not on male. Regarding user operation preference, it was out of expectation that no significant difference was found. Lastly, an innovative indoor environmental data-processing framework was proposed. This framework can automatically optimize lighting configuration for different learning context by gathering and analyzing a variety of classroom data and student data, including learning context, illumination settings, environmental data, student performance and some demographic information. It made it possible to shift the research practice from traditional controlled laboratory experiments to emerging Big Data and machine learning methods.

Although this study was only a preliminary work towards the best lighting settings in classrooms, it established a solid foundation (the smart lighting system) and embarked on a novel approach (the self-optimizable framework) for research in this area. Some ideas and topics for future study were also discussed.

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List of Abbreviations

AC	Alternating Current
ADC	Analog to Digital Conversion
ADHD	Attention Deficit Hyperactivity Disorder
AI	Artificial Intelligence
AKT	Aventura Karimov Table
ALS	Ambient Light Sensor
ANOVA	Analysis of Variance
CAGR	Compound Annual Growth Rate
CIE	Commission Internationale de l´Eclairage or International Commission on illumination
CCT	Correlated Color Temperature
CoAP	Constrained Application Protocol
CRI	Color-rending Index
DAC	Digital to Analog Conversion
DTLS	Datagram Transport Layer Security
DC	Direct Current
DV	Dependent Variable
ECG	Electrocardiogram
EDA	Electrodermal Activity, or Exploratory Data Analysis
EEG	Electroencephalogram
ETL	Extract Transform Load
GPIO	General-purpose Input and Output
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEQ	Indoor Environment Quality
IAES	Integrated Ambient Environment Sensor
IoT	Internet of Things
IV	Independent Variable
KSS	Karolinska Sleep Scale
LAN	Local Area Network
LDO	Low Dropout
LED	Light-emitting Diode
lx	lx or lux
MANOVA	Multivariate Analysis of Variance

MCU	Microcontroller Unit
MQ	Message Queue
MQTT	Message Queuing Telemetry Transport
OTA	Over the Air
PBL	Problem-based Learning
PCB	Printed Circuit Board
PIR	Passive Infrared
PVT	Psychomotor Vigilance Task
PWM	Pulse Width Modulation
RAM	Random Access Memory
RCT	Reciprocal Colour Temperature
RF	Radio Frequency
RL	Reinforcement Learning
SPI	Serial Peripheral Interface
SSCCS	State Self Control Capacity Scale
TBL	Team-based Learning
TTL	Time to Live
TTL	Transistor-Transistor Logic
TVOC	Total Volatile Organic Compounds
UAT	User Acceptance Testing
UGR	Unified Glare Rating
UI	User Interface
VVM	Visual and Verbal Memory
WAN	Wide Area Network
ZVT	German Zahlen Verbindungs Test

Disclaimer

This study is the main part of the cooperation research project “Smart lighting and student performance” (SRA#077079), which was sponsored by Data Tellit Inc. The project timeline was initially from November 1, 2017, to October 31, 2019. In September 2019, the schedule was extended to December 31, 2020, due to the delay of data provision.

Chapter 1
Introduction

1.1 Overview

Indoor environment, like classroom and office, is an integrated and complex system, which involves physical layout, interior design, infrastructure, furniture, and equipment, as well as indoor environmental factors including light, temperature, humidity, air quality and acoustics. The impact of indoor environmental quality (IEQ) on occupants' comfort and wellbeing is critical but very complicated (Al horr et al., 2016). As to students, existing studies have proved that IEQ of classroom can significantly impact on their well-being and performance (Blackmore et al., 2011; Earthman, 2004; Gabrielle Wall, 2016; Gilavand & Jamshidnezhad, 2016; Higgins et al., 2005; Yang et al., 2013; Y. Zhang et al., 2016). More particularly, lighting environment is believed to be one of the most important factors among all environmental aspects in classroom. For instance, the result of data study regarding 153 classrooms in 27 schools in England showed that light explained 21% to the increase in student progress and contributed the biggest share among seven environmental factors, including light, sound, temperature, air quality, links to nature, ownership and flexibility (Barrett et al., 2015).

Even though the importance of light in classroom is generally recognized, knowledge about the most suitable settings of illumination for a diversified educational situation and practice is still insufficient and sometimes controversial. Moreover, most of existing related knowledge were established on the findings of controlled laboratory experiments with limited data samples, whereas we did not find lighting control systems in place that were designed to support research for exploring better lighting configuration based on machine learning method with large dataset. To make breakthrough in this field, researchers need innovative lighting control system and research approach.

As a starting point of game-changing development within its field, there are many benefits of this research. With regard to engineering, this work brought an advanced smart lighting system to school users in pragmatic way. From both technical and commercial point of view, the proposed system can be extensively adopted and benefit the majority of students. As to academia, this study not only practiced a natural experiment in real world, but also made it possible to shift research in the area from traditional controlled laboratory experiments to emerging Big Data and machine learning methods. The research team believes it can develop into a systematic methodology towards the best lighting settings in classrooms.

1.2 Objectives

The ultimate goal of our research is to establish an intelligent indoor environment control system that integrates both artificial intelligence (AI) and psychological knowledge. Single deployment of this system can train itself, and dynamically adjust environmental parameter according to the circumstance. In addition, models can also be shared across the network of system instances. It means that a new deployment can acquire the best possible initial settings from similar systems.

However, it requires lots of data and research efforts to achieve the goal. At the early stage of the research, this thesis particularly focused only on lighting environment in classroom, aimed to prepare a technical framework and setup a rough but fundamental reference for further research. Precisely, the objectives of this thesis include three aspects:

1) to develop a learning-context based smart lighting control system that can support the data-driven brightness and CCT control,
2) to design and execute a natural field study, and establish a base line of optimized lighting configuration by analyzing data from the study,
3) to design and verify a classroom environmental data-processing framework that can support the novel research idea of self-optimization.

1.3 Structure of Thesis

The following sections of the thesis are briefly introduced below:

Chapter 1: Introduction contains the overview, objectives, and structure of this thesis.

Chapter 2: Background Information contains a detailed literature review of studies about the changes of understanding about classroom lighting environment in recent 20 years, as well as the state-of-the-art smart lighting systems.

Chapter 3: Classroom Illumination and Student Performance contains a concise summary on illumination standards in classroom, then introduces the existing findings and controversial topics regarding the relationship between lighting environment in classroom and student performance, and also explains a group of proposed lighting modes as common references corresponding to different kind of learning contexts.

Chapter 4: Learning-context Based Smart Lighting System introduces the design and technical details of the proposed smart lighting system.

Chapter 5: Study Design and Data Analysis describes the design and execution of the natural field study, as well as the procedure used to collect and analyse data.

Chapter 6: Results and Discussion presents the statistical results of the field study, highlighting the effect of learning-context based illumination settings on student academic performance. It also lists the limitations of this study, explains possible reasons, and suggests ways it could be improved in the future.

Chapter 7: Conclusion and Future Work summarizes the main findings and contributions of this study, and then proposes a few directions that may guide further research in this field.

Chapter 2
Background Information

Young students who are in the process of developing physically and mentally need to spend a lot of time in classrooms. Lighting system is indispensable to classroom and has tremendous influence on student's well-being and performance. Exploring the most appropriate lighting environment for classroom has been a recurrent research topic for decades. Chapter 2 provides background information in this area. Firstly, some key attributes of light in classroom were introduced in section 2.1 and 2.2. Then in section 2.3, we went through a series of studies on classroom lighting environment in recent 20 years and tried to delineate the change and trend of relevant research over time. In section 2.4, we turned to information technology domain and introduced the development of contemporary smart lighting systems, since new technology always plays an important role in driving the academic progress.

2.1 Light Sources in Classroom

Generally, illuminance in classroom is a mixture use of daylight and artificial light. Due to the difference of their features and availability, contemporary illuminant settings in classroom are prone to mainly depend on artificial light and take the advantage of daylight as much as possible.

2.1.1 Daylight

Daylight comes from the natural and was once the primary light source before artificial light became widely available. Initially, people intended to tell the preference of users and different effects between daylight and artificial lighting. Eventually, many researchers have reached consensus that daylight is not only preferable by teachers and students (Earthman, 2004; Heschong, 2003), but also reduces the risk of myopia (Ballina, 2016; Torii et al., 2017; Y. Wang et al., 2015).

However, daylight featured by its variability in amount, spectrum and distribution due to the time, weather and site (Peter Robert Boyce, 2014) can not solely support activities in classroom. In most cases, artificial light dominates indoor illuminance, while daylight acts as a supplementary light source.

2.1.2 Artificial Light

Since the advent of Edison light bulb, the lighting industry has developed for more than one century. Though there are several thousand different types of electric lamps, those can be put into three categories: 1) incandescent lamps, e.g. the filament light bulbs and halogen lamps; 2) discharge lamps, e.g. fluorescent lamps; and 3) solid-state lamps, e.g. light-emitting diodes (LED) (Peter Robert Boyce, 2014).

Although fluorescent lamps still hold a considerable market share, LED replacement of traditional lamps is accelerating at about 13% CAGR (Compound Annual Growth Rate) globally (Zion Market Research, 2017). Compared to incandescent and fluorescent lamps, the advantages of adopting LED in schools include not only higher brightness, longer life span, lower maintenance cost, and more savings on energy, but also the capability of being precisely controlled in terms of the brightness level and CCT. It is cogent that LED will predominate in learning spaces in near future. This may be one of the reasons that most relevant research in recent years were all under LED environment, as is this study.

2.2 Main Characteristics of Light in Classroom

When we talk about the impact of lighting on student, it is necessary to investigate the main characteristics of light source. It needs to be noted that some characteristics are negative. This means we should hold high standard for them to benefit the users or avoid photobiological hazards. In this study, we classified these characteristics as the quality of light source. In contrast, some characteristics are neutral. This means the optimal setting of these factors can vary depending on the circumstance. The two categories of characteristics are summarized in table 1, and then discussed individually in the rest of this section.

Table 1. Two categories of lighting characteristics in classroom

Category	Quality of light source	Neutral attributes of light source
Characteristics in this category	Glare, flicker, blue light hazard, Color-rending Index (CRI), illuminance uniformity	Brightness, CCT
Preferred settings of this category	The higher standard produces the better outcome or less hazard.	The optimal setting varies according to the application.

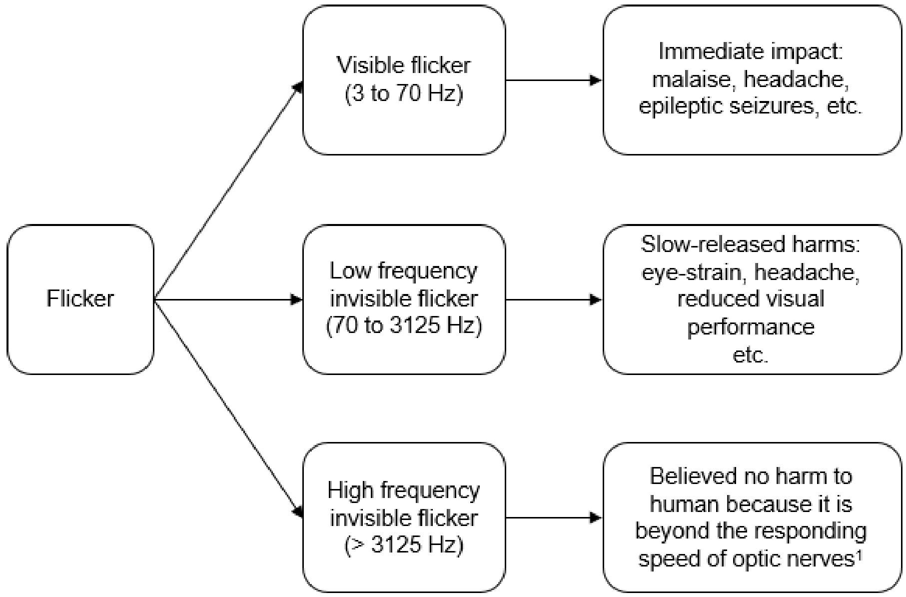
2.2.1 Quality of Light Source

2.2.1.1 Glare

Glare is the "sensation produced by luminance within the visual filed that is sufficiently greater that the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss of visual performance and visibility" (Zion Market Research, 2017). Glare can be induced by a couple of reasons, including excessive luminous intensity, direct light (sunlight or lamps), and non-uniform spatial distribution of luminance. Classroom should avoid all kinds of glare by applying blinds or curtains and using glare-free LED lamps with rational layout. In practice, the Unified Glare Rating (UGR) (Commission Internationale de l'Eclairage, 1983) is widely recognized as a glare metric for indoor lighting. The degree of UGR ranges from 7 (insensitive) to 31 (unbearable). In classroom, the value of UGR is usually restricted below 19 according to the standards of many countries.

2.2.1.2 Flicker

Flicker is defined as "a rapid and repeated change over time in the brightness of light" (Wilkins et al., 2010). It should be noticed that almost all types of light sources could produce flicker. As shown in figure 1, flicker whose frequency ranges from 3 Hz to 70 Hz is called visible flicker, which means it can be consciously perceived by human. Visible flicker can cause immediate health impact, such as malaise, headache, and epileptic seizures. On other hand, invisible flicker can be divided into two categories. Flicker with frequency above 3125 Hz is considered safe to human, because human's optic nerves can not sense that high frequency. So lighting sources with 3125 Hz or higher frequency are exempt from flicker testing by international standards including IEEE and IEC (IEC TR 61547-1, 2017; IEEE Power Electronics Society, 2015). However, invisible flicker with lower frequency may lead to discomfort and chronic health problems, like eyestrain, headache, reduced visual performance, etc. In practice, low frequency invisible flicker requires much vigilance, because it is not perceptible, and people can get hurt without knowing it.



[1] IEEE Std 1789-2015

Figure 1. Types of flickers and their impact to human

2.2.1.3 Blue Light Hazard

Although blue ray is one of ubiquitous components of daylight and almost all artificial light sources, exposure to excessive blue light is risky to human's photobiological safety. The consequences of blue light hazard include eye-strain, visual fatigue, circadian disruption and photo retinitis (Leccese et al., 2015). When we investigate blue light hazard, two factors need to be examined. Hazardous wavelength that human can visually percept is mainly at 430 nm to 480 nm out of the entire blue spectrum between 300 nm and 700 nm. Besides the wavelength, the other key factor is the luminance. That is because higher luminance tends to incur greater risk of blue light hazard. International and domestic standards, like CIE S009/E:2002, European EN 62471 and Chinese GB/T 20145-2006, have consistent description regarding the risk levels of blue light hazard. Light source can be classified into one of the four risk groups (RG0 to RG3). RG0 means no risk or exempt from exam. According to these standards, the blue light hazard is closely related to the brightness intensity per unit area, also known as the luminous. If the luminance of a source is less than 10,000 cd/m^2 (candela per square meter), it can be treated as RG0. Likewise, RG1, RG2 and RG3 correspond to low risk, moderate risk, and high risk respectively.

2.2.1.4 Color-rending Index (CRI)

CRI is defined as "measure of the degree to which the psychophysical color of an object illuminated by the test illuminant conforms to that of the same object illuminated by the reference illuminant, suitable allowance having been made for the state of chromatic adaptation" (Schanda, 2016). Since sunlight is generally used as the reference illuminant, so in other words, higher CRI produces as closer perceptive colors of objects as that of under sunlight. The maximum value of CRI is 100, which means an illuminant with CRI 100 can display exactly the same color appearance of objects as their color appearance under sunlight.

2.2.1.5 Illuminance Uniformity

As a critical aspect of a LED light source, illuminance uniformity represents the homogeneity of light distributed onto the work plane (Moreno & Tzonchev, 2004). In classroom settings, a group of lighting sources work together and produce unevenly spatial luminance distribution on both desktop and blackboard areas. One of the typical methods to quantify the illuminance uniformity of a work plane is to calculate the ratio of the minimum illuminance value to the average illuminance value of the given area. In practise, in order to reduce the data points, the illuminated area is usually divided into small blocks evenly. In the illustrated example, a 4m ×1.2m blackboard is divided into 30 blocks (10 ×3), so the size of each block is 0.4m × 0.4m. To calculate the illuminance uniformity of the blackboard, we only need to measure the illuminance value (Lux) at the center of each block, and we can get 30 data points. The illuminance uniformity equites to the minimum value divided by the mean value of the 30 data points.

○	○	○	○	○	○	○	○	○	○
○	○	○	○	○	○	○	○	○	○
○	○	○	○	○	○	○	○	○	○

Note: a ○ stands for a measuring point of the blackboard

Figure 2. Grid-based illuminance uniformity measurement of a blackboard

As it can be seen, the value of illuminance uniformity is between 0 to 1. The value closer to 1 means the better uniformity, but more difficult to achieve. Therefore, a lot of national and industrial standards regarding indoor lighting environment elaborated the requirements regarding illuminance uniformity. Although the details may vary, many standards hold similar bottom limit. For example, desktop uniformity should not be below 0.7 under minimum 300 lux of illuminance according to the standards of many countries, like USA, EU, Japan, China, etc. In addition, Chinese standards (GB 7793-2010) also require that uniformity on the blackboard should not be below 0.8 under minimum 500 lux of illuminance.

2.2.2 Attributes of Light Source

2.2.2.1 Brightness

Brightness or illuminance level, whose metric unit is lux, refers to the intensity of light projected on the surface of a given area. One lux is equivalent to the luminous flux per square meter of the subject exposed vertically to a light source with one-meter distance and a luminous intensity of one candlelight light source.

It is easy to understand that sufficient brightness in classroom is essential to wellbeing of students. Although almost all related standards stipulated the minimum level of brightness in classroom, there are still a lot of students who are suffering insufficiency of illuminance in classrooms. According a national-wide random survey in China in 2019, nearly 60% classrooms are below the national standards (GB 7793-2010) in terms of illuminance level.

On the other hand, is the lighting in classroom the brighter, the better? The answer is no. Although some studies showed that high lighting levels (1000 lux) can benefit learners by improving their concentration (Singh & Arora, 2014; Sleegers et al., 2013), suppressing sleepiness, enhancing brain activity, and increasing arousal and alertness (Fabio et al., 2015; Smolders & de Kort, 2014), other researchers (Osterhaus, 2005; Winterbottom & Wilkins, 2009) argued that excessive illuminance can cause discomfort and disability glare. Therefore, they suggested to regulate lighting levels below 1000 lux by means of versatile blinds and dimmable luminaries. In addition, (Leichtfried et al., 2015) alleged that there was no significant difference between bright light and dim light on the change of serum melatonin levels, which failed to support the common viewpoint about the relationship between ambient brightness and occupants' alertness. But bright light (5000 lux) had negatively impact on cognitive performance.

2.2.2.2 CCT

CCT, the acronym of Correlated Color Temperature, is measured in Kelvins or K. It refers to when the color performance of a light source is similar to the hue radiated by the blackbody at a certain temperature, then the CCT of the light source is represented by the temperature of the blackbody. Light sources with high CCT display cool colors (blue and white), while those with low CCT tend to warm colors (red and yellow).

Despite few conflicting evidence and disputation regarding the optimum configuration of CCT in classroom, forceful opinions on the effects of CCT have been established. Studies demonstrated that different illumination configurations, including brightness and CCT (Borbély et al., 2001), had different impacts on students' behavior and cognition, but the impact differed depending on learning context and age group (Ballina, 2016; Fabio et al., 2015; Keis et al., 2014; Singh & Arora, 2014; Sleegers et al., 2013; Smolders & de Kort, 2014; Wessolowski et al., 2014).

Furthermore, CCT settings may also have influence on energy-efficiency, which attribute to the occupant's thermal perception under different CCT condition. Some recent studies argued that occupants sensed warmer under lower CCT (warm light) environment (Golasi et al., 2019; Toftum et al., 2018) and this could lead to around 8% of the annual energy savings (Toftum et al., 2018).

2.2.2.3 Kruithof Curve: correlation of brightness and CCT

The combination of color temperature and illumination has a more complex effect on occupants. In general, it can be roughly evaluated by kruithof's curve (Davis & Ginthner, 1990). As demonstrated in Figure 3, the horizontal and vertical coordinates of the figure are CCT and illuminance, respectively. The middle part is the pleasing zone with preferred combination of color temperature and illumination, while other zones are considered uncomfortable. The upper left zone appears reddish (low CCT and high illumination), and the lower right zone appears bluish (high CCT and low illumination). Therefore, when determining the classroom lighting settings, we should keep in mind to constraint the pair of parameters within the pleasing zone.

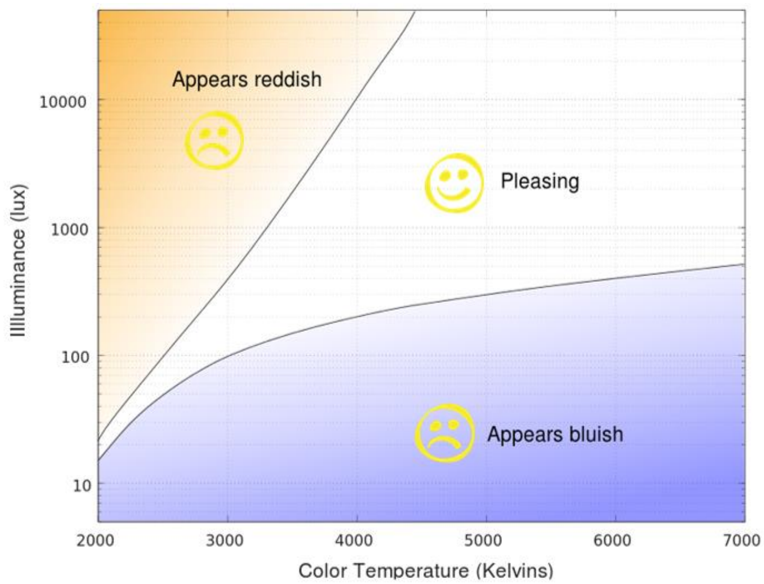


Figure 3. An example of Kruithof Curve

Revised from "Figure 1 - Kruithof Curve" (Davis & Ginthner, 1990)

2.3 Studies about Classroom Lighting Environment

Indoor lighting is a complex system, involving many aspects, such as the characteristics of the light source, the application and context, the preference and difference of occupants and so on. With the development of lighting technology as well as the ever-changing of application environment, research focus on classroom lighting environment has kept shifting throughout decades. By reviewing and compiling this progress, we can delineate the track and trend of development. As shown in Figure 4, the course of development to date can be segmented into five phases.

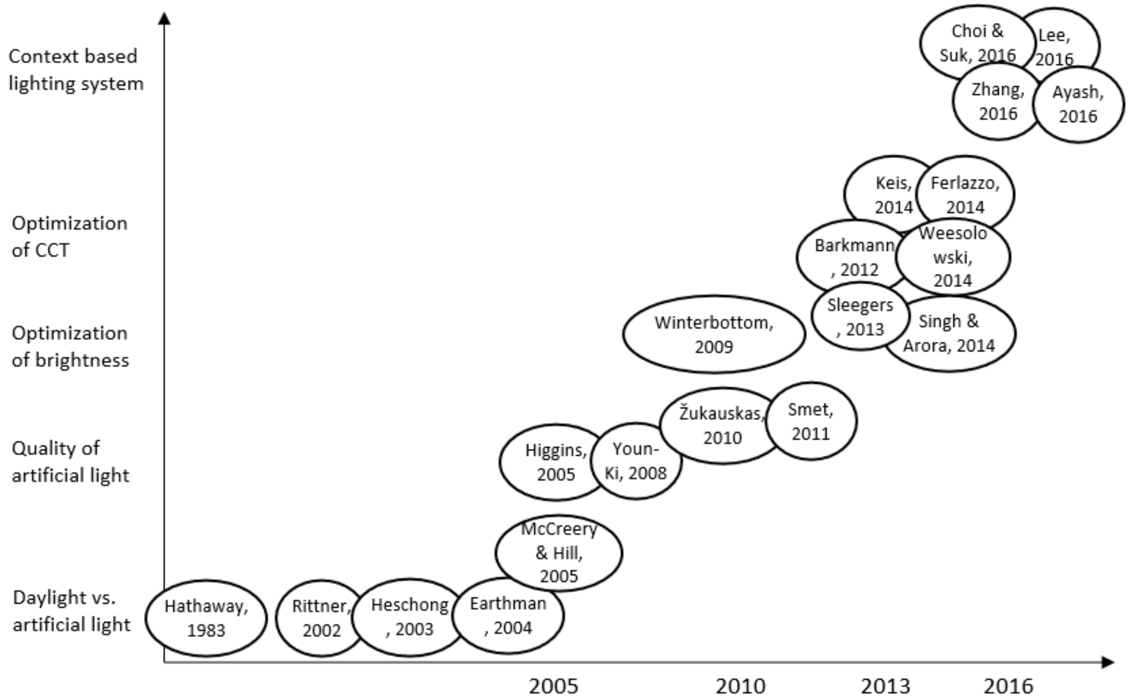


Figure 4. Development of research about indoor lighting (Sun et al., 2018)

2.3.1 Phase I: daylight vs. artificial light

Before 2005, research mainly focused on the difference between daylight and artificial lighting, and their impact on occupants. Hathaway (Hathaway, 1983) found that teachers and pupils preferred natural light, and subsequent studies (Earthman, 2004; Heschong, 2003; Rittner-Heir, 2002) have shown that daylight has a more positive impact on students. However, replying only on daylight is not realistic (Higgins et al., 2005), either too much daylight or insufficient illuminance will be complained by students (Singh & Arora, 2014). Therefore, controlled daylight combined with appropriate artificial lighting is very important for learning environment and students' performance (McCreery & Hill, 2005).

Considering that the control of daylight mainly depends on windows, blinds, or curtains after a building is finished, the adjustment scale is very limited. Therefore, studies of indoor lighting had gradually turned to artificial lighting.

2.3.2 Phase II: quality of artificial light

After study focus turned to artificial lighting around 2005, researchers primarily paid rapt attention to the quality of artificial lighting sources that relates to people's wellbeing. Quality issues, including glare, flicker, low color-rendering index (CRI), and blackening phenomenon of fluorescent lamps, can cause considerable health problems. Many complaints were reported in this regard, such as headaches, eyestrain, fatigue, distraction, and myopia (Higgins et al., 2005; Youn-Ki et al., 2008). With the improvement of schools' environmental quality standards, because of its high efficiency, compact in size, savings on energy and environmental friendliness, as well as real-time tunability of spectrum (Artūras Žukauskas et al., 2010; Kevin A.G. Smet et al., 2011), LEDs have become the most popular lighting sources and been used to replace fluorescent lamps, which used to dominate classrooms. When the quality of artificial lighting was no longer a concern, light settings such as brightness and CCT, became the primary research topic of the area.

2.3.3 Phase III: optimization of brightness

More and more studies regarding the optimum brightness in learning environment can be found. started to find from around 2010. In general, these studies tried to answer a few questions including: is the lighting in classroom the brighter, the better? Even though many countries, like the US, UK and China, require the lighting level for general teaching spaces to be not less than 300 lux, is this always the case? Is uniform distribution of illuminating throughout the classroom optimized under any circumstance? One short answer to all three questions is NO. Some studies claimed that high lighting levels (1000 lux) can benefit learners by improving their concentration (Singh & Arora, 2014; Sleegers et al., 2013), suppressing sleepiness, enhancing brain activity, and increasing arousal and alertness (Fabio et al., 2015; Smolders & de Kort, 2014). However, other researchers (Kim & Koga, 2005; Osterhaus, 2005; Winterbottom & Wilkins, 2009) argued that excessive illuminance could cause discomfort and disability glare. Therefore, they suggested to constrain the brightness less than 1000 lux, which can be achieved by using blinds and dimmable lamps. In addition, evidence (Leichtfried et al., 2015) showed there was no significant difference on the change of serum melatonin levels under difference brightness levels. But high brightness (5000 lux) had negatively impact on cognitive performance. Moreover, a survey in the UK (Y. Zhang et al., 2016) pointed out that computer interactive smart boards have been widely used in primary school classrooms and a high brightness level may not be desirable most of the time. According to the survey, teachers preferred a balanced illuminance solution with low enough and bright enough brightness as using smart board and studying on desktop, respectively. In particular, brightness distribution needs to be adjusted in some specific learning contexts. For example, during the occurrence of teaching the light level should be brighter at the black/white board area than at the student seats area, while the reversed brightness setting is more appropriate for the in-class self-study situation. When playing media or slides, we usually need to restrain the daylight and turn off the lamps near the screen but leave some illuminance at the audience zone. Impromptu speech requires spotlight effect, and group discussion may need focus lighting for each group to reduce interfere between groups.

Phase IV: optimization of CCT

Shortly later, the correlation between CCT and students' performance became a popular research topic. Sleegers (Sleegers et al., 2013) concluded that high CCT (6500K) helps students gain more concentration. As to student's cognitive performance, Ferlazzo (Ferlazzo et al., 2014) found that cooler light (4000K) exposure improves the cognitive system's capacity to deal with multiple task representations and 3-D visuo-spatial ability, whereas researchers from Ulm university (Keis et al., 2014) argued that blue-enriched white light can lead to faster cognitive processing speed and better concentration, but has no effects on short-term encoding and retrieval of memories.

As mentioned before, CCT settings are also related to energy-savings (Golasi et al., 2019; Toftum et al., 2018). When putting all these considerations into account, it will be very interesting and challenging to determine the proper illuminance configuration for a learning space.

2.3.4 Phase V: context-based lighting system

Furthermore, several state-of-the-art studies began to engage in the diverse requirements of light schema for different learning contexts. Ayash (AL-Ayash et al., 2016) said that the hue had a significant impact on students' emotions, and vivid color conditions significantly improved their reading scores. Weesolowski (Wessolowski et al., 2014) discovered that variable light could reduce pupils' restlessness and improve their social behaviors. Two researchers of South Korea (Choi & Suk, 2016) suggested to shift color temperature among 3500K, 5000K and 6500K in accordance with easy, standard and intensive learning activities respectively. In the same year, another Korean team (Lee et al., 2016) proposed and tested an adaptable lighting control system with five illuminance settings for five different educational contexts, such as language/memorizing, mathematics, P.E., arts, and rest.

As can be noticed, with the development and diversification of learning contexts and teaching methods, the requirements for lighting in classroom are refining and upgrading. Thanks to the development of technology, including LED, smart devices, and Internet of Things (IoT), large-scale deployment of dynamic lighting control systems has become viable. However, the knowledge of optimized lighting schemas is still limited. Especially, there is neither solid evidence about how flexible lighting solutions affect students' real academic performance, nor feasible methodology for adjusting better light settings corresponding to a variety of real learning contexts.

2.4 Studies about Lighting Control System

Along with the progress of research about indoor lighting environment, technology also has been playing an important role. It can be observed that every big leap in this field we mentioned in Section 2.3 has its technological momentum in the background. From the point of view of technology, lighting control system with the cutting-edge lighting products not only supports relevant academic research, but also benefits our daily life with more energy efficiency, better user-experience, and lower maintenance cost.

However, there is not lighting control solution that can satisfy all situations due to the variety of classroom's physical attributes, learning context, as well as the diversity of students' characteristics and preferences. Lang (Lang, 2002) pointed out that lighting preferences are not fixed but vary depending on many factors, such as classroom size, teaching activity, and individual needs of teachers and students. Therefore, it is strongly advised that classroom lighting systems should provide users with the flexibility of lighting control.

2.4.1 A Conceptual Model for Lighting Control System

By reviewing existing studied about lighting control system, we found the majority of them focused on energy saving, and they achieved considerable outcomes (Chew et al., 2017). As summarized in a review on lighting control technologies (Haq et al., 2014), the saving on energy ranged from 35% to 68% in classroom and office environment. An abstracted lighting control system model for energy saving is shown in Figure 5, which is developed based on the control strategies suggested by Martirano (Martirano, 2011). Fundamentally, adopting high energy-efficiency LED and turning off or dimming the lights whenever possible are major methods to save energy. A study about the trend of lighting industry indicated that the benefits of promoting LED include not only energy saving and environment conservation, but also increasing automation (Z. Li et al., 2018). Therefore, almost all pertinent studies used LED as the light source and applied on-off control. Most of them implemented brightness control at the same time, whereas a few of studies implemented CCT control. One motivation using CCT control to improve energy-efficiency might be the influence of different CCT on the occupant's thermal perception as we covered in Section 2.2.2.2. However, inconsistent reports can also be found, which rejected the hypothesis of correlation between CCT and thermal sensation

(Baniya et al., 2018). Essentially, lighting control systems require relevant input data to decide when and how to control the lights. The input data employed by existing studies included different combinations of user configuration and sensor data, such as occupancy and ambient light, zone settings, schedule information, and user preference. Eventually, the core of the system is the algorithm that determines how to drive the lights according to the input data.

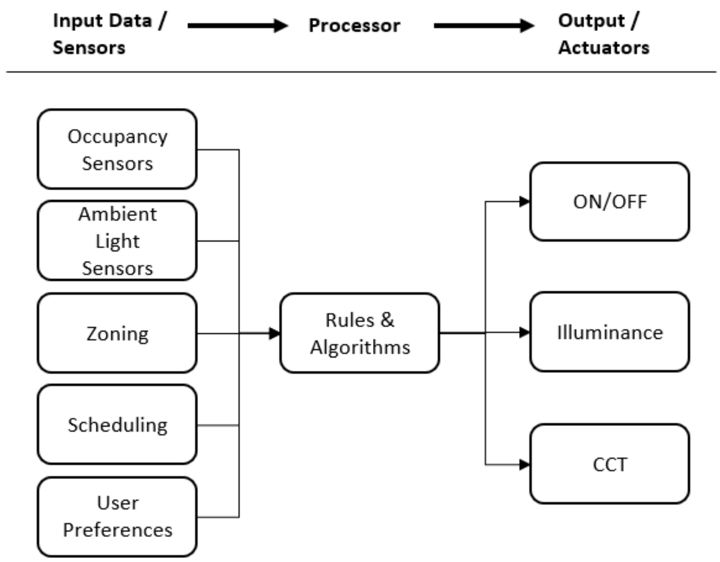


Figure 5. A conceptual lighting control system model (Sun et al., 2020)

2.4.2 A Recap of Existing Studies about Lighting Control System

There have been many studies in the literature about lighting control systems. We selected a few representative studies, and made a comparison shown in Table 2 in terms of main purposes and techniques.

Table 2. Comparison of studies on lighting control systems (Sun et al., 2020)

Research	Main Purposes				Techniques and Methods							
	Energy Saving	Manageability	Better User Experience	Students' Performance Improvement	Occupancy Detection	Ambient Light Sensing	Control by Zones	Scheduling	Dimming (Adjustment of Luminous Level)	Adjustment of Color Temperature	Mobile Application	Learning Context Awareness
Martirano, 2011	√		√		√	√	√	√	√			
Byun et al., 2013	√		√		√	√	√		√			
May & Mohd Yaseen, 2013	√		√		√	√	√		√			
Middleton-White et al., 2013	√		√		√	√	√		√			
Martirano, 2014	√				√	√	√		√			
Parise et al., 2014	√		√		√	√	√	√	√			
Kwon et al., 2014	√		√		√		√	√	√	√		√
M. Li et al., 2015	√	√				√			√			
Rossi et al., 2015	√				√	√			√			
Kamienski et al., 2015	√				√	√			√			
Suresh S. et al., 2016	√		√		√		√				√	
Choi & Suk, 2016				√						√	√	√
Moon et al., 2016			√	√		√		√	√	√	√	√
Lee et al., 2016	√		√	√	√			√	√	√		√
Zhong et al., 2016	√		√	√	√				√	√		√
X.-Z. Zhang & Liu, 2018	√				√	√	√					
de Rubeis et al., 2017	√				√	√			√			
Castillo-Martinez et al., 2018	√	√	√	√		√	√		√		√	
This Study	√	√	√	√	√	√	√	√	√	√	√	√

Besides energy-savings, almost all lighting control systems had multi-objectives. Some studies also considered to improve user experience (Byun et al., 2013; May & Mohd Yaseen, 2013; Parise et al., 2014b). Some researchers advocated the integrated lighting control with occupancy sensors, photocells, and central control module for users' convenience and better experience (Middleton-White et al., 2013). A few researchers developed mobile applications for better user experience in terms of operability and mobility (Choi & Suk, 2016b; de Rubeis et al., 2017; Moon et al., 2016; Suresh S. et al., 2016). Evidence indicated that a well-designed mobile application can not only improve user experience, but also guarantee the compliance of illumination regulations and reduce energy consumption (Castillo-Martinez et al., 2018). In other studies, both illuminance and CCT were considered for improving users' visual comfort and wellbeing by adapting lighting environment to users' activity (Kwon et al., 2014; Lee et al., 2016).

It is interesting to note that in recent years studies increasingly focused on the improvement of control algorithms. Statistics, data modelling, and machine learning methods have been used for energy saving purpose, but yet rarely for other objectives. For example, a neural network controller was designed and tested. It could control the lighting level of lamps in a classroom with regard to the ambient illuminance and the number of people (Chen & Sun, 2013). In another study (L. Wang et al., 2015), in order to optimize the output of the lighting system by calculating daylight contribution, a data model based on statistics records was developed to determine the layout of lux sensors in large industrial buildings. Up to 80% energy savings on cloudy days was reported. Similarly, a statistical method was employed to optimize lighting control parameters, including sampling rate, converging speed, and error range of brightness, which achieved 55% or more energy savings (Chew et al., 2016). In a later study (Borile et al., 2017), an advanced daylight harvesting model was proposed, which could map the daylight contribution from ceiling to workplaces. It was reported to have better energy efficiency comparing to a reference method.

2.4.3 The-state-of-the-art lighting control systems

Recently, more and more learning-context based lighting control systems have been proposed (Choi & Suk, 2016b). By referring existing psychological research findings that can be found in Section 3.4, these proposed systems generally applied lower brightness and CCT for subjects like arts and language, and higher brightness and CCT for subjects like science and mathematics (Lee et al., 2016; Moon et al., 2016; Zhong et al., 2016). As summarized in Table 3, these systems provided illumination settings and control methods for a few basic learning scenarios. However, the lighting parameters and learning scenarios discussed in these studies were limited. First, the number of scenarios was not enough to cover the real-world educational activities. For example, elementary and secondary schools in China usually offer more than 10 subjects and activities; and the learning contents and teaching tools also keep changing with the development of economy and society. Second, the lighting configurations were either crude or static, without any dynamic and adaptive mechanisms. Third, the existing systems were only deployed in a few selected classrooms for experiments. Large-scale deployment for educational practice has not been reported.

Table 3. Learning scenarios and lighting parameters of reference studies

Study	No. of Learning Scenarios	Subject	Illumination Settings	
			CCT (K)	Brightness (lux)
Moon et al., 2016	5	Concentration/Mathematics	6500	600
		Language/Society	4500	400
		Creativity/Arts	3500	300
		Rest	3500	180
		Sleep	3000	<10
Lee et al., 2016	4	Mathematics and Science	5000–6000	600
		Language/Memorizing	4000–5000	400
		Arts	3000–4000	300
		Rest	N/A	N/A
Zhong et al., 2016	6 [1]	Arts, Science, Recess, Rest, Self-study and Exam	3000–5500	>300

[1] Focused on the functions and technical implementation but did not specify corresponding settings for each scenario.

Chapter 3

Classroom Illumination and Student Performance: Theory, Framework and Methodology

Researchers generally believe that brightness and CCT conditions in classroom have impact on learning performance. As we discussed before, the focus in this field has shifted to the learning-context phase, with research and engineering priorities to discover and support better lighting configurations for different classroom activities. However, the widely accepted knowledge for optimum learning-context based lighting schemas is still far to established. Inconsistent observations were reported from time to time, even under similar experiment settings. By revisiting existing research frameworks and methods, we realized that it is difficult to make big progress by using traditional methodology. But new approach based on existing knowledge and empowered by innovative technology can be develop and hopefully make breakthrough.

3.1 Relevant Standards

When determining indoor lighting configuration, no matter for research purpose or real practise, related standards and regulations must be considered. In other words, compliance with related standards should be the bottom line. There are a lot of national and industrial standards regarding indoor lighting environment around the worlds. Although the details may vary, these standards have many key indices in common. For example, desktop illuminance and uniformity should not be below 300 lux and 0.7 respectively according to the standards of many countries, like USA, EU, Japan, China, etc. Moreover, some countries, e.g., China, USA, and England, have dedicated lighting standard for schools. Workplace and classroom share many properties, but there are also many significant differences, such as activities, occupant density, and occupants themselves. For example, Chinese standards (*GB 7793-2010*) require that the illuminance and uniformity on the blackboard should not be below 500 lux and 0.8 respectively. Table 4 lists some most common standards from different countries and regions.

Table 4. Major indoor lighting standards

Standard	Country / Region	Year	Scope of application
GB 7793-2010. Hygienic Standard for Day Lighting and Artificial Lighting for Middle and Elementary School	China	2010	Middle and elementary schools
JIS Z 9110: 2010 General Rules Of Recommended Lighting Levels	Japan	2010	General indoor environment
EN 12464-1:2011. Light and lighting. Lighting of work places. Part 1	European Committee for Standardization	2011	Indoor workplace
ANSI/IES RP-3-13. American National Standard Practice on Lighting for Educational Facilities	USA	2014	Schools
Canada Occupational Health and Safety Regulations Règlement canadien sur la santé et la sécurité au travail	Canada	2015	General workplace
IEC TR 61547-1:2017 Equipment for general lighting purposes	International	2017	General indoor environment

3.2 Existing Research Frameworks

A conceptual framework about indoor lighting and human behavior, no matter it comes from theoretical duction or empirical induction, is relational statements that describes the relationship between lighting variables and their impact on the occupants. It makes the concepts clear and easily understood and can explain or predict the phenomenon in a general manner. Researchers have developed quite a few conceptual frameworks in this field. Although these frameworks were constructed from different perspective, their insights and drawbacks inspire us to design new approach. Here we summarized six representative frameworks.

Boyce (P R Boyce, 2004) proposed in the conceptual framework of three paths in which lighting affects job performance (see Figure 6) that visual effect directly or indirectly influences human performance through cognitive performance, task performance and motor performance. This model contains many factors, which makes it the most complex of the six models. It can help people to fully understand the mechanism of lighting factors working on human performance.

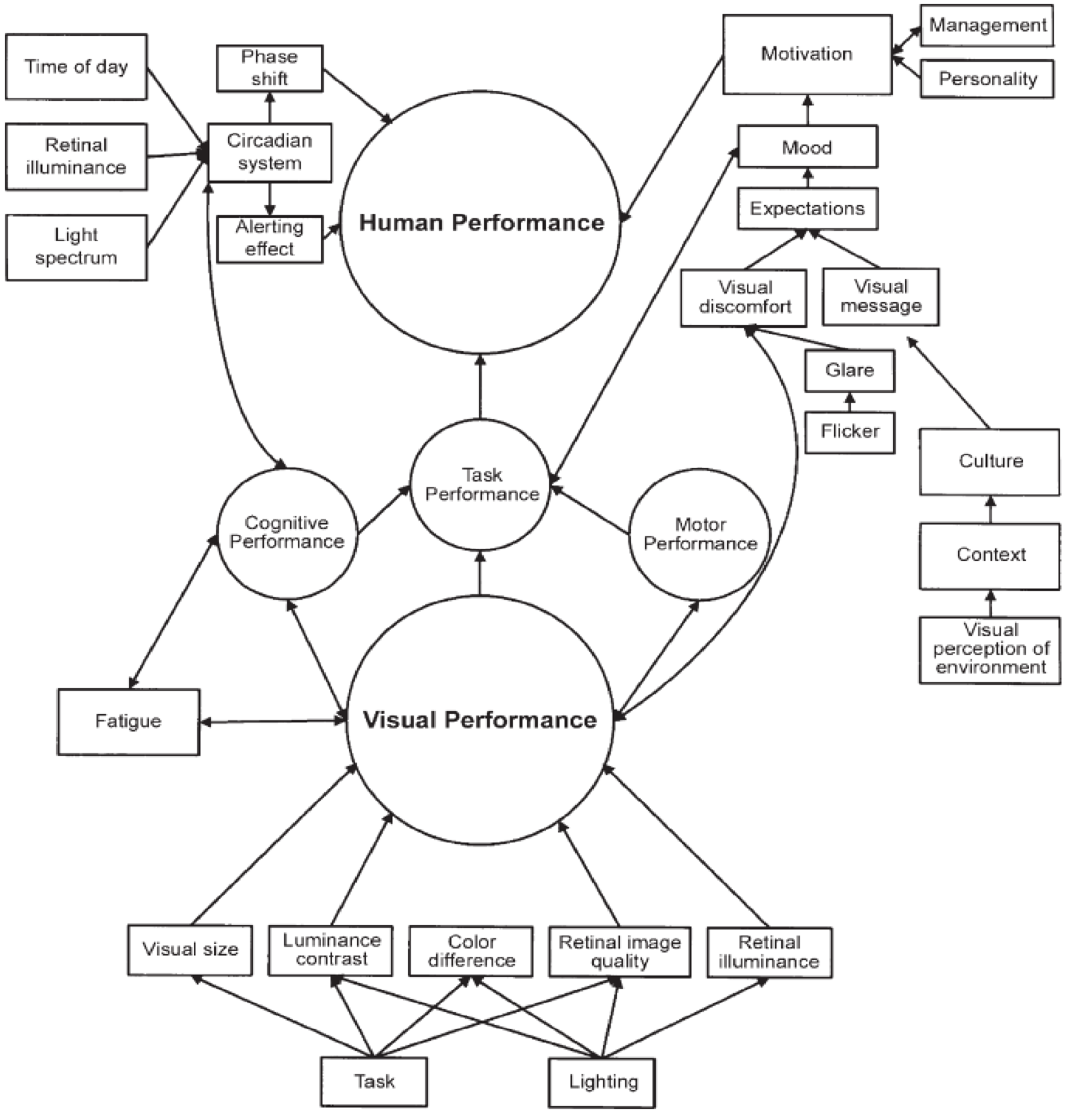


Figure 6. A conceptual framework with three paths whereby lighting influences human performance (P R Boyce, 2004)

Based on Boyce's model, Kretschmer (Kretschmer et al., 2012) proposed a simplified two channel conceptual model (see Figure 7). The innovation of this model is that the influence of light on cognitive performance can be divided into visual effect and non-visual effect.

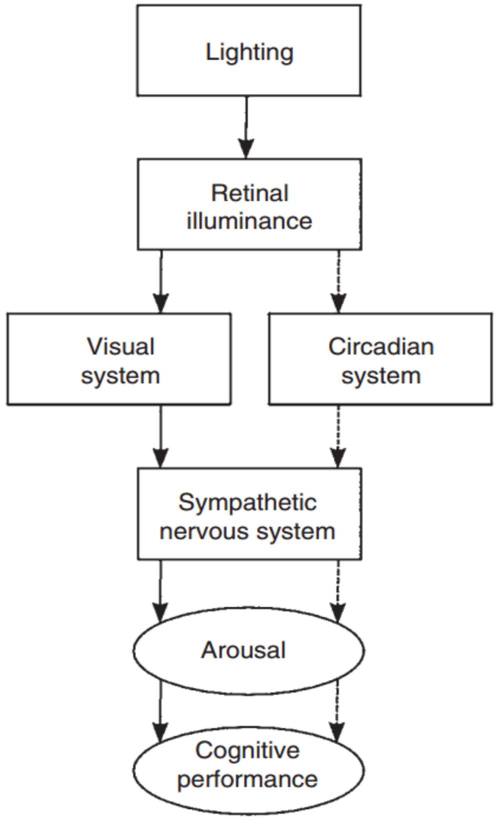


Figure 7. A simplified conceptual model of the relationship between lighting and performance including two pathways (Kretschmer et al., 2012)

Mott (Mott et al., 2012) proposed a conceptual framework for the impact of dynamic lighting on students' learning effect (see Figure 8). The framework is more targeted and distinguishes between natural light and artificial lighting, which has guiding value for engineering and practical application.

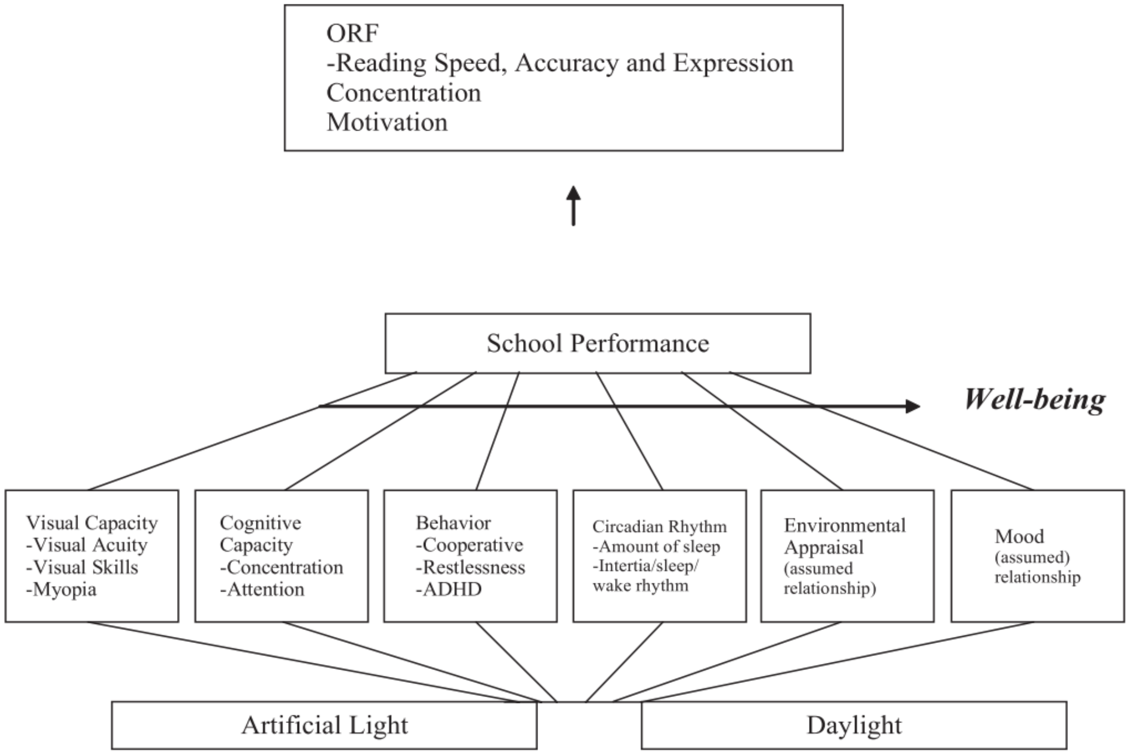


Figure 8. A conceptual framework of the influence of dynamic lighting on students' learning performance (Mott et al., 2012), ADHD: Attention Deficit Hyperactivity Disorder

Refer to Figure 9, a variable-based research framework (Samani, 2012) summarized the influencing factors into lighting quality, color, and individual differences (age and gender). It was innovative to study individual differences. However, individual differences cover a wide range, far beyond age and gender. In addition to physiological and psychological differences, cultural differences can not be ignored.

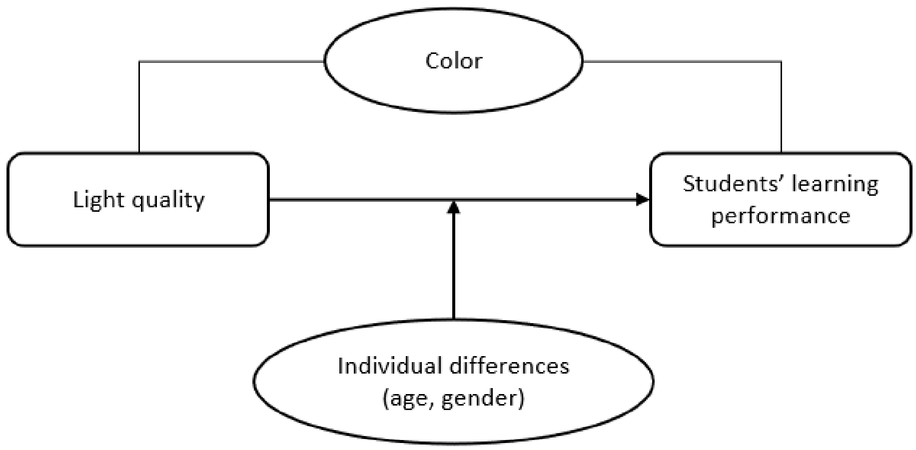


Figure 9. A variable-based research framework (Samani, 2012)

In a framework with pathways of lighting effect on psychological functioning proposed in 2014 (de Kort & Veitch, 2014), includes two parts: visual influence and non-visual influence. In the case, it is similar to that from Kretschmer (Kretschmer et al., 2012). As can be seen in Figure 10, the main difference is that the later one added the interaction between visual and non-visual influences.

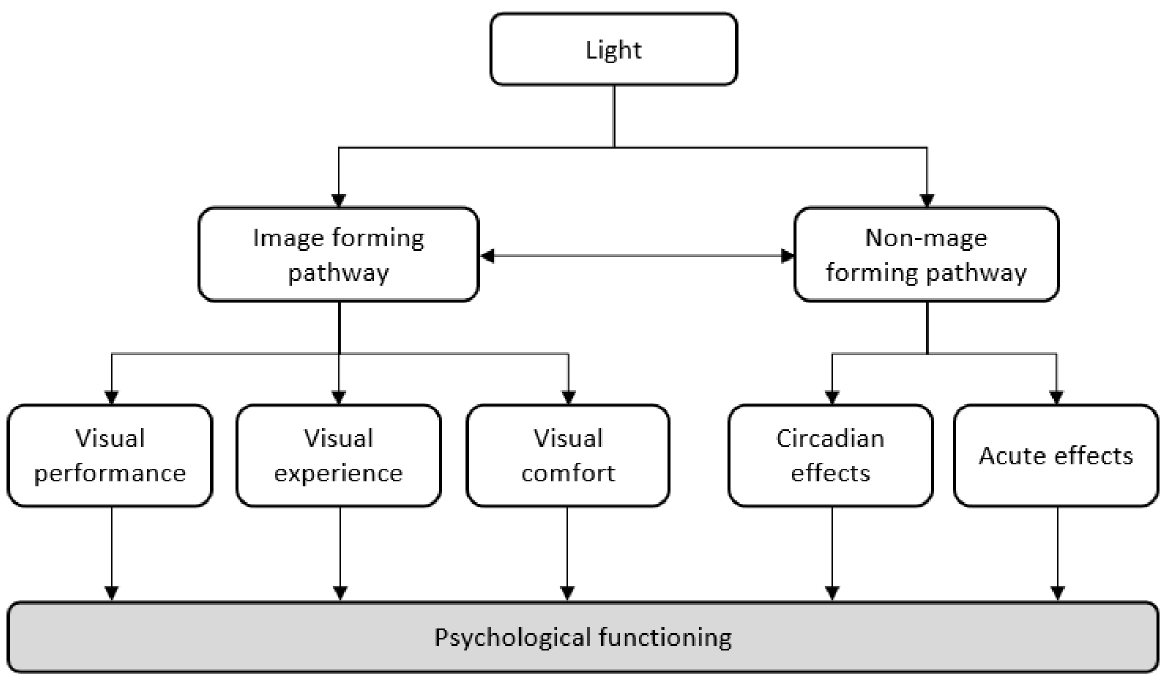


Figure 10. Pathways of light relevant to psychological functioning (de Kort & Veitch, 2014)

As shown in Figure 11, the conceptual framework proposed by Pulay (Pulay, 2015) divides the influence of light on students into behavior and cognition, and there is interaction between them. These effects come from three aspects: physiological, psychological and hormonal. But only CCT was tested in Pulay's study.

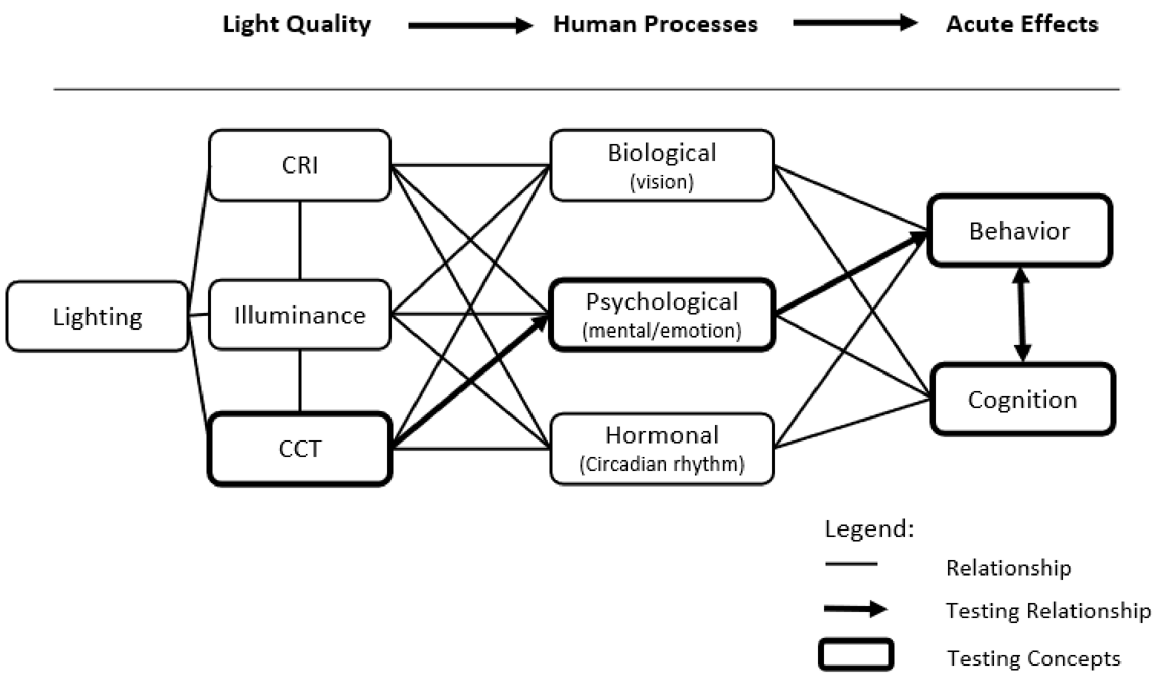


Figure 11. A conceptual theoretical framework of the influence of light on students (Pulay, 2015)

3.3 Traditional Experiment Methods and Tools

The design of control group and experimental group was used in the previous related experimental research, and most of them included both pre-test and post-test. The sample size of most of experiments is less than 100 ($n < 100$). The measurement of dependent variables in these experiments can be divided into the following four categories.

1. **Physiological indicators:** the physical signs of the participants were measured with physiological equipment, and the physiological or psychological state of the participants was reflected by the measured data. The specific methods include electrocardiogram (ECG), electroencephalogram (EEG) and electrodermal activity (EDA). For example, Choi & Suk (2016) used ECG as a pilot experiment to confirm that different color temperatures can trigger different physiological reactions; Shin et al. (2013), Park (2015) measured EEG to determine

the degree of attention and relaxation of subjects; Smolders & de Kort (2017) used ECG and EDA as auxiliary means to record the physiological changes of subjects during the test.

2. **Cognitive task indicators:** include the performance of reading, arithmetic, typing, puzzles and other tasks.

3. **Cognitive psychology tests and scales:** d2 visual search attention test; Karolinska Sleep Scale (KSS); Psychomotor Vigilance Task (PVT); State Self-control Capacity Scale (SSCCS); Aventura Karimov Table (AKT). The references of related methods are shown in Table 5.

4. **Subjective questionnaire:** questionnaire is widely used in related research to measure the subjective feelings and preferences of subjects. In most studies, subjective questionnaires were used as supplementary methods; some studies were all based on questionnaires (Gilavand, 2016).

Table 5. Commonly used psychological test methods (Sun et al., 2018)

Purpose	Method	Type	Description	Evaluating Indicator
Self Control Ability	SSCCS (Smolders & de Kort, 2014)	Subjective test	The test consisted of 25 questions. The participants chose 1 (incorrect) to 7 (very correct) for each question.	The higher the score meams the weaker the self-control ability.
Vigilance	KSS (Kaida et al., 2006)	Subjective test	The participants chose their own level of alertness according to their subjective feelings.	From 1 to 9, 1 indicates extreme alertness and 9 indicates very sleepy.
Vigilance	PVT (Graw et al., 2004)	Reaction test	The reaction speed of participants to random visual signals was tested by 5 to 10 minutes.	The main statistics are the times of not responding in time.
Attention	d2 (BATES	Reaction	From a series of texts	1. Attention: the number

	& LEMAY, 2004)	test	composed of the letters *d* and *p* and one or four short lines above or below the letter, find the symbol combination of *d* and two short lines.	of entries handled correctly minus the number of violations 2. Quality of work: percentage of errors
On-task Performance	AKT (Yong-hong et al., 2010)	Reaction test	1. Attention: the number of entries handled correctly minus the number of violations. 2. Quality of work: percentage of errors ABCEHKNX eight letters were randomly arranged into 30 lines and 40 columns, each letter appeared 150 times, a total of 1200 characters. Participants are asked to cross out the assigned letters.	The reading speed (words per minute), error rate and mental work ability are calculated. Mental work ability = number of words read / 2 × (number to be deleted - number of errors deleted) / number of words to be deleted.

Table 5 cont. Commonly used psychological test methods (Sun et al., 2018)

In addition, it should be noted that many studies use more than one testing methods, such as EEG combined with simple tasks, D2 combined with questionnaire, and so on. In a study with multiple testing methods, some were for different indicators, while some were for cross-verification to the same goal. However, in a few studies, two tests for the same goal gave contradictory results. For example, the results of d2 test and subjective questionnaire in the research of Sleegers et al. (2013) were inconsistent.

3.4 Existing Findings and Inconsistency

As we stated in Section 2.3, the focus of classroom lighting research has gradually shifted to the phase of learning-context based lighting. Previous studies focused on the effects of lighting parameters, such as different brightness and CCT, on the physiological and cognitive performance indicators of students. Recently, a few researchers began to pay attention to the influence of lighting configuration on students' learning performance in different teaching scenarios. Although these studies have different definitions of teaching scenarios (such as simple, standard and intense, or mathematics, art, social interaction, and rest), their goals are consistent, that is, to find the optimal lighting configuration that matches the teaching context and teaching objectives. We summarized some representative studies, as shown in Table 6. From the literature that can be retrieved, research on this direction is insufficient. There are still many inconsistent conclusions.

Table 6. Existing studies and findings about learning-context based lighting and student performance (Sun et al., 2018)

Study	Country/ Region	Age	Sample size	Duration	Test Scene	Lighting Modes	Test Method	Conclusion
Barkmann et al. (2012)	Germany	8 and 16	94	9 months	Real life	7 modes. But only one of them was tested	d2 test, reading test and survey	High brightness and high CCT (1060 lux, 5800 K) reduced students' errors in attention test and improved reading speed, but the improvement of reading comprehension was not significant.
Wessolowski et al. (2014)	Germany	8 and 16	92	9 months	Real life	7 modes. But only one of them was tested	Move-it, Conners Rating Scales, Agressivenness Scale, etc.	Low brightness and low CCT (325 lux, 3500 K) improved students' social behavior.

Sleegers et al. (2013)	Holland	9 and 12	89	1.5 months	Real life	4 modes. But only one of them was tested	d2 test	High brightness and high CCT (1000 lux, 6500 K) significantly increased the attention of students from grade 4, but not significant for students from grade 6
Keis et al. (2014)	Germany	17 to 22	58	5 weeks	Lab	3 modes: 300 lux with 3000/3500/ 5500K	d2 test, ZVT test, VVM and survey	Compared with 3000 K and 3500 K, CCT 5500 K improved attention and cognitive processing speed, but had no significant effect on working memory processing and retrieval
Choi & Suk (2016)	Korea	10	Test 1: 31 Test 2: 54	Test 1: 30 minitu es Test 2: 2 weeks	Lab	3 modes: 500 lux with 3500/5000/ 6500K	Math test and survey	No reasonable conclusion drew from Test 1. The Test 2 showed that CCT 6500 K could improve mathematics performance, and 3500 K was more popular among students during rest.
Lee et al. (2016)	Korea	N/A	N/A	N/A	Real life	5 modes	N/A	All the lighting settings were in the Kruithof comfort zone, but there was no result regarding performance reported.

Table 6 cont. Existing studies and findings about learning-context based lighting and student performance (Sun et al., 2018)

According on the summary of existing studies, researchers generally support that brightness and CCT have an impact on learning performance. In addition, most of them believe that high brightness and high CTT can improve attention and cognitive performance. However, in fact, this opinion is still lack of sufficient research data support, and even some related studies have reported conflicting conclusions (Higgins et al., 2005). For example, based on experimental data, Park (2015) argued that neither higher CCT improved students' attention and cognitive activities, nor lower CCT made students more relaxed and quiet. The experimental results of another study (Smolders & de Kort, 2017) showed that compared with lower CCT, higher CCT environment did not bring significant beneficial impact on the mental state and performance of college students, nor did it produce physiological activation effect. In addition, an experiment in China (Yong-hong et al., 2010) reported that college students' learning efficiency was the highest in the medium CCT (4000 K) environment, and the visual / brain fatigue was the lowest in the environment of high CCT (6500 K). Furthermore, some experiments showed that there was no significant difference between the responses to light of female participants and male participants, while others gave the opposite results (Knez & Kers, 2000). Even in some experiments, the same lighting environment was reported to have significant impact on the students of grade 4, but no significant impact on those of grade 6, and the results of attention test and subjective questionnaire were also contradictory (Sleegers et al., 2013).

3.5 Proposed Theoretical Framework

It is commonly accepted that lighting environment has impact on performance, and many researchers believe that dynamic lighting settings benefit students in multiple learning contexts. However, the individual difference has barely been examined so far. As covered in Section 3.2, existing conceptual frameworks tended to dive into detailed pathways that indoor lighting could have influence on human performance. This may either make a framework too complicated with many possible links, or too dedicated with limited logic route. Inspired by the idea of machine learning, a simplified theoretical framework was proposed and illustrated in Figure 12. This framework does not consider the impact of the independent variables or the controlled variables individually. Instead, it treats a group of pertinent variables as one composed input component. The framework can take more than one input components, and each component can contain multiple features. The student with group and individual features is acting as a processor. The processor takes inputs from the components and produces the output of interest.

In our case, one input component is the classroom lighting environment, which contains different combinations of brightness and CCT. The other input component is the learning context. They work on the students and yield performance data.

In addition, a smart lighting system is plugged into the framework. It records data from all other modules and dynamically control the lighting environment, which means as long as long the system can accumulate enough data, it will eventually lead to the best output for any learning context.

The framework can also be extended to include more environmental variables, like temperature, humidity, noise, PM2.5, TVOC, CO2, etc. It gives the framework great generality.

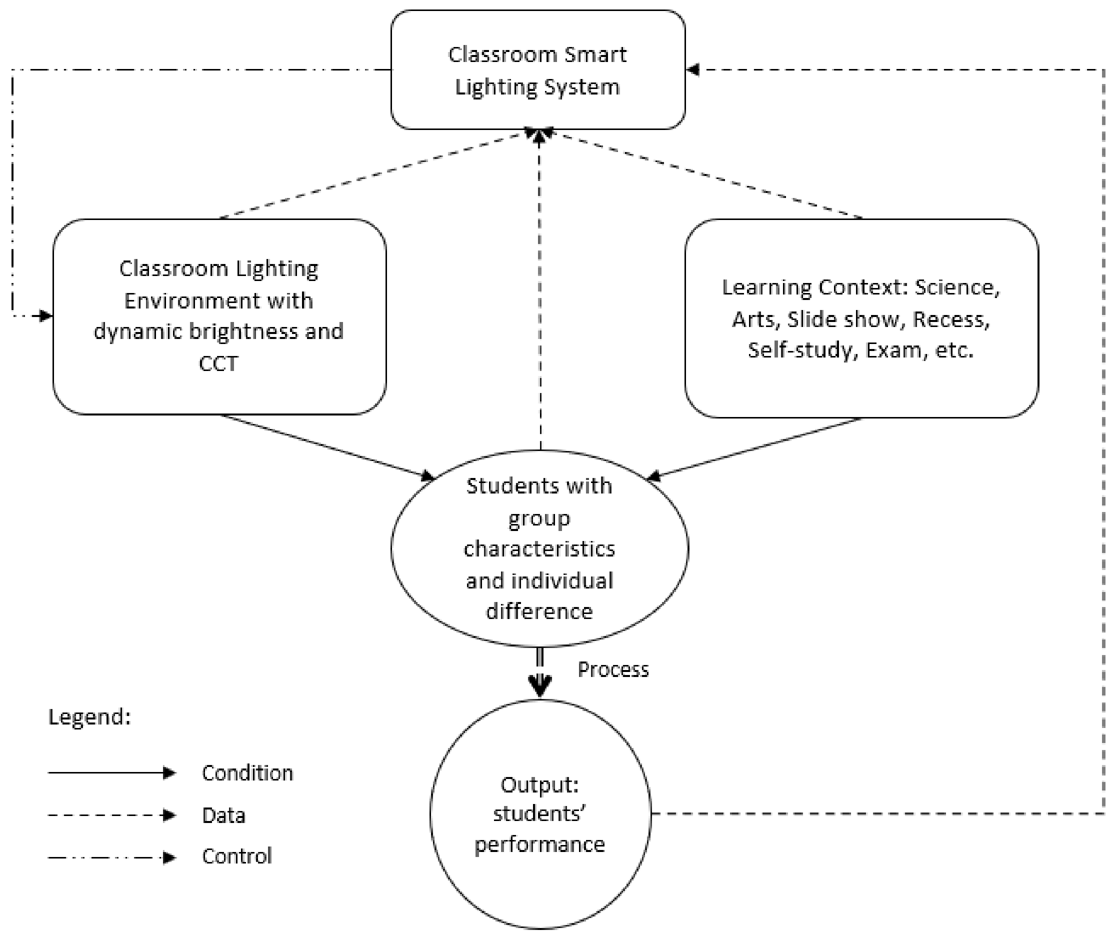


Figure 12. Proposed theoretical framework for classroom lighting

3.6 Ten Proposed Lighting Modes

In this study, we proposed 10 lighting modes to match different kinds of educational activities in classroom. Table 7 describes the settings and the purpose of each mode.

Table 7. Ten proposed lighting modes for common learning contexts

Learning Context	Illumination Settings		Purposes
	Teacher Zone	Student Zone	
* Standard	350 Lux, 5500 K	350 Lux, 5500 K	Regular settings can act as default configuration
* Science	800 Lux, 6500 K	500 Lux, 6500 K	Enhance alertness and arousal, better for science courses like physics, math, chemistry, etc.
* Arts	800 Lux, 5000 K	500 Lux, 4000 K	Bright and warm environment can inspire creativity, better for courses like music, painting, language, etc.
* Recess Time	Off	200 Lux, 3000 K	Easy and relaxing lights for better rest and recovery for next class
* Slideshow	Off	5000 K, Front/Middle/Rear: 100/200/300 Lux	Better screen vision for slideshow
* Self-study	Off	500 Lux, 5000 K	More focus on one's own work
* Class Over	Off	Off	Energy saving
Exam	Off	650 Lux, 6500 K	Altering and concentrating yields better results
Performing	800 Lux, 6000 K	Off	Center of attention
Group Teaching	450 Lux, 4500K	On team working, keep overhead lights of each team at 450 Lux and 4500 K; On presenting of specific team, dim up the lights of that team to 600 Lux and dim down those of other teams to 300 Lux.	Encourage interaction within team members, but suppress disturbance between teams

Note: those with "*" mark are frequently used lighting mode.

These proposed lighting modes were designed by consulting the conclusions from existing scientific studies in a comprehensive way and complying with related lighting standards and regulations (refer to Section 3.1). For example, brighter light (1000 Lux) was believed to improve vigilance and self-control capacity (Smolders & de Kort, 2014), and students showed more focused attention in challenging tasks under higher illuminance (1000 Lux) with higher CCT (6500 K) (Sleegers et al., 2013). Meanwhile, students performed better for highly sensitive cognitive tasks (Fabio et al., 2015) and 3D objects rotation tasks (Ferlazzo et al., 2014) under neutral white light (CCT = 4000 K), while variable light could reduce students' restlessness and improve their social behaviors (Wessolowski et al., 2014). Furthermore, shifting CCT among 3500 K, 5000 K, and 6500 K was suggested in accordance with easy, standard, and intensive learning activities, respectively (Choi & Suk, 2016).

3.7 Revised Kruithof Curve with Constraint

Although there is no uniform regulation on brightness level and color temperature level in lighting industry and academia, most researchers tend to take lux value below 300 lux as low brightness, 300 to 600 lux as medium brightness, and 600 to 1000 lux as high brightness. Brightness of higher than 1000 lux could do harm to occupants, and cost more energy, as is not recommended. On the other hand, 2700 to 3500 K, 3500 to 5000 K, and 5000 to 6500 K are considered as low CCT, medium CCT and high CCT, respectively.

When the above constraints are applied on the Kruithof curve, we can get a revised Kruithof curve. Then it is employed to examine every proposed lighting mode. As shown in Figure 13, the combinations of illuminance and CCT of all lighting modes stay inside the pleasing zone of the revised Kruithof curve. It is reasonable that the brightness of recess mode is below the constrain (300 lux) because we do not really need concentration but relax during recess time, and lower brightness can also save electricity.

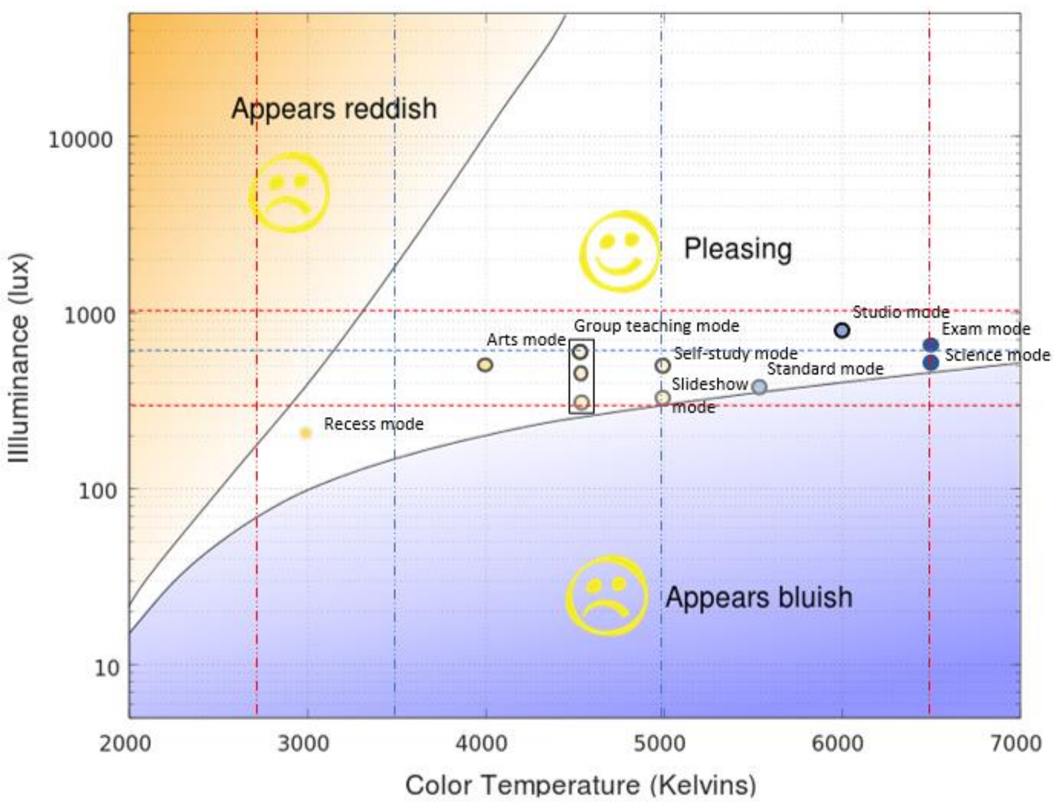


Figure 13. Proposed lighting modes on the revised Kruithof curve with constraint

Enhanced version of Figure 16 “Proposed lighting modes within pleasing zone of Kruithof Curve” (Sun et al., 2020)

3.8 Proposed System Framework: Classroom Environment Data-Collection and Self-Optimization System

Existing findings about lighting configuration and student performance were mostly obtained from controlled laboratory experiments. Such a method is limited due to small sample sizes, short test duration, and limited variables considered in each study. These restrictions were believed to be the major causes that led to inconsistency among existing results from previous studies (Fabio et al., 2015; Moon et al., 2016; Sleegers et al., 2013). Although the uses of IoT technology provide the context for new data sources, a real challenge is the integration of multiple systems and datasets (M. Bublitz et al., 2019). A new approach to solve this problem is to utilize Big Data methodology and technology. By taking the advantage of real world data and machine learning, a classroom environmental data processing framework with the following features was proposed.

1. Using student test results and exam grades to evaluate the impact of lighting configuration on students' performance.
2. Automatic data processing and parameter optimization
3. Allowing interaction and intervention of users
4. Generalizability and extensibility

Figure 14 illustrates the mechanism and workflow of the proposed system framework, which is comprised of two pivotal processes: The control flow and the self-optimization flow.

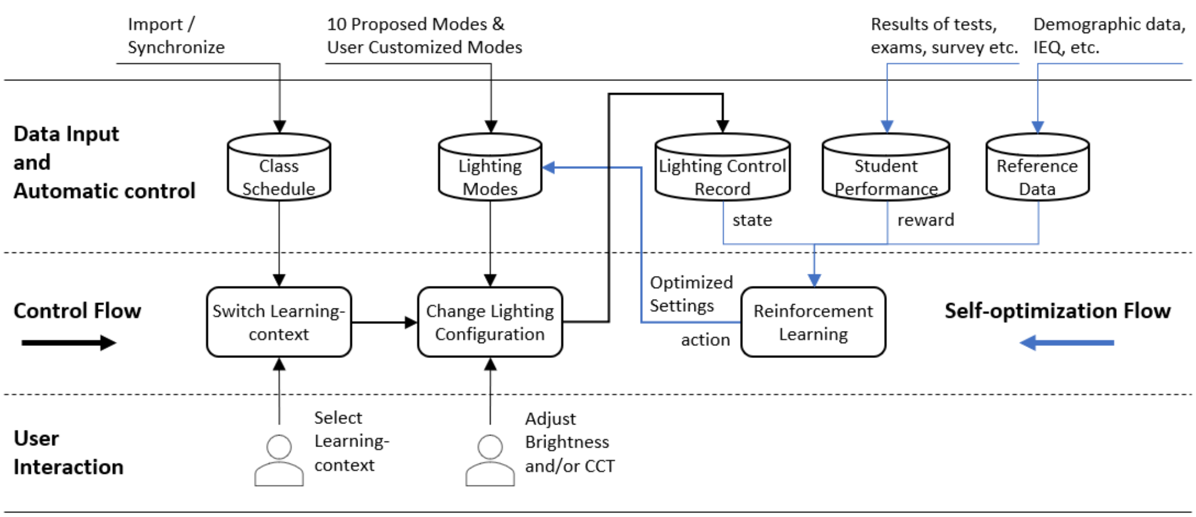


Figure 14. Classroom lighting environment self-optimization framework (Sun et al., 2020)

The control flow automatically reads class schedule and switches learning context accordingly, while the teacher can manually select learning context. Once learning context is changed, the system will load the corresponding lighting configuration from the lighting mode database, which initially contains the 10 proposed modes as introduced in Section 3.6. In this case, a user is allowed to customize lighting modes or apply ad-hoc settings on site. Any change of lighting system, whether automatic or manual, will be recorded for algorithm training.

The core part of the self-optimization flow is a set of learning agents of a reinforcement learning (RL) model. One agent corresponds to a specific learning context and its objective is to maximize the classroom's average test score of the courses associated with that learning context. The agent takes the corresponding lighting configurations during a period (can be configured) as the current state of the environment. The agent uses the test scores of the corresponding courses during the same period to calculate the reward and determines how to optimize the lighting parameters for the learning context. Above is the basic idea of the RL model, whereas the detailed discussion of the algorithm is beyond the scope of this article and will be reported in a separate paper.

Theoretically, through long-term data accumulation and self-training, the lighting configuration can be gradually optimized. However, a few practical questions should be considered and dealt with.

- The demographic diversity of students should be considered. The system should support the input of demographic data, such as age and gender. Different learning agents of RL can be made for different demographic groups.
- The effects of other environmental factors need to be considered. The system should be able to collect other environmental data such as temperature, humidity, and CO_2 density. Then, the scope of the RL can include more environmental variables in addition to lighting configuration in support of more comprehensive models.
- The changes of classrooms should be considered. Students usually change their classrooms in different grades. The system needs to record the changes and properly maintain the connection between students and their classroom assignment for the RL model.

Moreover, this framework can be extended by considering other dependent variables about student wellbeing such as myopia rate, sick leaves, and mental health. The data collected from this framework will support the analysis of the impact of classroom environmental factors on student wellbeing.

Chapter 4
Learning-context Based Smart Lighting System

Traditionally, research about the impact of classroom lighting on students' performance belongs to psychological domain, while the smart lighting system is usually categorized into engineering domain. As we summarized in Chapter 2, there were rarely interdisciplinary studies that converged the cutting-edge technology and the state-of-the-art research topics. Considering that there are still many inconsistencies regardless the already years-of-research about the learning-context based lighting, we believe it would hardly make breakthrough if we kept following the traditional methodology. In order to support the new research framework (see Section 3.5), an innovative lighting control system is needed. Such a system, including both hardware and software, should meet the following requirements:

1. Can control both brightness level and CCT.
2. Can control based on zones in the classroom.
3. Allows automatic control of lighting based on classroom learning context, in additional to manual control.
4. Optimizes classroom lighting environment for best student performance by applying knowledge from scientific research.
5. Can take feedback such as students' performance data and continuously improve lighting configurations.

We designed and developed a learning-context based smart lighting system, which provides more lighting scenarios and supports dynamic control of luminous level, CCT, and illuminance distribution. It has multiple objectives including students' performance (most important), energy saving, manageability, and user experience. The system had been deployed in eight schools by the end of December 2019.

4.1 System Structure

As shown in Figure 15, the learning-context based smart lighting system mainly consists of four parts at the near-end, including the IoT gateway, the LED lights with driver controls, the control panel, and the sensor groups, as well as a cloud platform at the far-end.

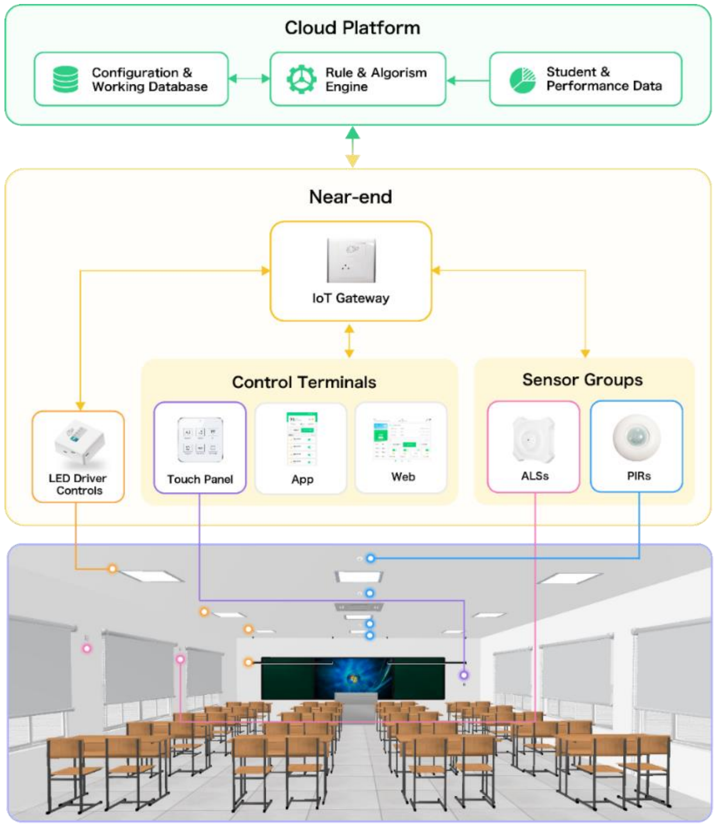


Figure 15. Structure of learning-context based smart lighting system (Sun et al., 2020)

ALS: Ambient light sensor; PIR: Passive infrared sensor

As the core device of the near-end system, IoT gateway, a.k.a. fog node, has a certain computational and storage capacity. It is the bridge between end-point devices and the cloud platform, responsible for message transfer and end-point devices management. One classroom is usually equipped with one IoT gateway.

In this design, each set of illumination unit includes an LED driver control and up-to-four LED fixtures. Each LED fixture supports dimming of brightness and CCT by means of PWM (Pulse Width Modulation). In order to save cost, one LED driver control is usually designated to one zone, where it requires isolated lighting control. For example, the classroom picture in Figure 2 delineates a typical configuration with four LED driver controls corresponding to four zones respectively, including one podium zone with two or three blackboard lights and three student zones (front, middle, and rear) with three classroom lights in each zone.

The control panel is a physical touch-panel with several function buttons. The control panel offers the user a convenient and quick way to operate the lighting system, including all lights on/off, zone on/off, and scene switching. Moreover, the button layout and function map of control panel can be customized according to users' requirements. In this study, two types of control panel as shown in Figure 16 are designed to meet users' preferences. The one with five touch-buttons is for zone-based switch. The other with six touch-buttons is for scene switching.

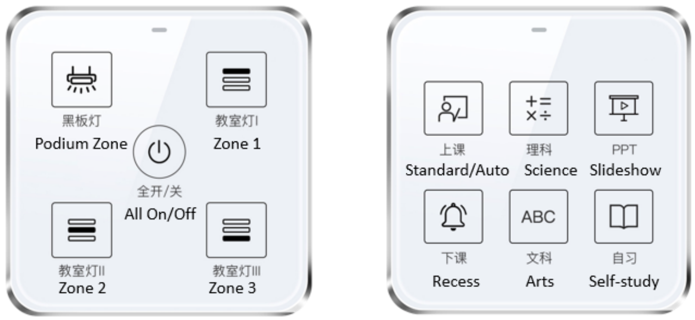


Figure 16. Control panels: Zone switch and Scene control (Sun et al., 2020)

A sensor group is a combination of ambient light sensor (ALS) and/or passive infrared (PIR) sensor distributed in one classroom zone. The ALS is used to measure luminous level of the zone, and the PIR detects movement in the zone. By integrating information from multiple sensor groups, the system can determine the illuminance distribution and occupancy in a classroom.

The cloud platform communicates with IoT gateways via Wi-Fi. The cloud platform can remotely manage and control LED drive controls and other near-end modules through the IoT gateway in a classroom. Other system level functions, such as system configuration, system management, system monitoring, data storage, and analysis, are also provided by the cloud platform.

It is notable that the near-end devices in a classroom are designed as an autonomous local star network on RF2.4G (Radio Frequency 2.4GHz). The IoT gateway is the central node of the star topology, which has a replica of the classroom's configuration. This means that the IoT gateway can independently manage the lighting system even if the connection to the cloud platform is lost. Such design ensures the robustness of the system. The loss of internet connection will only affect a few non-critical functions such as updating configuration, uploading sensor data, and internet remote control.

4.2 Hardware Design and Implementation

The main parts of the smart lighting system include IoT gateway, LED control, control panel, sensor modules and LED fixtures. Except for LED fixtures, all the other hardware parts are originally designed and implemented by the research team. Table 8 lists the key components of these system hardware. And Figure 17 shows the block diagram and the PCB (printed circuit board) of the IoT gateway.

Table 8. Key components of system hardware parts

Component	Model	Main Parts				
		IoT G/W	Control Panel	LED Control	PIR	ALS
32-bit MCU	Particle P1	√				
8-bit MCU	STM8L151K4		√	√	√	√
RF2.4G	nRF24L01P	√	√	√	√	√
Relay	G3MB-202P	√				
AC-DC	NJ02-AXXL	√				
AC-DC	HLK-PM01		√	√		
Battery	Lithium Battery				√	√
Digital Touch Sensor	TTP226			√		
Infrared Sensor	RE200B				√	
Photo Resistor	5516					√

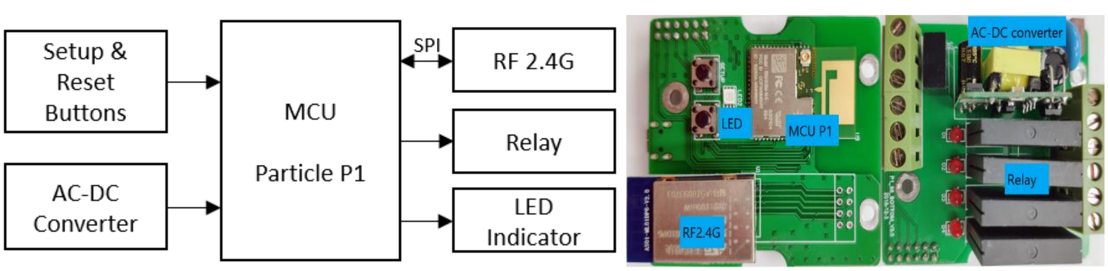


Figure 17. Internet of Things (IoT) gateway block diagram and working board (Sun et al., 2020)

The LED fixtures with power drivers are purchased from local professional manufacturer. The LED fixtures support precisely control luminous level (maximum 3550 LM) and CCT (3000K to 6500K) by means of PWM. Although the system has specific requirements to the LED fixtures, it is easy for most LED manufacturers to produce by following the specification.

Please refer to our published article (Sun et al., 2020) for detailed design and more information about system hardware.

4.3 Software Design and Implementation

4.3.1 Lighting Mode Control Flow

4.3.1.1 Manual Control

As shown in Figure 18, users have several ways to invoke a lighting mode switching instruction, such as control panel, remote control, software (e.g., APP, HTML5 page, WeChat) and voice command. The instruction is transmitted to the IoT gateway, then passed to the corresponding LED power controls by the gateway. On the other hand, the gateway gathers status of subordinate nodes and reports to the cloud. The cloud platform reflects the change of status on the UI.

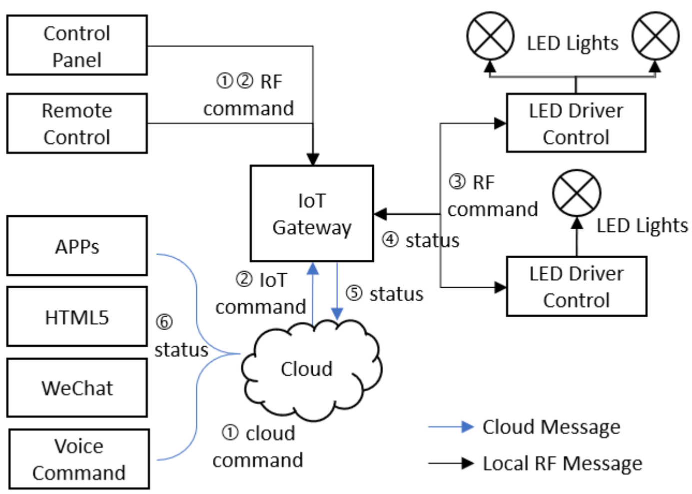


Figure 18. Flowchart of manual control of lighting mode (Sun et al., 2020)

4.3.1.2 Learning-context Automation

Besides manual operation, the suggested system also supports lighting mode and class schedule association. After the linkage is set, the system can automatically change lighting modes according to the current learning context. The control flow is depicted in Figure 19.

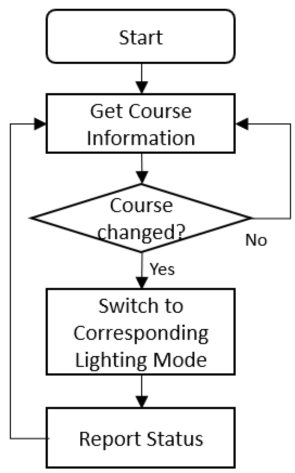


Figure 19. Flowchart of learning-context automation (Sun et al., 2020)

4.3.2 User Interface

As demonstrated in Figure 20, the purposes of user interface (UI) of the suggested system can be roughly put into two categories: Control and monitoring. The control features of UI allow users to control each lighting fixture or each zone of lighting fixtures, switch lighting mode, as well as add user-defined mode and change the settings of existing lighting modes, including switch state, luminous level, and CCT. The monitoring features of UI give users intuitive views of real-time states and data for lighting fixtures and sensors. Additionally, all user interfaces of the system are built with HTML5 and suit both tablet and smartphone screen modes to meet the needs of different kinds of interaction scenarios.

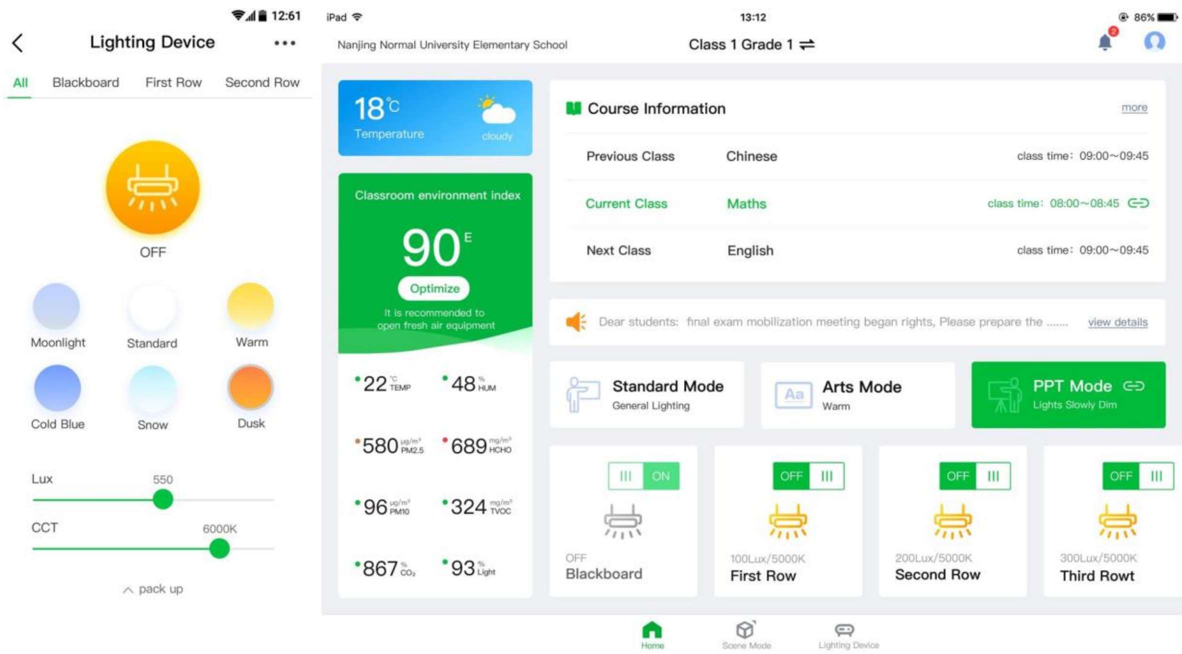


Figure 20. User interface of smart classroom lighting system (left: smartphone; right: tablet) (Sun et al., 2020)

4.3.3 IoT Gateway Software Design

As shown in Figure 21, the embedded software on IoT gateway is composed of three major modules: One core processor and two message processors. The local message processor is responsible for message exchange within the local RF2.4G network, while the cloud message processor is in charge of communication with the cloud platform. The core processor primarily contains a node management module, a business logic module, a configuration module, and a log module. The node management module oversees registration, presence management, and real-time monitoring of sub-nodes at the near end. As the pivotal component of the core processor, the business logic module controls the procedure of business logic, such as scene switching, rule matching, and automation. The configuration module manages the settings of the gateway and synchronizes local configuration with the cloud platform if needed. The log module records the gateway's working log, which can be used for system alerts and troubleshooting.

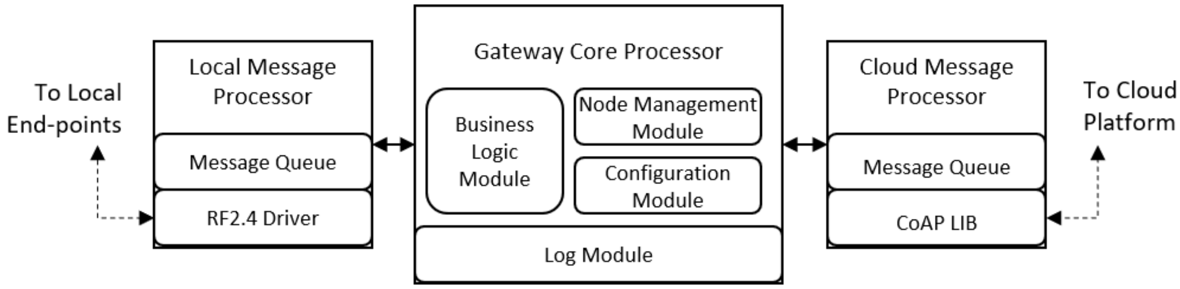


Figure 21. Software high-level design diagram of IoT gateway (Sun et al., 2020)

Essentially, the business logic module is an embedded rule engine. To achieve an ultra-lightweight rule engine that can run offline with limited MCU resources, we designed a new 'SMART' architecture, which is composed of five components. As shown in Figure 22, among the five components, 'S' stands for scenario and corresponds to a specific learning context. 'M' stands for alarm & timer and is used for timing control. 'A' stands for action and is a set of control messages for one or more nodes. 'R' stands for rule. A rule links the scenario, timer, and action together, and can specify trigger conditions. T stands for table & report. The statistical report is used to record data statistics for specific sensor data, actuator status and rule execution. The data of statistical report can not only be used for analysis and display, but also be used as trigger conditions of rules.

The IoT gateway has the ability to function independently without the supervision of the cloud. This means that the IoT gateway can independently manage the lighting system even if the connection to the cloud platform is down.

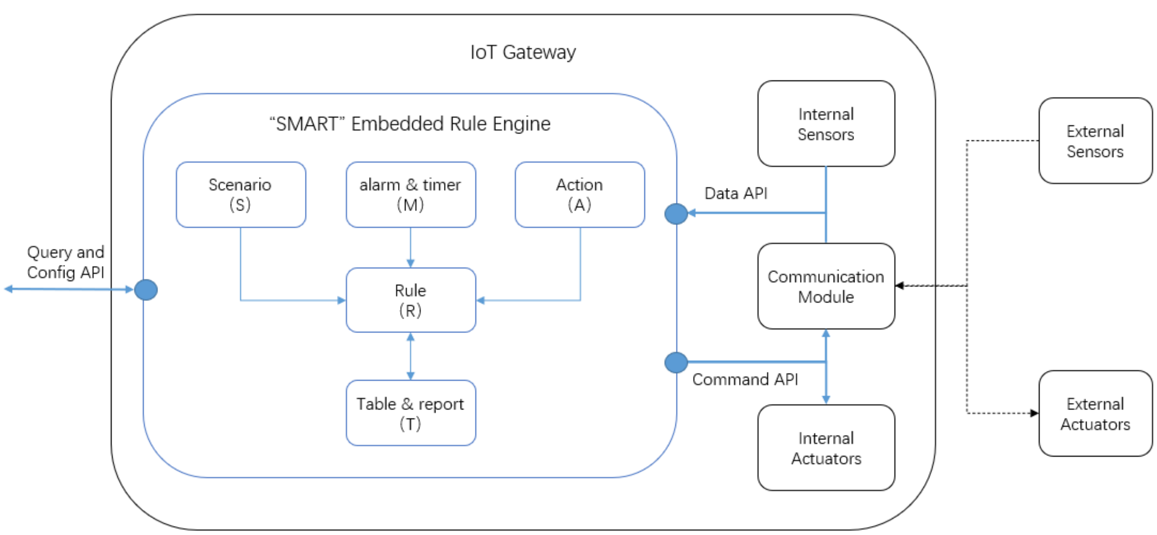


Figure 22. Structure of the embedded rule engine on IoT gateway

4.3.4 Cloud Platform and Communication

4.3.4.1 Open-Source Cloud Platform

The cloud platform was an enhanced version of Spark-server, which is an open-source project on GitHub (https://github.com/particle-iot/spark-server). The major improvements performed by us focused on manageability and reliability, including system monitoring and alerting, gateway management, user and permission management, statistics, firmware version, and upgrade management.

4.3.4.2 Cloud Communication Protocol

The IoT gateway communicates with the cloud platform via Wi-Fi module, and the CoAP (Constrained Application Protocol) is employed for message transmission. The cloud messages are assembled into json format, and Table 9 gives some examples of them.

Furthermore, the service applications on the cloud platform speak to each other by means of message queue (Rabbit MQ), and https protocol is used for interaction between the UI and the backend services to achieve improved security.

Table 9. Cloud message examples (Sun et al., 2020)

Function	Example	Description
Set Switch	{‘cmd’:1, ‘nd’:1, ‘state’:1}	Turn #1 light on
	{‘cmd’:1, ‘nd’:1, ‘state’:0}	Turn #1 light off
Set Brightness	{‘cmd’:3, ‘nd’:1, ‘value’:60}	Set #1 light to 60% brightness
Set CCT	{‘cmd’:5, ‘nd’:1, ‘value’:3500}	Set CCT of #1 light to 3500K
Set Light State	{‘cmd’:2, ‘nd’:1, ‘ring’: [0,1,60,3500]}	Turn on #1 light with 60% brightness and 3500 K CCT

Please refer to our published article (Sun et al., 2020) more details regarding the software design and implementation, such as RF2.4G protocol, end point software and workflow, security and reliability considerations, etc.

4.4 Deployment of the smart lighting system

After the development of the proposed smart lighting system, it has been deployed at eight schools of China since August 2017. The largest deployment among them was at an elementary school located in Langfang, Hebei province. In this deployment, the florescent tubes of 13 classrooms were replaced by the new LED smart lighting system. The photographs in Figure 23 demonstrate the changes of the replacement. Specifically, the devices of the smart lighting system equipped a classroom are listed in Table 10.

Figure 23. Comparison before and after classroom renovation (Sun et al., 2020)

Table 10. Smart lighting devices installed in one classroom

Device	Quantity	Functions
IoT G/W	1	Device management, comminication bridge and edge computing
ALS	3	Measuring illuminance by zone
PIR	4	Occupancy detection on zone basis
IAES [1]	1	Collecting indoor environmental parameters for futhure analysis
LED blackboard-fixture [2]	2	Dimmable lighting for podium zone
LED classroom-fixture [2]	9	Nine (3 by 3) dimmable LED classroom-fixtures with the power driver. One row of three fixtures forms a zone.
Zone switch panel	1	Zone lights on/off control
Scene control panel	1	Fast switching lighting mode
Android tablet	1	Optional user interaction device, which is usually attached beside the front door of the classroom or embedded into the podium.

[1] IAES (Integrated Ambient Environment Sensor) integrates multiple sensors into one board. It can sense a couple of environmental indices, including temperature, humidity, CO_2 density, formaldehyde density, PM2.5 density, and PM10 density.

[2] All lighting fixtures are both luminous level and CCT dimmable.

In addition, the layout of the classroom and the distribution of the smart lighting devices are illustrated in Figure 24. As can be seen, the classroom space is divided into four zones: the podium zone, the front-row zone, the middle-row zone, and the rear-row zone. The lights can be controlled individually, together, or by zone. Each zone is equipped with one PIR sensor to control the zone lights during non-working hours for energy saving. The three ALSs are distributed at the front, middle, and rear, respectively, on the side wall facing the windows.

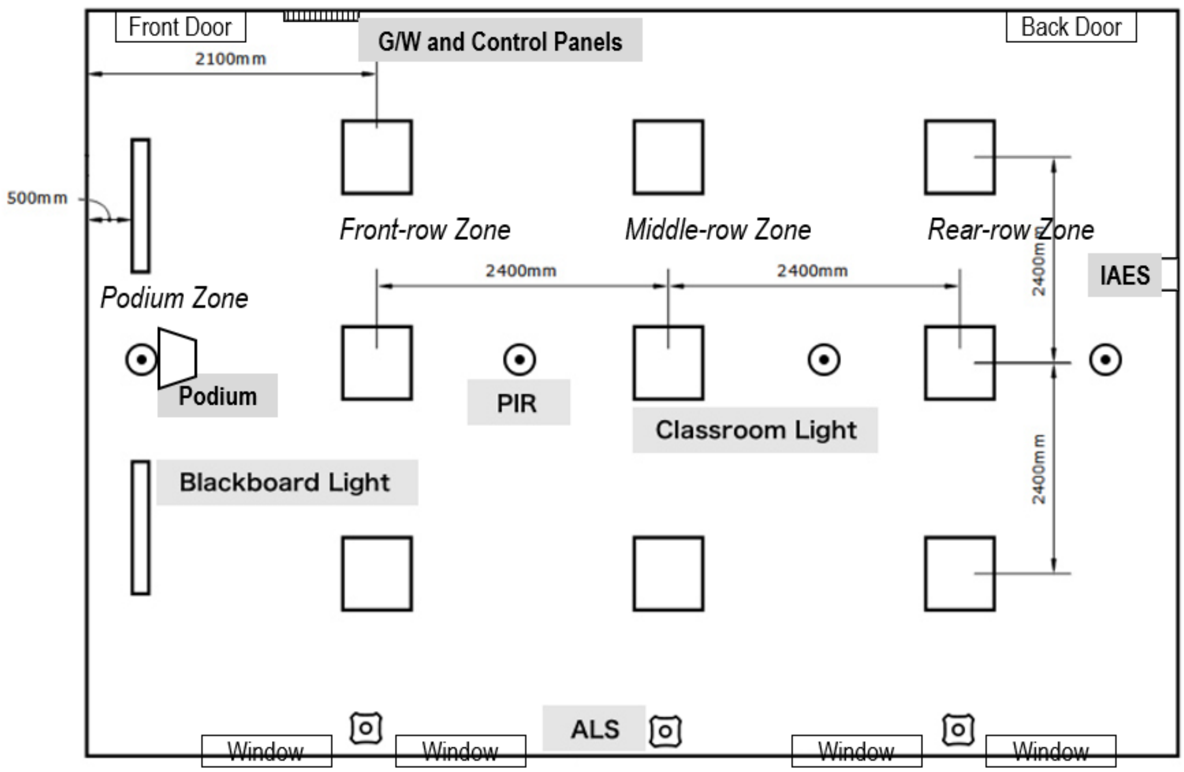
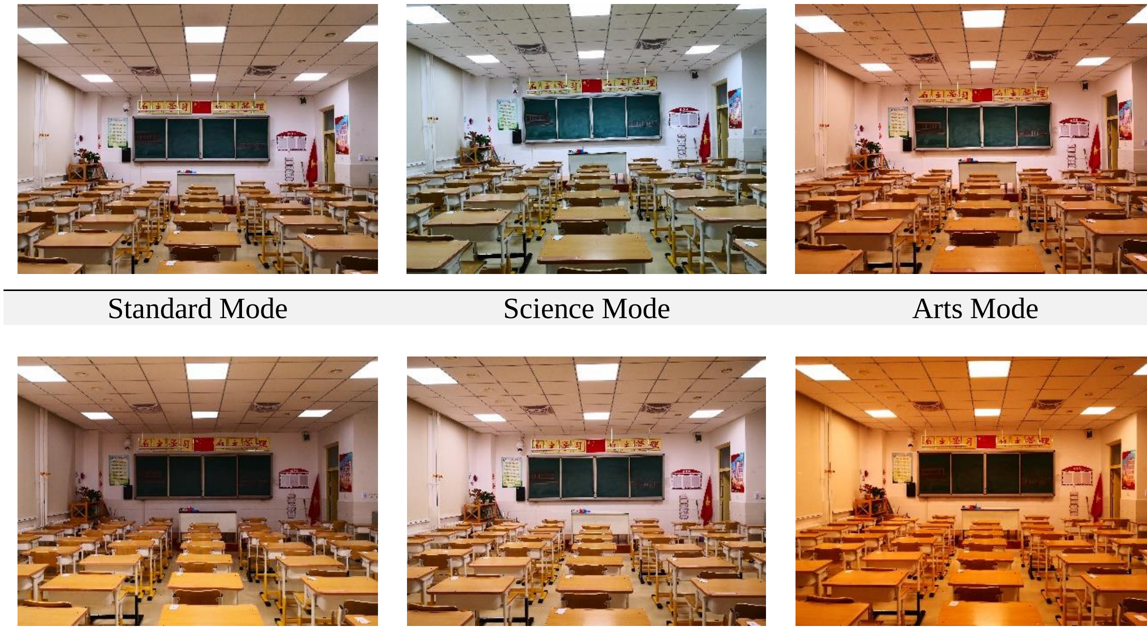


Figure 24. Standard classroom layout and device location (Sun et al., 2020)

In this deployment, six lighting modes out of ten (refer to Section 3.6) were chosen by the school, including the standard mode, the arts mode, the science mode, the slideshow mode, the self-study mode, and the recess time mode. Pictures in Figure 25 demonstrate the actual effect of these modes in a classroom.



Standard Mode	Science Mode	Arts Mode
Slideshow Mode	Self-study Mode	Recess Time

Figure 25. The six lighting modes applied in this school (Sun et al., 2020)

Chapter 5
Study Design and Data Processing

Thanks to the implementation and deployment of the learning-context based smart lighting system, research to investigate the impact of an optimized lighting environment on student performance was able to be conducted. Chapter 5 begins with the purposes and importance of the field study. Then, it describes how the study was designed, executed, and examined. As cooperative research with the IT company who was in charge of the school lighting renovation project, the division of responsibility and how the data was collected and provided to the research team are also explained in this chapter.

5.1 Uniqueness

This study aims to confirm the effect of learning-context based light settings by tracking and comparing students' academic performance of experimental groups (under optimized lighting program) and control groups (under standard lighting program). More importantly, we designed and performed the study in a unique way. The following key points differentiate this study from previous studies.

First and foremost, although studies regarding this topic can be found in many countries, research on elementary school in China is nearly blank so far.

Secondly, classroom environment in this study is not temporarily setup for an experiment, but permanently built for daily usage. The whole procedure of the study was based on real classroom activities and real learning contexts.

Thirdly, school report cards or real exam results rather than experimental tests were used to evaluate the influence of different lighting solutions.

Lastly, no external intervention was required during this study. School educational activities go naturally without any involvement of the research team. Therefore, the study can be easily extended and iterate with new lighting programs. Theoretically, we can finally approach the best illuminance settings according to the self-optimization framework introduced in Section 3.8.

5.2 Objectives

Although the interdisciplinary nature of this study gives us many questions to explore, we focused on a few fundamental objectives at this stage.

1. To evaluate the indoor environment quality and user operation preference that produced by the new lighting system.
2. To examine the hypothesis regarding the impact of learning-context based lighting environment on student performance.
3. To determine future working directions towards the optimized classroom lighting environment in terms of both engineering and ergonomics.

5.3 Hypotheses

With the deployment of the smart lighting system, the research team was interested in knowing how it would change the users' operational behavior. Since there were very few proper references to make a presumption, a hypothesis should be proposed after the system operation log is roughly summarized.

More importantly, hypotheses about the impact of lighting environment on students' performance need to be tested.

Firstly, as mentioned in Section 3.4, regardless few inconsistencies, existing studies tend to support that learning-context based lighting environment has significant impact on student performance. By compiling and integrating the established knowledge from earlier studies, ten lighting modes (see Section 3.6) for the most common learning contexts were proposed, and six of them were applied in the lighting renovation project (refer to Section 4.4). Given this fundamental setting of the study, it is rational to hypothesize that students in the context-based lighting environment would overall outperform those in the standard lighting environment.

In addition, it is hypothesized that the significancy of differences among academic subjects and demographic groups vary. Result of some subgroups may even be contrary to the overall outcome. For instance, boys and girls may gain differently in the context-based lighting environment. And the adaptive lighting modes may have different impact on mathematics, language and arts. When taking both gender and subject into account, student performance of smaller subgroups will show more diverse response to the context-based lighting environment. This reflects the complexity of the questions to be answers in this field, and more studies are necessary to enrich the knowledge base.

5.4 Study Design

In Section 3.5, a simplified theoretical model regrading classroom lighting and student performance was proposed, which is the Occam's Razor of this study. By following the idea of the model, the study was designed to preserve the daily learning procedure of the school with minimum experimental footprint:

- Twelve classrooms equipped with smart lightings system were selected. Six of them belong to the control group, and the other six are treated as the experimental group.
- To ensure the consistency of control variables, the twelve classrooms are all regular-paced class. No fast-paced class or special source-of-student class was included.
- To avoid placebo effect, all classrooms in the experiment not only have similar layout and interior finish, but also have been equally renovated with the same LED lighting system.
- During the experiment, learning-context based lighting settings with six proposed lighting modes was applied to the experimental group. As to the control group, standard mode was the only option for all in-class learning activities. All these lighting settings comply with the national standards (GB 7793-2010) to guarantee the wellbeing of the students.
- Learning-context automation (refer to Section 4.3.1.2) was also applied to the experimental group. This means the corresponding lighting mode can be automatically activated according to the class schedule. In the meantime, manual operations were available to both groups. Teachers and students can switch lights on/off and change lighting mode by using the control-panels on the wall, while the in-class teacher can also tune the brightness and CCT by using smartphone or tablet.
- No student nor teacher was required to make any change to their daily routines or do any extra task for the experiment. In other words, all learning activities during the study reflected the fidelity of a typical elementary school's operation in China.
- In this study, researchers were more like data observers rather than experiment performers. Data were generated naturally and continuously with day-to-day educational activities. Researchers' work was to gather, analyzed and interpreted those data.
- Given above design, one-way ANOVA of repeated measuring was employed to analyze overall performance. The within-subject factor is the time of test/exam (two terms), and the between-subject independent variable is the lighting environment (standard or learning-context based). And two-way ANOVA was used for analysis of by-gender overall performance. In addition,

one-way MANOVA was employed to perform detailed analysis regarding different academic subjects. And two-way MANOVA was used for by-gender and by-subject analysis.

5.4.1 Variables

5.4.1.1 Independent Variables

Classroom lighting environment is the main independent variable in this study. And it has two levels:

1. **Standard lighting environment**

Standard lighting environment sustains brightness not less than 350 lux with CCT of 5500 K for all in-class learning activities. This is also the most common lighting configuration for primary and secondary schools in China.

2. **Learning-context based lighting environment**

Under this environment, six proposed lighting modes, including standard, science, arts, slide show, self-study, and recess time, will be activated automatically according to pre-set learning schedule. For example, the lighting mode will switch to science mode at the beginning of mathematics course, and it will change to arts mode for language class.

Besides, gender is the second independent variable, which has two levels (female and male) in this study.

5.4.1.2 Dependent Variables

This study focused on the changes of students' academic performance and took the delta value of overall test/exam score between two terms as the main dependent variable.

Additionally, score changes of individual subject was also examined. In this study, scores of two subjects, including Language (Chinese) and Mathematics, were obtained.

5.4.1.3 Model Design

In accordance with the combinations of IV and DV, models of three levels need to be examined. At the top level, average score of all subjects was used to reflect the overall difference between the experimental group and the control group, as well as the changes of both groups over time. At the second level, average score by-subject and by-gender of each group was employed to investigate detailed differences. At the third level, cross subject-and-gender score was checked for more complicated point of interests.

Table 11. Models of three levels

By-subject \ By-gender	Overall	Female	Male
Overall	Top level Model	Level-2 Model	Level-2 Model
Language (Chinese)	Level-2 Model	Level-3 Model	Level-3 Model
Mathematics	Level-2 Model	Level-3 Model	Level-3 Model

5.4.1.4 Control Variables

Student performance can be influenced by many factors. In this study, considering all students are from the same district and share similar demographic properties, students' off-campus situations were assumed steady. Therefore, control variables are mainly on-campus factors, which can be classified into three categories: the physical attributes of classroom, the indoor environment, and the teachers. It is critical to hold the control variables steady during the field study. For example, the physical attributes of classroom include storey, orientation, furniture, layout, decoration, etc. The classrooms must be deliberately selected and have these attributes in common. In addition, classrooms in this study share the same curriculum and teaching resources. As for indoor environment, major factors, including light, temperature, humidity, air quality (CO_2 density, formaldehyde density, PM2.5 density, and PM10 density), are all monitored by environment sensors, and kept consistent (except for the independent variable) throughout these classrooms.

5.4.2 Sample Size and Grouping

An a priori analysis was done to determine the necessary sample size before the study took place. By calculating with GPower software (Faul et al., 2007), total sample size of the two groups is 84 and

210 if the effect size is set to 0.25 and 0.4 respectively. Details of the calculation are recorded in Table 12. Since this study involves twelve classrooms with more than 500 students, the sample size is large enough.

Table 12. GPower output: sample size calculation of a priori analysis

F tests – ANOVA: Fixed effects, omnibus, one-way			**F tests** – ANOVA: Fixed effects, omnibus, one-way		
Analysis: A priori: Compute required sample size			**Analysis:** A priori: Compute required sample size		
Input:	Effect size f	= 0.25	**Input:**	Effect size f	= 0.4
	α err prob	= 0.05		α err prob	= 0.05
	Power (1–β err prob)	= 0.95		Power (1–β err prob)	= 0.95
	Number of groups	= 2		Number of groups	= 2
Output:	Noncentrality parameter λ	= 13.125000	**Output:**	Noncentrality parameter λ	= 13.440000
	Critical F	= 3.8865546		Critical F	= 3.9573883
	Numerator df	= 1		Numerator df	= 1
	Denominator df	= 208		Denominator df	= 82
	Total sample size	= **210**		Total sample size	= **84**
	Actual power	= 0.9501287		Actual power	= 0.9518269

Although it was acceptable to randomly put half of the classrooms into the control group and the experimental group respectively, after taking floor and orientation into account, the research team decided to group these classrooms deliberately to minimize the disequilibrium. The floor plan with grouping information can be found in Figure 26. As can be seen, the experimental group and the control group each with six classrooms are equally allocated on two floors. And for each group, four classrooms are located on the south side and two classrooms are located on the north side. Detailed information of the twelve classrooms can be found in Table 13.

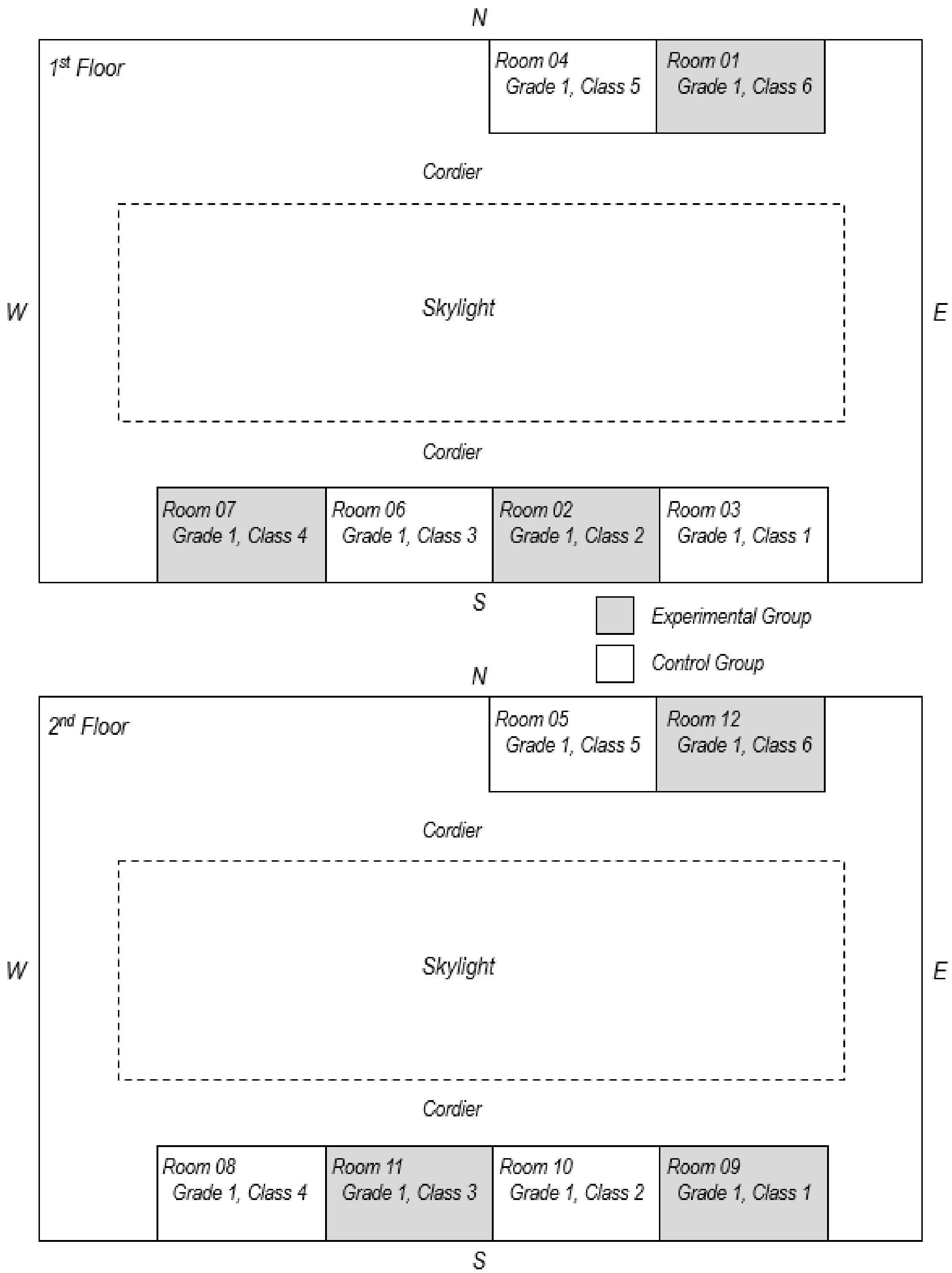


Figure 26. The six lighting modes applied in this school

Table 13. Detailed information of the twelve classrooms

No.	Group	Room	Grade	Class	Floor	Space (m^2)	Orientation	Ceiling Height	Daylight	Vantilation	External Noise
1	Control	03	1	1	1	63	S	250	4-Good	4-Good	4-Quiet
2	Control	06	1	3	1	63	S	250	4-Good	4-Good	4-Quiet
3	Control	04	1	5	1	63	N	250	3-Normal	4-Good	4-Quiet
4	Control	10	1	8	2	63	S	250	5-Sufficient	4-Good	4-Quiet
5	Control	08	1	10	2	63	S	250	5-Sufficient	4-Good	4-Quiet
6	Control	05	2	1	2	63	N	250	3-Normal	4-Good	4-Quiet
7	Experimental	02	1	2	1	63	S	250	4-Good	4-Good	4-Quiet
8	Experimental	07	1	4	1	63	S	250	4-Good	4-Good	4-Quiet
9	Experimental	01	1	6	1	63	N	250	3-Normal	4-Good	4-Quiet
10	Experimental	09	1	7	2	63	S	250	5-Sufficient	4-Good	4-Quiet
11	Experimental	11	1	9	2	63	S	250	5-Sufficient	4-Good	4-Quiet
12	Experimental	12	2	2	2	63	N	250	3-Normal	4-Good	4-Quiet

5.5 Methodology

5.5.1 Background Information

The collaborating school located in Langfang, Hebei Province is a typical public school in north China. The nine-year compulsory education school has nearly 5,000 students and 96 classrooms distributed in four buildings. The students are basically from nearby communities. It implies the homogeneous source-of-student.

Ten classrooms from Grade 1 and two from Grade 2 participated this study. As shown in Table 14, both grades share similar syllabus and class schedule. For the original information, please refer to Appendix A.3. To be noticed, the two main courses, including Mathematics, and Language (Chinese), are not only exam subjects evaluated with centesimal grade (0 to 100), but also directly associate with the independent variable of the study. Hence, the scores of the two main courses are employed to represent students' academic performance.

Table 14. Curriculum and class schedule of grade one and two [1]

Course	Grade One	Grade Two
Morality and Life	3	3
Language (Chinese) [2]	8	8
Mathematics [2]	4	4
Physical Education	5	5
Music	2	2
Visual Arts	2	2
School Autonomous Courses	2	2
Weekly Total Class Hours	**26**	**26**
Annual Total Class Hours	**910**	**910**

[1] Translated from the curriculum and class schedule of compulsory education in Hebei Province.

[2] Exam subjects evaluated with centesimal grade.

5.5.2 Collaboration and Responsibility

As an internationally cooperative project, this study involves UW research team, the project sponsor (DataTellIt Inc.), the collaborating school in China, and the local bureau of education. According to the sponsored research agreement (SRA#077079), UW research team is mainly responsible for study design and data analysis, while the sponsor with its Chinese branch office takes the ownership of other tasks, including system implementation, communicating with the school and local government, data collecting, etc. Specifically, the division of responsibility is described in Table 15.

Table 15. Division of responsibility

Task	UW research team	Project sponsor
Stduy design	95%	5%
System Design	15%	85%
System Development	0	100%
Installation and Implementation	0	100%
Project Communication	10%	90%

Data Collecting	0	100%
Data Processing	80%	20%
Data analysis	100%	0
Data report	90%	10%
Report translation into Chinese	10%	90%

Table 15 cont. Division of responsibility

5.5.3 Timeline

The study that started in the end of February 2019 with an on-site kick-off meeting on March 4, 2019 (refer to Appendix A.2.1) is divided into four phases. As shown in the project plan (Figure 27), phase I is the preparation phase, which consists of several steps, such as planning, study design, kick-off meeting, readiness of both IT system and fundamental data, user training, etc. In phase II and III, data of interests for both control group and experimental group are gathered and processed. Each phase corresponds to one term. Finally, data analysis and data report are performed in phase IV. Meanwhile, conclusions are expected to be drawn.

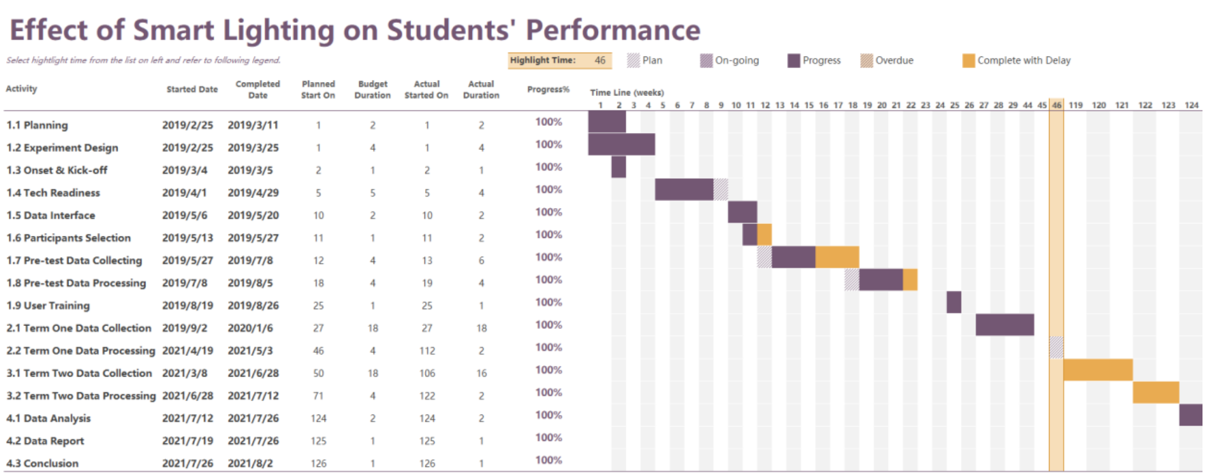


Figure 27. The research project plan

The project went well on schedule until January 2020, when the school was closed, and all courses were switched online due to the pandemic. Despite the short-term resumption of on-campus learning in the fall of 2020, the school had to switch to online teaching again in the end of 2020 due to the regional resurgence of the virus, and it did not fully recover until March 2021. Consequently, the data collecting had been interrupted for about one year. It resulted in a discontinuous dataset rather that the planned collection of two consecutive terms. To maintain the consistency of the experimental settings, the twelve classes did not change rooms throughout the study.

A concise project timeline regarding the data collecting is shown in Figure 28. As can be seen, the system kept collecting the indoor environment data and the operation log automatically as long as the school was open. For the first term, the standard lighting mode was applied on both groups. In the end of term 1, the experimental group switched to the learning-context based lighting mode, while the control group stayed in the standard lighting environment. And final exams were held at the end of each term.

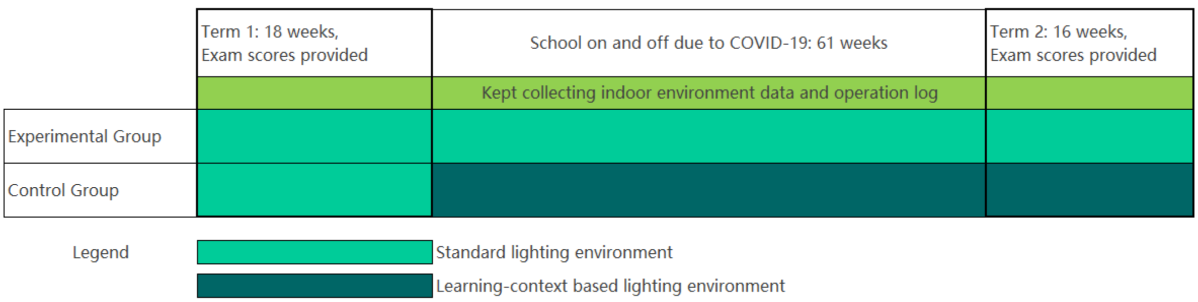


Figure 28. The executive project timeline

5.6 Data Processing

5.6.1 Data Structure

A total of 568 students from 12 classrooms were equally divided into the experimental group and the control group. And the ratio of male to female is 1.029:1 (288 vs 280). Although there were few students moving in or out from/to other schools during the study, considering the percentage is lower than 1.6% (9 out of 568), it should not have significant impact on the statistical results. More information about the data structure can be found in Table 16.

Table 16. Information of the classrooms and students

No.	Group	Room	Grade	Class	Capacity	Student Number [1]	Girls	Boys	Student Changed [2]
1	Control	03	1	1	50	49	24	25	1
2	Control	06	1	3	50	48	24	24	1
3	Control	04	1	5	50	47	23	24	0
4	Control	10	1	8	50	47	23	24	1
5	Control	08	1	10	50	47	23	24	1
6	Control	05	2	1	50	46	23	23	1
Control Group Subtotal						284	140	144	5
7	Experimental	02	1	2	50	48	24	24	1
8	Experimental	07	1	4	50	48	24	24	0
9	Experimental	01	1	6	50	48	23	25	1
10	Experimental	09	1	7	50	47	23	24	1
11	Experimental	11	1	9	50	47	23	24	0
12	Experimental	12	2	2	50	46	23	23	1
Experimental Group Subtotal						284	140	144	4
Total Participants						568	280	288	9

[1] The numbers were recorded at the beginning of the study.

[2] This is the number of students that transferred in or out during the study.

5.6.2 Data Collection

Three categories of datasets were collected for this study. They are the environmental data, the operation log, and the exam marks of students.

The environmental data, including temperature, humidity, CO_2 density, formaldehyde density, PM2.5 density, etc., are mainly generated by IAES. During the study, indoor environment quality was monitored to ensure that all students and teachers were in a healthy and steady learning environment.

The operation log records all device control operations in a classroom. Each log item describes when and how an operation was executed. The operation, such as turning lights on/off, switching lighting mode, can be triggered automatically or by means of control panel, mobile application, and voice command. In this study, operation log was used to analyze users' interactive behaviour and preference.

The environment data and the operation log were automatically recorded by the smart lighting system and updated onto the cloud database in real-time. By collecting these data day and night, the smart lighting system is also establishing data assets for future research, even if this study did not yet make the most out of them.

Final exams are regularly held at the end of each term. Since exam results are sensitive data, data masking must be performed to remove identity information of student before the dataset was provided to the research team. Specifically, the student ID and name were replaced with a random item number, while gender information was kept for in-deep analysis. One identical item number (RID a.k.a. Record ID) crossing datasets of term 1 and term 2 corresponds to the same student only if whose exam results exist in both datasets. The exam results including language (Chinese) and mathematics were provided separately by classroom and subject. Thus, it is not possible to trace exam results for individual student. The description of dataset obtained for this study are listed in Table 17. In addition, the dataset along with the source code (in R language) can be found at *https://github.com/sunbaoshi1975/UWThesisDataset* for reproducible check or future research.

Table 17. Dataset description

No.	Dataset	Data Providor	Description
1	IEQ_data	System record	Environment data of all classrooms
2	operation_log	System record	Operation log of all classrooms
3 to 14	rm[01 to 12]_term1_exam	The school	Term one final exam marks of classroom 01 to 12
15 to 26	rm[01 to 12]_term2_exam	The school	Term two final exam marks of classroom 01 to 12

5.6.3 ANOVA Assumption Checks

5.6.3.1 Difference of Initial Performance

It was presumed that there was no significant difference in terms of the initial performance between the control group and the experimental group. Since the lighting mode for both groups was the same by the end of term 1, the scores of term 1 were considered as the initial performance. A two-sample two-tailed t-test with 95% confidence interval was performed on the overall scores, as well as each subject. The result indicated that there was no significant difference for either Chinese ($t(549) = 1.3568$, $p = .1754$), Mathematics ($t(564) = 0.86516$, $p = .3873$) or the overall performance ($t(559) = 1.2224$, $p = .2221$).

5.6.3.2 Normality Test

Although it is not necessary given the sample size is large ($n > 200$), the normality test on the exam data was still conducted in this study. The Anderson-Darling test function in R was employed to violate the normality assumption. The result rejected the hypothesis of normality ($p < 0.05$).

```
        Anderson-Darling normality test

data:  work.df$Total
A = 54.479, p-value < 2.2e-16
```

In fact, a negatively skewed distribution can be determined when plotting the data in Figure 29. It means there are more high scores in the dataset. This makes sense because the students were grade one and grade two students, and the exam must be easy.

5.6.3.3 Homogeneity Test

Considering the dataset does not follow the normal distribution, Fligner-Killeen test was employed to carry out the homogeneity test. The result below indicates the assumption of homogeneity can be accepted ($p > 0.05$).

```
        Fligner-Killeen test of homogeneity of variances

data:  work.df$Total by work.df$Group
Fligner-Killeen:med chi-squared = 1.6534, df = 1, p-value = 0.1985
```

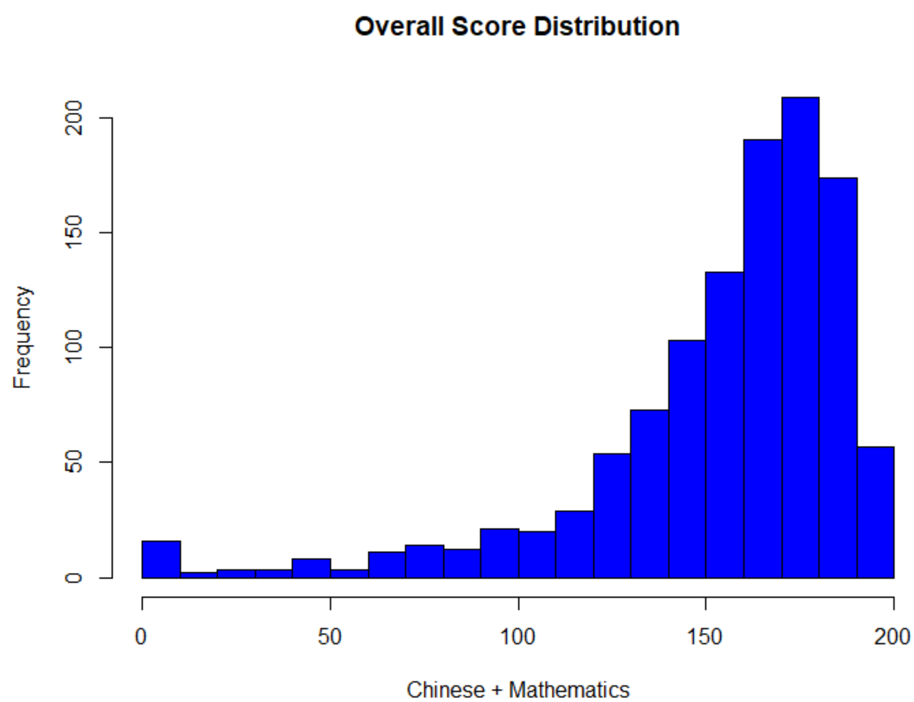


Figure 29. Distribution of the overall scores

5.6.4 Unpaired Record Removal

It can also be noticed in Figure 29 that there are some zero scores. When looking into the dataset, some unpaired records were distinguished. One major reason that caused this issue might be some students missed one exam in either term 1 or term 2. To suppress the impact of those unpaired records on the test result, a straightforward way is to remove them according to the RID field, though it may not be accurate because the raw data do not contain the actual identification information, such as student name or ID. As the result, 25 records were removed from the dataset. This operation left 543 valid records out of the total 568.

Chapter 6
Results and Discussion

6.1 Indoor Environmental Quality Report

After the smart lighting system was installed in the classrooms, the user acceptance testing (UAT) was performed. As listed in Table 18 and Table 19, the UAT results showed that the major illuminance indicators and other major environmental factors had met or exceeded the national standards.

Table 18. The illuminance indicators measured on the UAT

Indicator	National Standard [1]	UAT Results [2]
Illuminance Level (desktop)	≥ 300 Lux	≥ 435 Lux
Illuminance Uniformity (desktop)	≥ 0.7	≥ 0.81
Illuminance Level (blackboard)	≥ 500 Lux	≥ 589 Lux
Illuminance Uniformity (blackboard)	≥ 0.8	≥ 0.85
Correlated Color Temperature (CCT)	N/A	5500 ± 100 K
Unified Glare Rating (UGR)	< 19	< 15.6
Color-rending Index (CRI)	≥ 80	≥ 95

[1] GB 7793-2010. Hygienic Standard for Day Lighting and Artificial Lighting for Middle and Elementary School; [2] Tested under the standard mode.

Table 19. Other major environmental indicators measured on the UAT

Indicator	National Standard [1]	UAT Results
PM2.5	< 75 ug/m^3	< 65 ug/m^3
CO_2	< 1000 ppm	< 260 ppm
HCHO [2]	⩽ 0.1 mg/m^3	⩽ 0.06 mg/m^3
TVOC [3]	⩽ 0.6 mg/m^3	⩽ 0.4 mg/m^3

[1] GB/T18883-2002. Indoor air quality standard of China (SEPA, 2002).

[2] Formaldehyde density was measured after windows-closed for 12 hours.

[3] The average value of the total volatile organic compounds in eight hours.

Moreover, the environmental data are continuously collected and uploaded onto the cloud platform. And rules are configured to automatically control appliances in classroom, like air conditioning, fresh air, fans, etc., in order to make sure all environmental indicators meet relevant national standards. Furthermore, accumulated indoor environmental data are also resources for future study.

6.2 User Operational Preference (UOP)

Based on the system operation log, the user preference of operating the lighting system was analyzed. In addition to the rule-based automatic control, users can control manually through five ways: tablet, mobile application, voice command, scene control panel, and zone switch panel. The first three ways can only be operated by teachers, and the other two ways can be operated both by teachers and students.

6.2.1 Descriptive Statistics

To gain a basic understanding about the user preference, the system operation log was summarized Microsoft Excel version 2107. As shown in Figure 30, on the whole, the using frequency of automatic control of the lighting system is slightly higher than that of manual control. The average operation times per day per classroom of auto-control 8.18 times, while the manual control is 7.85 times. Among the five manual control methods, the zone switch panel is the most frequently used, accounting for 4.43 times or 56.4%, followed by the scene control panel, accounting for 2.44 times or 31.1%. These two methods contribute nearly 90% of all manual operations, indicating that users are used to the traditional panel control. In contrast, the new methods, such as tablet, mobile application, and voice control, occurred less than 1 time in a classroom per day. Obviously, these control methods may be fancy, but not practical for daily usage. In addition, given the total proportion of the three methods is only 12.5%, the tablet solely accounts for 8.3%. In this case, it may be attributed to the better accessibility of dedicated tablets than mobile application and voice command. This result indicates that the convenience of the operation method directly determines the user's using frequency.

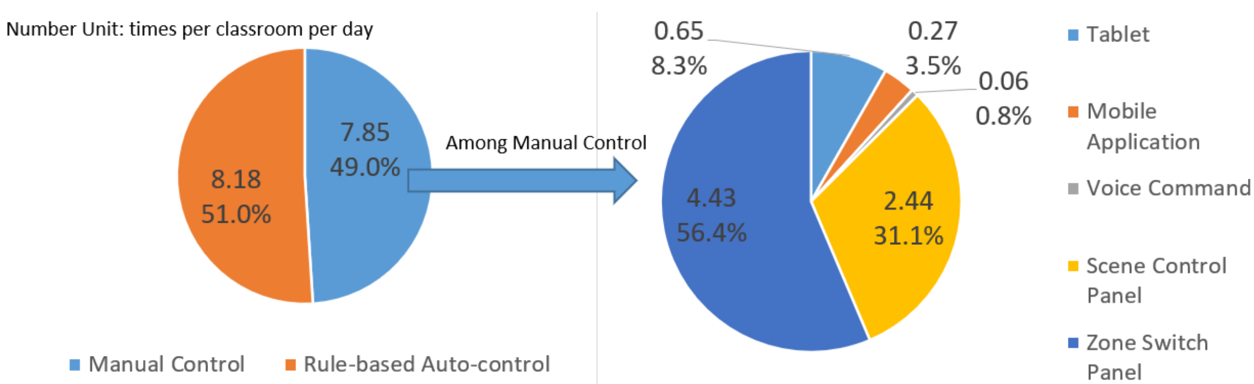


Figure 30. Overall auto-control vs. manual-control, and types of manual-control

Furthermore, by comparing the operation data of the control group and the experimental group, it can be found that although the number of automatic controls in the control group and the experimental group is close, which is 8.46 times and 7.89 times respectively, the number of manual controls in the control group is significantly more than that in the experimental group, which is 9.05 times vs. 6.66 times. As a result, the percentage of automatic control exceeded that of manual control in the experimental group, as shown in Figure 31. This shows that the experimental group with context-based lighting settings significantly reduced the number of users' manual intervention.

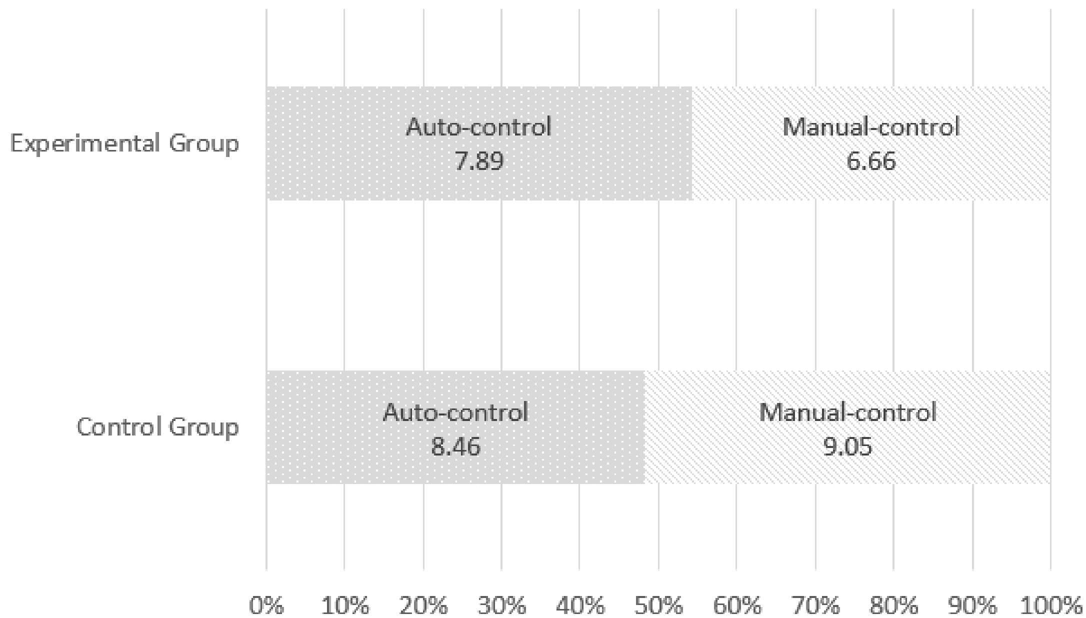


Figure 31. By-group auto-control vs. manual-control

See Table 20 for detailed statistics of system operation log.

Table 20. Statistics of system operation log

No.	Type	Operation Method	Control Group			Experimental Group			Total Operation Times	Percentage	Times per Room per Day [1]
			Operation Times	Percentage	Times per Room per Day	Operation Times	Percentage	Times per Room per Day			
1	Manual	Tablet	2,931	8.2%	0.74	2,223	8.4%	0.56	5,154	8.3%	0.65
2	Manual	Mobile Application	1,135	3.2%	0.29	1,037	3.9%	0.26	2,172	3.5%	0.27
3	Manual	Voice Command	246	0.7%	0.06	242	0.9%	0.06	488	0.8%	0.06
4	Manual	Scene Control Panel	10,798	30.0%	2.72	8,599	32.5%	2.16	19,397	31.1%	2.44
5	Manual	Zone Switch Panel	20,837	58.0%	5.25	14,347	54.2%	3.61	35,184	56.4%	4.43
Manual Control Sub-total			35,947	51.7%	9.05	26,448	45.8%	6.66	62,395	49.0%	7.85
6	Auto	Rule-based Control	33,608	48.3%	8.46	31,352	54.2%	7.89	64,960	51.0%	8.18
Total			**69,555**	**100.0%**	**17.51**	**57,800**	**100.0%**	**14.55**	**127,355**	**100.0%**	**16.03**

[1] During the experimental period, there are 662 days that have control records.

6.2.2 Inferential Statistics

6.2.2.1 Hypothesis and Method

The exploratory analysis above indicated that the classrooms of the experimental group were recorded much fewer manual operations than the classrooms in the control group. The hypothesis can be stated as:

$$H_0: \mu_1 = \mu_2 \qquad H_1: \mu_1 > \mu_2 \ ,$$

where μ_1 and μ_2 is the mean value of manual operation times that occurred in the classrooms of the control group and the experimental group, respectively. In this case, the sample size (n) of both groups is as small as 6. Therefore, a two-sample one-tailed t-test was carried out using R version 4.1.0 64 bit with R Studio version 1.4.1717. And a 95% confidence interval was used to regulate the statistical results.

6.2.2.2 Result

A two-sample one-tailed t-test was carried out on the operation log to examine the effects of standard lighting environment and learning-context based lighting environment on user operational preference (Figure 32). The result indicated that there was no significant effect, $t(10) = 1.0437$, $p = .1629$, in spite of the fact that the control group (*M* = 9.05, *SD* = 4.76) showed nearly 36% larger of mean value of manual operations per day than the experimental group (*M* = 6.66, *SD* = 2.97).

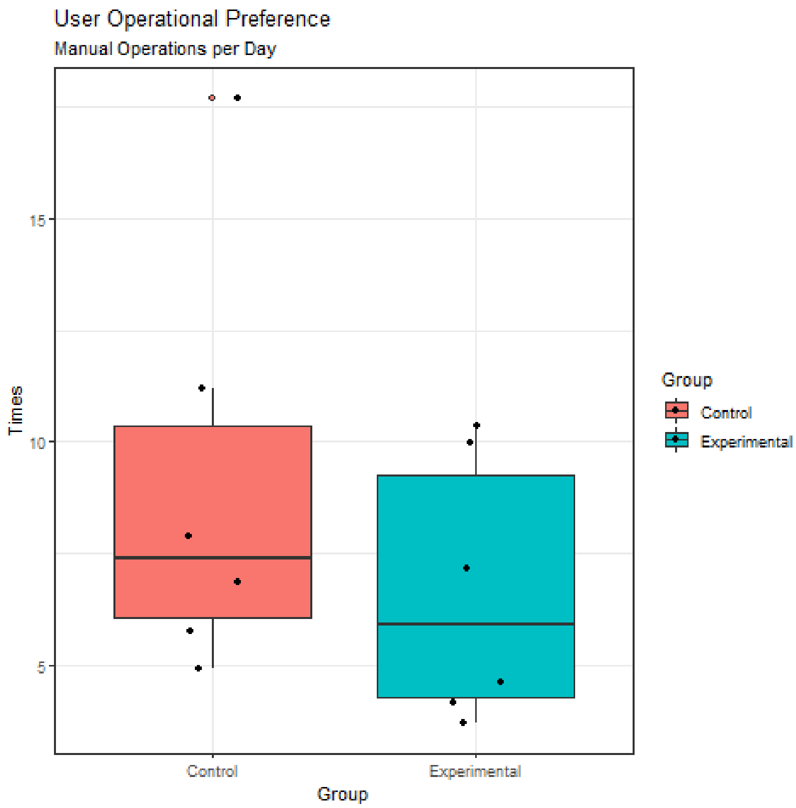


Figure 32. Comparison of daily average UOP

6.3 Overall Performance Changes (OPC)

The main purpose of this study is to investigate the changes of student performance under context-based lighting environment as opposed to those under standard lighting environment. After the student performance data were provided, data analysis regarding the changes of overall performance, by-subject performance t, by-gender performance, as well as by-subject-and-gender performance was conducted by using R Studio.

6.3.1 Descriptive Statistics

As can be observed from Figure 33 and Table 21, the overall performance of both groups is improved. But the improvement of the experimental group is 6.6 (from 149.6 to 156.2), which is much higher than that of the control group whose increase is 3.1 (from 153.5 to 156.6).

It is notable that the initial score of the control group is higher than that of the experimental group, and by the second term, the scores of the two groups are very close. The reason may be that some classrooms with higher scores happened to be assigned to the control group, while some classrooms with lower scores was randomly put into the experimental group. This can be testified by looking at the mean score of each classroom in Table 22. The three classrooms with the highest scores in the first term belong to the control group, while three of the four classrooms with lower scores are from the experimental group. Nevertheless, the score changes from term 1 to term 2 of each classroom in Figure 34 and Table 23 strongly indicate that the experimental group got a higher rise than the control group.

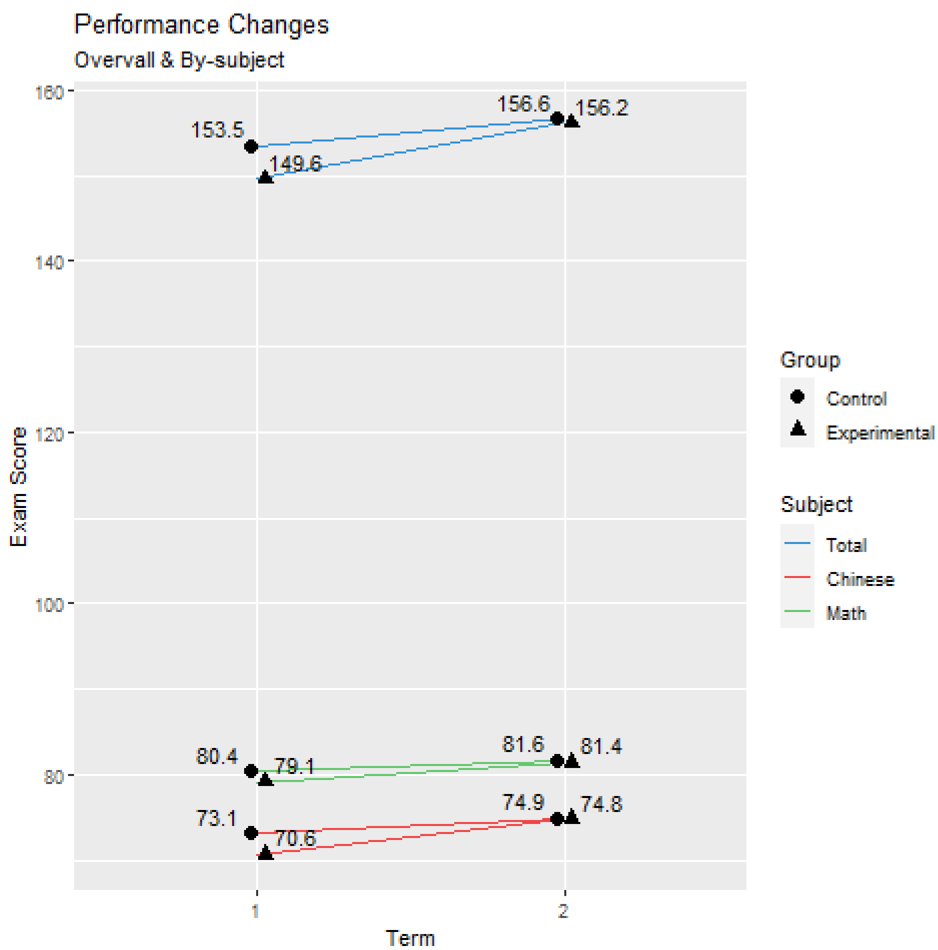


Figure 33. Overall and by-subject performance changes

Table 21. Mean values of exam scores and their changes by group

Term <fctr>	Group <fctr>	Chinese <dbl>	chgCN <dbl>	Math <dbl>	chgMath <dbl>	Total <dbl>	chgTotal <dbl>
1	Control	73.1	NA	80.4	NA	153.5	NA
2	Control	74.9	1.8	81.6	1.2	156.6	3.1
1	Experimental	70.6	NA	79.1	NA	149.6	NA
2	Experimental	74.8	4.2	81.4	2.3	156.2	6.6

4 rows

Table 22. Sorted mean scores of each classroom

Term	Group	Room	Chinese	Math	Total
1	Control	8	74.9	84.4	159.3
1	Control	5	73.8	83.1	156.9
1	Control	3	74.2	82.4	156.6
1	Experimental	9	73.6	81.3	154.9
1	Experimental	11	72.6	81.5	154.2
1	Experimental	12	71.9	81.7	153.6
1	Control	10	72.9	80.7	153.5
1	Control	4	73.3	79.3	152.6
1	Experimental	2	70.6	77.2	147.8
1	Experimental	1	69.2	78.0	147.3
1	Control	6	69.7	72.5	142.3
1	Experimental	7	65.6	74.8	140.4
2	Experimental	9	76.8	84.3	161.0
2	Control	3	77.0	83.4	160.4
2	Control	8	75.5	83.7	159.2
2	Experimental	11	76.2	82.9	159.1
2	Control	5	75.2	83.7	158.9
2	Experimental	12	75.2	82.1	157.3
2	Control	4	75.4	81.6	157.1
2	Control	10	73.9	80.9	154.8
2	Experimental	1	74.6	80.0	154.5
2	Experimental	2	73.8	79.6	153.4
2	Experimental	3	72.1	79.8	151.9
2	Control	6	72.4	76.6	149.0

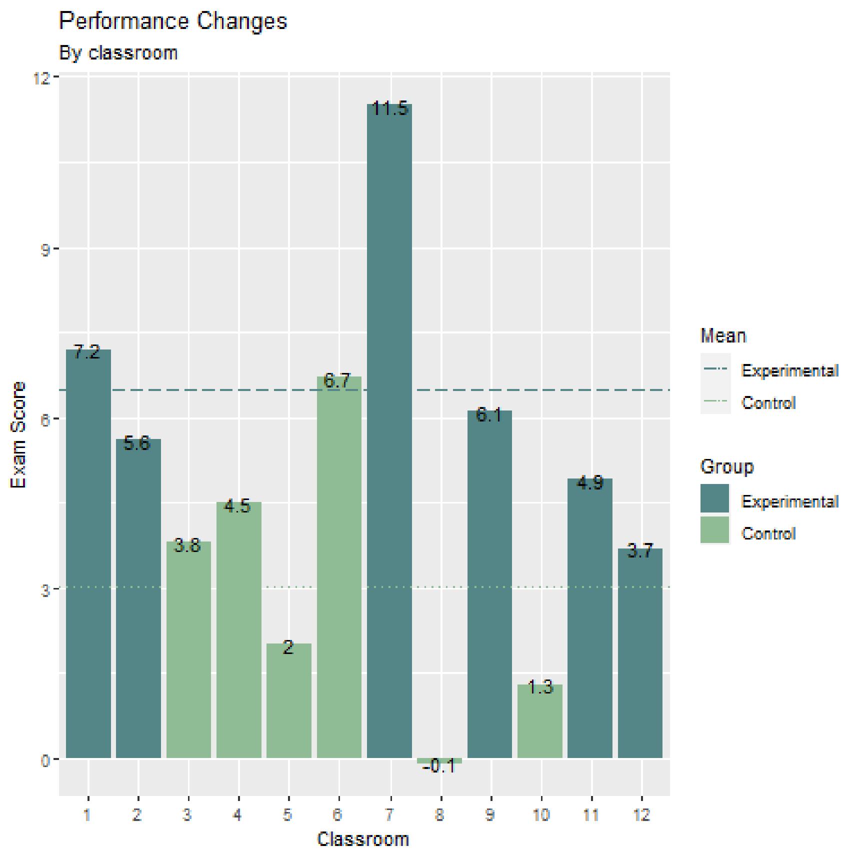


Figure 34. Overall performance changes of classroom

Table 23. Mean score changes of classroom

	Group	Room	chgCN	chgMath	chgTotal
1	Control	10	1.0	0.2	1.3
2	Control	3	2.8	1.0	3.8
3	Control	4	2.1	2.3	4.5
4	Control	5	1.4	0.6	2.0
5	Control	6	2.7	4.1	6.7
6	Control	8	0.6	-0.7	-0.1
7	Experimental	1	5.4	2.0	7.2
8	Experimental	11	3.6	1.4	4.9
9	Experimental	12	3.3	0.4	3.7
10	Experimental	2	3.2	2.4	5.6
11	Experimental	7	6.5	5.0	11.5
12	Experimental	9	3.2	3.0	6.1

6.3.2 Inferential Statistics

6.3.2.1 Hypothesis and Method

It is rational to believe the experimental group gained more improvement on students' overall academic performance. Accordingly, the hypothesis can be stated as:

$$H_0: \mu_1 = \mu_2 \qquad H_1: \mu_1 > \mu_2 \ ,$$

where μ_1 and μ_2 is the mean increment of the overall scores (Chinese plus Mathematics) received by the students from the experimental group and the control group, respectively. And 284 is the sample size (n) for both groups. A one-way ANOVA of repeated measuring was employed to analyze the changes of overall performance by using R version 4.1.0 64 bit with R Studio version 1.4.1717. And a 95% confidence interval was used to regulate the statistical results.

6.3.2.2 Result

A one-way ANOVA was employed to check the effect of two lighting settings on students' OPC. After data cleansing as mentioned in Section 5.6.4, the dataset was composed of 543 paired records of the two terms. Figure 35 illustrates a graph comparing the increments of overall scores (Chinese plus Mathematics) of the two groups. The result indicates that the effect of lighting condition was significant ($F(1, 542) = 8.579$, $p = .00354$, η2 = 0.02). As shown in Table 24, Tukey HSD post-hoc test was also suggested a significant difference ($p = 0.035$). In the learning-context based lighting environment, the students' overall performance improved 3.174 points or 2.07% higher compared with the standard lighting environment.

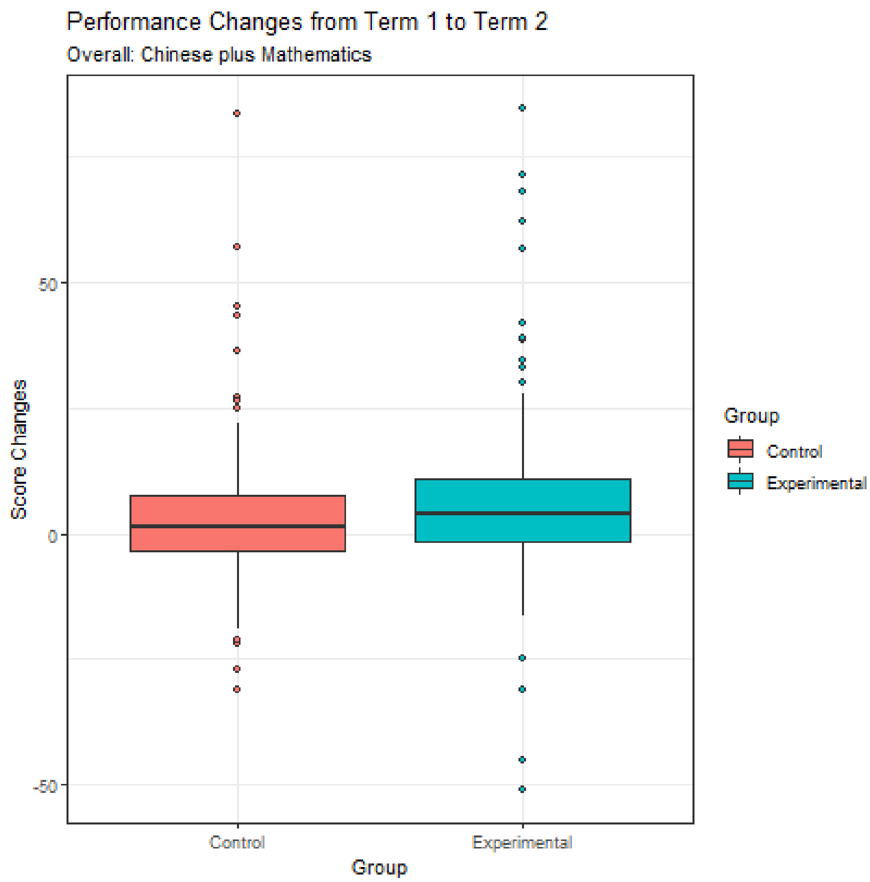


Figure 35. Comparison of mean of OPC

Table 24. Result of Tukey HSD test on OPC

Contrast	*Difference*	*Lower*	*Upper*	*p adjusted*
Experimental-Control	3.174	1.045	5.303	0.0035

6.4 Performance Changes by Subject (PC-S)

6.4.1 Descriptive Statistics

The increasing trend of by-subject performance can be observed with larger slopes for the experimental group. The mean of the experimental group increased 4.2 and 2.3 for Chinese and Mathematics respectively, while that of the control group only raised 1.8 and 1.2.

6.4.2 Inferential Statistics

6.4.2.1 Hypothesis and Method

Likewise, the hypothesis assumes both subjects of the experimental group gained larger increment. It can be stated as:

$$H_0:\ (\mu_1\, \nu_1) = (\mu_2\, \nu_2) \qquad H_1:\ (\mu_1\, \nu_1) > (\mu_2\, \nu_2)\ ,$$

where μ and υ stands for the mean increment of Chinese scores and Mathematics scores, respectively. The subscript 1 corresponds to the experimental group, and the subscript 2 is for the control group. The sample size (n) is 284 for both groups. In this case, a one-way MANOVA of repeated measuring was used for the composition analyzing of both subjects. R version 4.1.0 64 bit with R Studio version 1.4.1717 and a 95% confidence interval was employed to perform the analysis.

6.4.2.2 Result

A one-way MANOVA was used to examine to the response of the two subjects as well as each of them. As shown is Table 25, the result of combination of Chinese and Mathematics showed significant effect ($F(2, 542) = 4.2867$, $p = .01422$, $\eta^2 = 0.02$), which was consistent with the result of the overall ANOVA. In addition, the tests of between-subjects found significant differences on each subject, as shown in Figure 36. The result was ($F(1, 542) = 6.7956$, $p = .00939$, $\eta^2 = 0.02$) for Chinese, and ($F(1, 542) = 4.5567$, $p = .03324$, $\eta^2 = 0.02$) for Mathematics.

Specifically, in the learning-context based lighting environment, the students' Chinese score improved 2.73% higher compared with the standard lighting environment. And as to Mathematics, the experimental group gained 1.48% higher improvement than the control group.

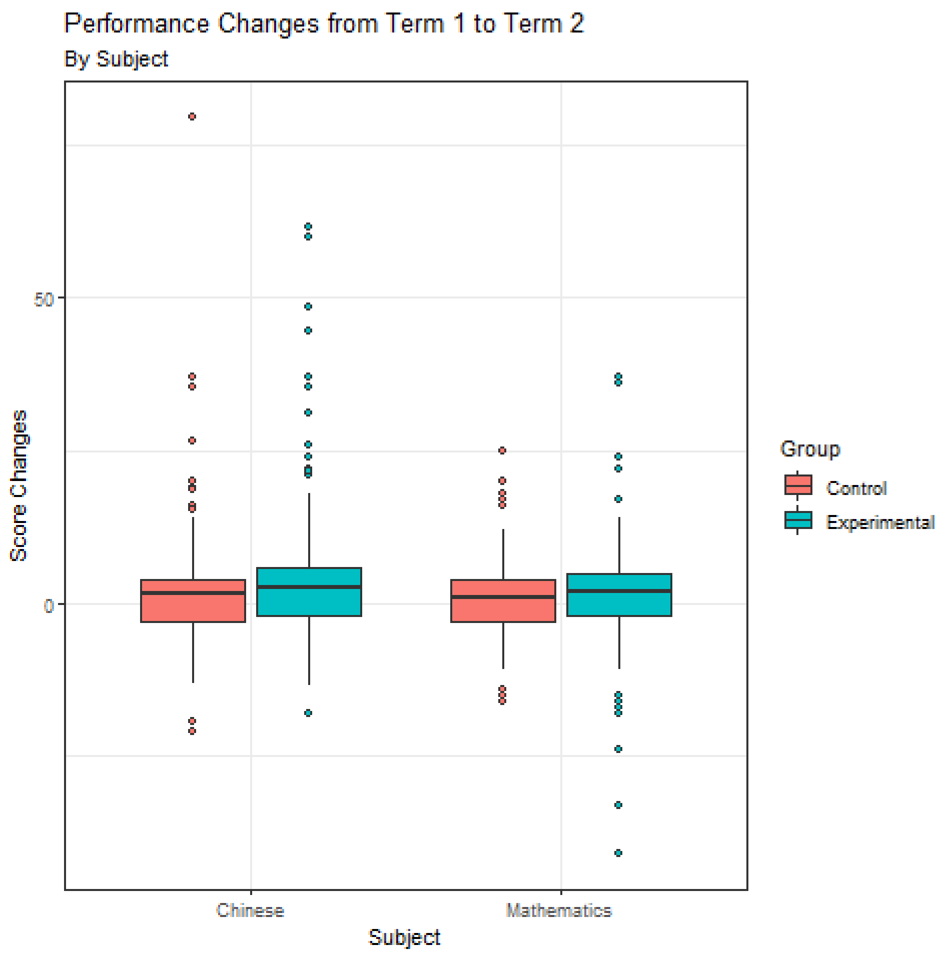


Figure 36. Comparison of mean of PC-S

Table 25. Result of MANOVA on PC-S

Dependent Variable	***df***	***Mean Square***	***F***	***p***	η^2
Chinese and Mathematics	(2, 542)	NA	4.2867	0.01422	0.02
Chinese	(1, 542)	531.23	6.7956	0.00939	0.02
Mathematics	(1, 542)	194.108	4.5567	0.03324	0.02

6.5 Performance Changes by Gender (PC-G)

6.5.1 Descriptive Statistics

Similar to that of the overall changes and the by-subject changes, the increasing trend can also be observed regarding the by-gender exam scores for both groups. And the experimental group demonstrated higher increments than the control group. The comparison between the two groups is 6.9 to 1.9 for female, and 6.2 to 4.2 for male. Please refer to Figure 37 and Table 26 for details.

Figure 37. By-gender performance changes

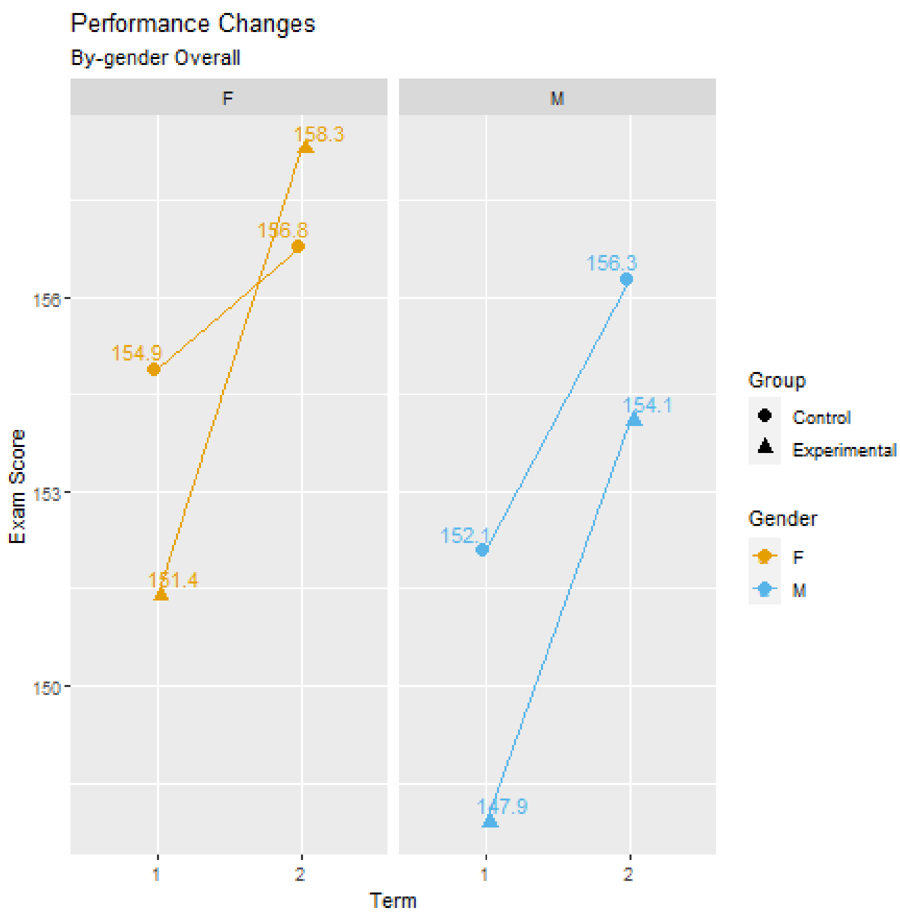


Table 26. Mean values of exam scores and their changes by gender

Term <fctr>	Gender <fctr>	Group <fctr>	Chinese <dbl>	chgCN <dbl>	Math <dbl>	chgMath <dbl>	Total <dbl>	chgTotal <dbl>
1	F	Control	73.9	NA	81.0	NA	154.9	NA
2	F	Control	75.3	1.4	81.6	0.6	156.8	1.9
1	M	Control	72.4	NA	79.8	NA	152.1	NA
2	M	Control	74.6	2.2	81.7	1.9	156.3	4.2
1	F	Experimental	72.1	NA	79.2	NA	151.4	NA
2	F	Experimental	76.0	3.9	82.3	3.1	158.3	6.9
1	M	Experimental	69.1	NA	78.9	NA	147.9	NA
2	M	Experimental	73.5	4.4	80.6	1.7	154.1	6.2

8 rows

6.5.2 Inferential Statistics

6.5.2.1 Hypothesis and Method

As for the by-gender analysis, the hypothesis looks like:

$$H_0: \mu_1 = \mu_2 \qquad H_1: \mu_1 > \mu_2 \ ,$$

where μ_1 and μ_2 is the mean increment of the overall scores (Chinese plus Mathematics) received by the female (n = 280) or male (n = 288) students from the experimental group and the control group, respectively. A two-way ANOVA of repeated measuring was employed to examine the lighting effect on each gender. R version 4.1.0 64 bit with R Studio version 1.4.1717 was the tool kits, and a 95% confidence interval was used to regulate the statistical results.

6.5.2.2 Result

With one accord, Figure 38 and two-sample t-tests demonstrate a notable difference on PC-G for female students ($t(259) = -3.6968$, $p = .00027$), but no significant difference for male students ($t(258) = -0.84472$, $p = .3991$), and similar but more detailed information can be observed in Figure 39. However, refer to Table 27, two-way ANOVA found no significant effect of gender ($F(1, 542) = 0.771$, $p = .3804$, $\eta^2 < 0.01$), or interaction ($F(1, 542) = 2.666$, $p = .1031$, $\eta^2 < 0.01$), but significancy of the main effect of lighting mode ($F(1, 542) = 8.602$, $p = .0035$, $\eta^2 = 0.02$). Tukey HSD post-hoc test confirmed the significancy of this main effect with the same p value ($p = 0.035$).

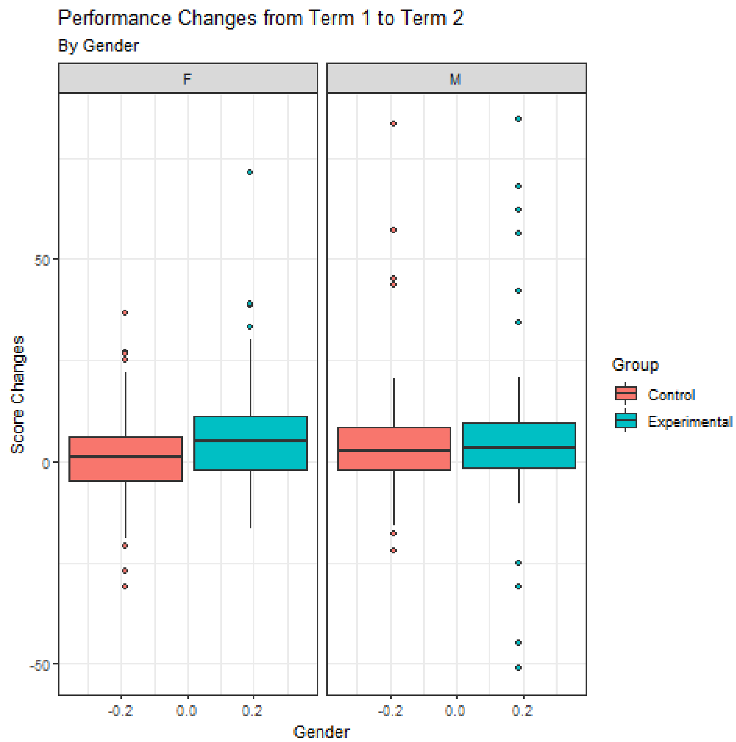


Figure 38. Comparison of mean of PC-G

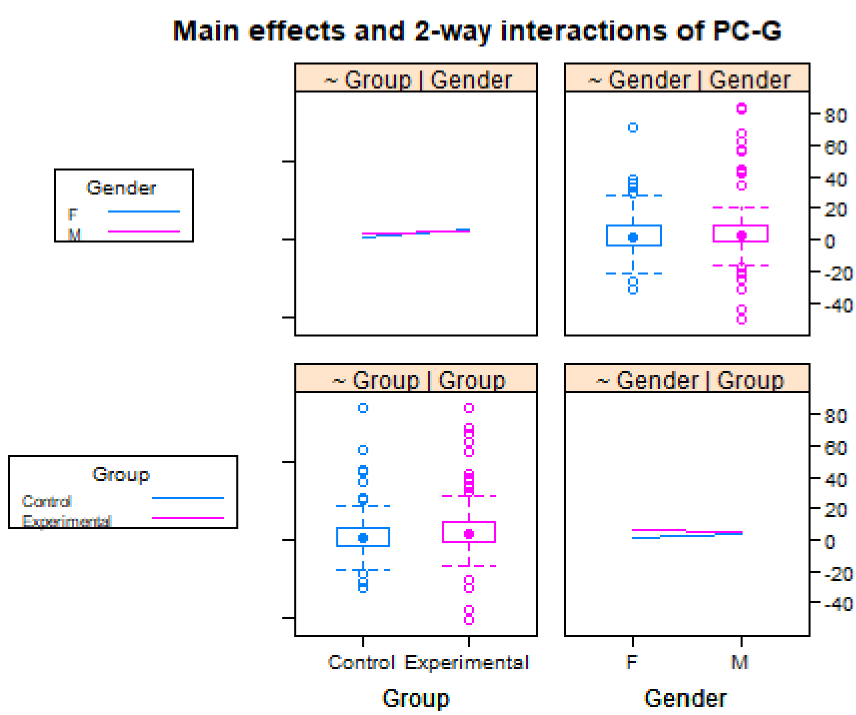


Figure 39. Main effects and interactions of PC-G

Table 27. Between-subject and Within-subject Effects on PC-G

Main/Interaction Effect	*df*	*Mean Square*	*F*	*p*	η^2
Lighting Mode	(1, 542)	1367.6	8.602	0.0035	0.02
Gender	(1, 542)	122.5	0.771	0.3804	< 0.01
Lighting Mode × Gender	(1, 552)	423.9	2.666	0.1031	< 0.01

6.6 Performance Changes By-subject and By-genders (PC-SG)

6.6.1 Descriptive Statistics

By examining Figure 40, it is interesting to notice that girls in the experimental group gained higher increment on both subjects, and their mean scores of the second term even surpassed that of the control group. However, for the boys, only Chinese of the experimental group appeared higher increment, and their mean scores of both terms stayed below that of the control group.

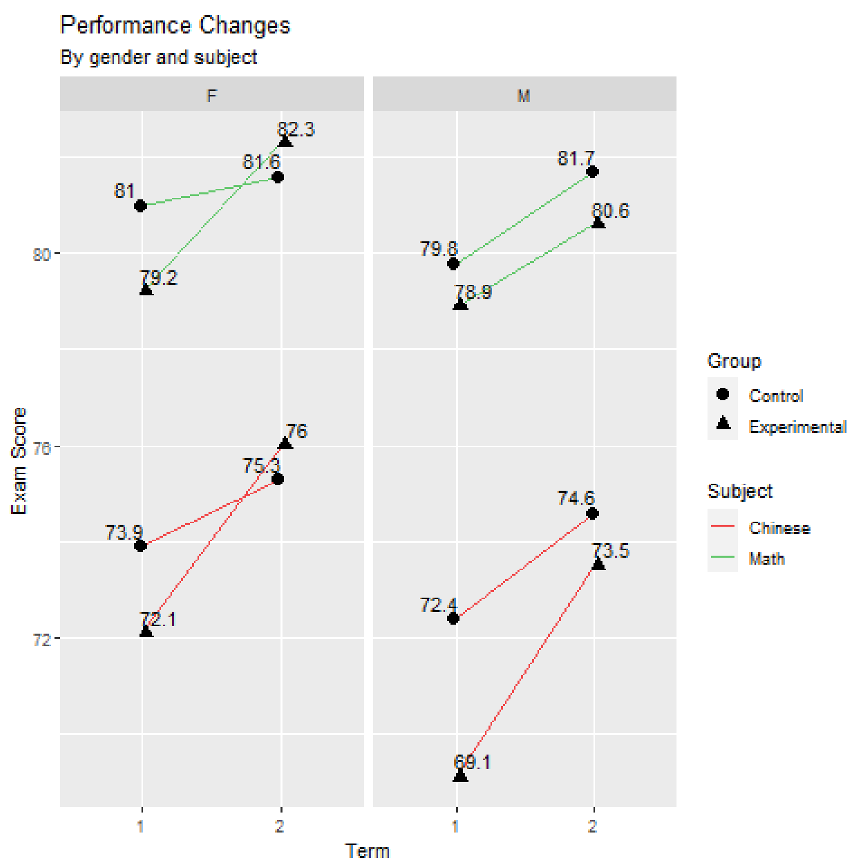


Figure 40. By-subject-gender performance changes

6.6.2 Inferential Statistics

6.6.2.1 Hypothesis and Method

Although there was uncertainty, the hypothesis still assumed both genders of the experimental group gained larger increment on both subjects, and was stated as:

$$H_0:\ (\mu_1\ \nu_1) = (\mu_2\ \nu_2) \qquad H_1:\ (\mu_1\ \nu_1) > (\mu_2\ \nu_2)\ ,$$

where μ and υ stands for the mean increment of Chinese scores and Mathematics scores received by the female (n = 280) or male (n = 288) students, respectively. The subscript 1 corresponds to the experimental group, and the subscript 2 is for the control group. A two-way MANOVA was performed for the composition analysing of both subjects. Again, R version 4.1.0 64 bit with R Studio version 1.4.1717 and a 95% confidence interval was the tools and condition.

6.6.2.2 Result

A two-way MANOVA was performed to analyze the detailed effects on different subject and different gender. As described in Table 28 and Figure 41, consistent results confirmed that regardless Chinese or Mathematics, gender had no significant effect ($F(1, 542) < 2$, $p > .16$, $\eta^2 < 0.01$). Meanwhile, significant effects of lighting mode were reported on Chinese ($F(1, 542) = 6.8069$, $p = .0039$, $\eta^2 = 0.02$), Mathematics ($F(1, 542) = 4.5495$, $p = .0334$, $\eta^2 = 0.02$), as well as their combination ($F(2, 541) = 4.2854$, $p = .0142$, $\eta^2 = 0.02$).

Table 28. Result of MANOVA on PC-SG

Dependent Variable	***Independent Variable***	***df***	***Mean Square***	***F***	***p***	η^2
Chinese and Mathematics	Lighting Mode	(2, 541)	NA	4.2854	0.0142	0.02
	Gender	(2, 541)	NA	1.175	0.3096	< 0.01
Chinese	Lighting Mode	(1, 542)	531.23	6.8069	0.0093	0.02
	Gender	(1, 542)	148.44	1.902	0.1684	< 0.01
Mathematics	Lighting Mode	(1, 552)	194.11	4.5495	0.0334	0.02
	Gender	(1, 552)	1.239	0.029	0.8648	< 0.01

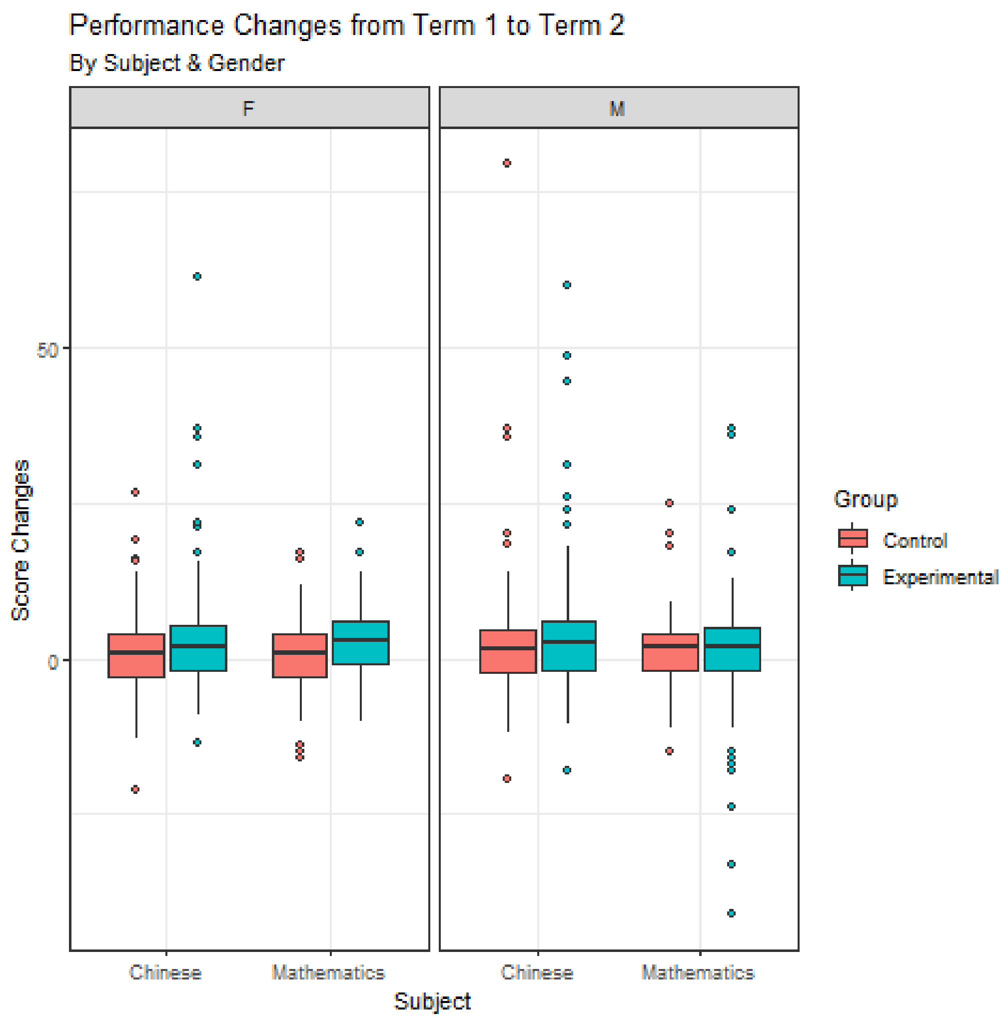


Figure 41. Comparison of mean of PC-SG

6.7 Discussion

Along with the consistent results of this study, there were a few anormal data or equivocal output need to be discussed.

The first question is about the disagreement between the assumption and the statistical result regarding the user operational preference. Although the control group demonstrated more manual times per day than the experimental group, no significant difference was confirmed statistically. Nevertheless, the research team still believe that the smart lighting system with rule-based automatic control can reduce the manual operation on the lighting system, so that users can pay more attention to their jobs. Small sample size (12 classrooms and one term) may be the main cause of insignificancy. It makes sense to collect more data and update the result in the future.

Secondly, many outliers can be easily observed in the box plots. The outliers represent the score records that extremely changed from term 1 to term 2. Given the fact that it was not practical to investigate into these individual records, the research team decided to keep the outliers in the analytical process based on the following considerations. First, although some outliers could be considered as abnormal data, such as students moving in and out in the middle of the project, students not performing well in the tests due to sickness or other reasons, and so on, the majority of outliers were believed to be normal data. It is understandable that students can improve or set back a lot throughout a year, especially for students of grade one and two. Since there was no way to distinguish few anomalies from many normal outliers, it was rational to keep all outliers to reflect the reality. In addition, modelling on original data without manual trimming will facilitate the implementing of the self-optimizable framework in the future.

Moreover, it is notable but not surprising that the effect size (η^2) in this study is small due to the nature of the dataset. Given the equation $\eta_A^2 = SS_A \,/\, (SS_A + SS_E)$, η_A^2 ought to be small when SS_A is significantly smaller than SS_E. In this study, the variance of exam scores within a classroom (SS_E) is much larger than the variance of mean scores between classrooms (SS_A). In other words, there are high-scored students and low-scored students in every classroom. The spectrum widely spreads within one classroom, but the distribution resembles between classrooms. This is a common phenomenon as long as students are randomly dispatched into each classroom.

6.8 Limitations

Subject to the actual situation, this study encountered some difficulties and inevitably had a few limitations, which could be improved in the future.

First of all, although the received data were the final exam scores of students studying on campus, they are not two consecutive semesters. Due to the pandemic, the research process had been interrupted for nearly one year. During this period, students spent most of their time learning from home. So, the effectiveness of their scores may be impacted by the interruption.

Secondly, according to the study design and configured rules, although at the beginning of each class, the classrooms of the control group would automatically switch to the standard lighting mode and the experimental group would automatically switch to the corresponding learning-context lighting mode, the system also allows users to manually adjust the brightness and CCT. Therefore, in the actual process, it could not be completely guaranteed that the classrooms of the control group were always in the standard lighting mode and the classrooms of the experimental group were always in the learning-context lighting mode. In addition, although for this particular study many factors, like the teaching resources, students’ demographic features, other indoor environmental parameters, were held consistent among all classrooms, different conclusions might be drawn in different school settings. So, strictly speaking, the data analysis results only correspond to these particular settings.

Third, the classrooms involved in this study were Grade 1 and Grade 2 of a primary school. Considering that junior students may have significant performance changes in the adaptation period, which could impact the effectiveness of data analysis results. If possible, it is also necessary to conduct relevant research on higher grades.

Finally, the dataset obtained by the research team was only the final exam scores of two terms and lacks the students' regular test results. The data batch was small, but the span was large, so it was impossible to analyze the trend and details of performance changes. The research team expected to get more data and perform in-depth analysis in the follow-up.

Chapter 7
Conclusion and Future Work

Previous studies have found the effects of environment lighting on human circadian rhythm, subject comfort, attention, and cognitive performance. The recent development on smart LED lighting systems provides new ways to control the brightness and color temperature of environment lighting in classrooms dynamically. However, there is no existing knowledge about how to optimize the lighting for different classroom activities, and it is still a question whether the new environment lighting system could improve student performance. This study recorded and compared students' performance under different classroom lighting schemes, improving the understanding about the effects of classroom lighting on student performance, and enriching the knowledge regarding how to implement smart lighting system in school from an interdisciplinary perspective. More importantly, this study pointed out some new directions for follow-up research.

7.1 Conclusion

Starting from reviewing related research about lighting environment in classroom, this study divided the development of nearly thirty years into five phases and argued that the focus in this field has shifted to the learning-context stage. By integrating the results of existing research, the research team proposed one theoretical framework for classroom lighting, one classroom lighting environment self optimization framework, and ten learning context-based lighting modes.

On the other hand, this study also summarized the development of engineering technology regarding the lighting control system and pointed out the key characteristics of smart lighting control system for learning. Furthermore, this study introduced in detail the system design, hardware and software of a complete learning-context based lighting control system, as well as the implementation of the system in an actual project.

Based on the proposed frameworks and engineering technology, it is possible to apply Big Data and machine learning methods to relevant human factors research fields. Although this part was not yet implemented at current stage, the research team pointed out that this may lead to systematic innovation and finally approach the optimal classroom environment parameters suitable for a variety of learning scenarios.

As a preliminary practice of the above theory and method, the cooperative company of this study perform a system trial by enabling the learning-context based lighting mode in six of the twelve classrooms of one of their projects, while the other classrooms maintained the standard lighting mode. The data including user operation log and students' academic performance of two terms were collected by the company during testing and improving their products. These data were analyzed by the research team and led to the following findings.

Data analysis on the user operation log found no significant difference between the control group and the experimental group in terms of UOP, which was inconsistent with the expectation. The possible causes to the contradiction were discussed, and the follow-up study was proposed.

Regarding the improvement of students' performance, significant effect was found on OPC as well as PC-S of each subject. Specifically, the students in the learning-context based lighting environment gained 2.07% higher overall performance than those in the standard lighting environment. As for Language and Mathematics, the experimental group achieved 2.73% and 1.48% higher improvement respectively compared with the control group.

Meanwhile, the by-gender analysis reported interesting results. The MANOVA found no significant effect of gender at all. However, the separated t-tests showed significant effect of lighting environment on the performance improvement of female students, but not significancy on male students.

7.2 Future Work

Based on the results and questions found in this study, there are many topics that need further research in both engineering and human factors domains.

In terms of engineering, this smart lighting system needs to be improved in at least five aspects.

First, besides the lighting system, the system needs to be able to control more types of devices, such as air conditioning, curtains, and fans. This is not only to make the system more in line with the actual needs of the users, but also to provide technical support for comprehensive environmental factors research.

Secondly, although the IAESs were installed in the classrooms, the details such as the installation location and sensor data calibration have not been deeply studied. And the effectiveness and consistency of the data have not been verified. In the follow-up, it is necessary to conduct special research on these problems. On this basis, it is also necessary to develop the sensor self-calibration technology, so that the system can be easily installed and implemented in large scale.

Third, although the smart lighting system was expected to achieve good energy-saving effect, the performance of the system in energy-saving has not been evaluated in this study. Follow up needs to be supplemented.

Fourth, to save the cost, the data infrastructure and architecture were not built for massive data purpose in the study. With the increasing of data volume, especially in order to support Big Data analysis, the system architecture and infrastructure need to be reconsidered.

Lastly, based on the above conditions, the self-optimization framework and the RL model proposed in Section 3.8 need to be developed and tested.

On the other hand, the following directions in human factors domain need to be further studied.

Firstly, besides Chinese and Mathematics, there are many other subjects in school. The proposed lighting modes may not have equivalent effect on each subject. More subjects should be tested, and more specific lighting mode may need to be developed accordingly.

Secondly, besides academic performance, it is also worth to investigate into the impact of lighting environment on students' well-beings, such as vision health.

Thirdly, although many types of environmental data were collected in this study, only the effect of lighting environment on students' performance was analyzed. The study of other environmental factors and the interactive effects between these factors need to be performed and can lead to many research topics.

In addition, students' individual characteristics, such as age, gender, regional and cultural differences, may have different responses to the environmental factors. The existing studies were still insufficient in this regard. If relevant data can be obtained, the research may achieve some valuable findings.

Last but not lease, applying Big Data methods in relate research is a challenging but game-changing work. Based on the proposed self-optimization framework and huge datasets, combining manual analysis and automatic analysis will get closer and closer to the optimal environment settings for different group of students in diverse learning context.

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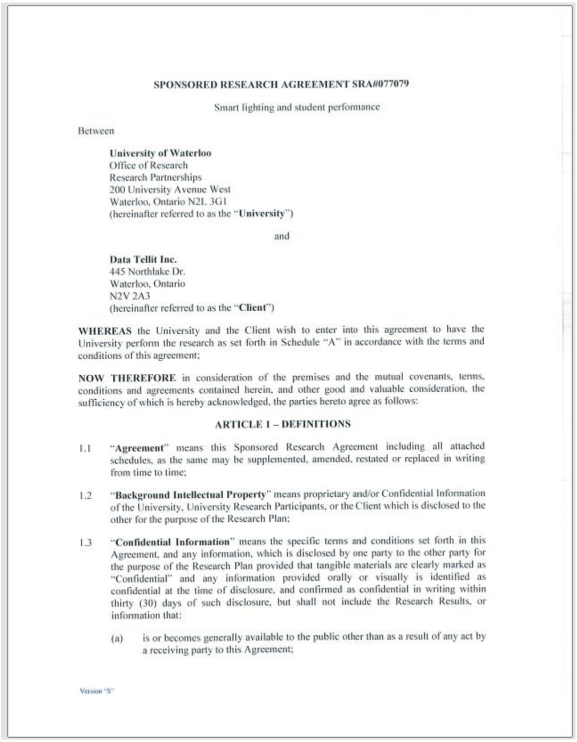
Appendix A
Supporting Material

A.1 Sponsor Agreement



SPONSORED RESEARCH AGREEMENT SRA#077079

Smart lighting and student performance

Between

University of Waterloo
Office of Research
Research Partnerships
200 University Avenue West
Waterloo, Ontario N2L 3G1
(hereinafter referred to as the "**University**")

and

Data Tellit Inc.
445 Northlake Dr.
Waterloo, Ontario
N2V 2A3
(hereinafter referred to as the "**Client**")

WHEREAS the University and the Client wish to enter into this agreement to have the University perform the research as set forth in Schedule "A" in accordance with the terms and conditions of this agreement;

NOW THEREFORE in consideration of the premises and the mutual covenants, terms, conditions and agreements contained herein, and other good and valuable consideration, the sufficiency of which is hereby acknowledged, the parties hereto agree as follows:

ARTICLE 1 – DEFINITIONS

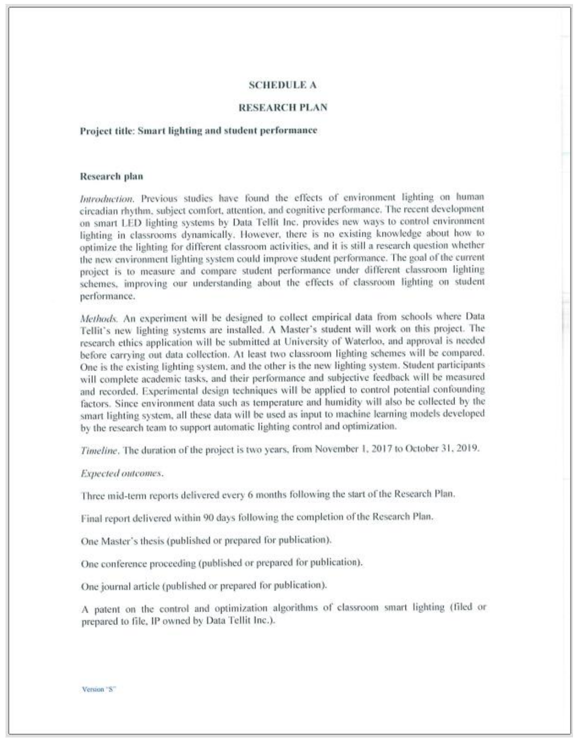
1.1 "**Agreement**" means this Sponsored Research Agreement including all attached schedules, as the same may be supplemented, amended, restated or replaced in writing from time to time;

1.2 "**Background Intellectual Property**" means proprietary and/or Confidential Information of the University, University Research Participants, or the Client which is disclosed to the other for the purpose of the Research Plan;

1.3 "**Confidential Information**" means the specific terms and conditions set forth in this Agreement, and any information, which is disclosed by one party to the other party for the purpose of the Research Plan provided that tangible materials are clearly marked as "Confidential" and any information provided orally or visually is identified as confidential at the time of disclosure, and confirmed as confidential in writing within thirty (30) days of such disclosure, but shall not include the Research Results, or information that:

(a) is or becomes generally available to the public other than as a result of any act by a receiving party to this Agreement;

Version "S"



SCHEDULE A

RESEARCH PLAN

Project title: Smart lighting and student performance

Research plan

Introduction. Previous studies have found the effects of environment lighting on human circadian rhythm, subject comfort, attention, and cognitive performance. The recent development on smart LED lighting systems by Data Tellit Inc. provides new ways to control environment lighting in classrooms dynamically. However, there is no existing knowledge about how to optimize the lighting for different classroom activities, and it is still a research question whether the new environment lighting system could improve student performance. The goal of the current project is to measure and compare student performance under different classroom lighting schemes, improving our understanding about the effects of classroom lighting on student performance.

Methods. An experiment will be designed to collect empirical data from schools where Data Tellit's new lighting systems are installed. A Master's student will work on this project. The research ethics application will be submitted at University of Waterloo, and approval is needed before carrying out data collection. At least two classroom lighting schemes will be compared. One is the existing lighting system, and the other is the new lighting system. Student participants will complete academic tasks, and their performance and subjective feedback will be measured and recorded. Experimental design techniques will be applied to control potential confounding factors. Since environment data such as temperature and humidity will also be collected by the smart lighting system, all these data will be used as input to machine learning models developed by the research team to support automatic lighting control and optimization.

Timeline. The duration of the project is two years, from November 1, 2017 to October 31, 2019.

Expected outcomes.

Three mid-term reports delivered every 6 months following the start of the Research Plan.

Final report delivered within 90 days following the completion of the Research Plan.

One Master's thesis (published or prepared for publication).

One conference proceeding (published or prepared for publication).

One journal article (published or prepared for publication).

A patent on the control and optimization algorithms of classroom smart lighting (filed or prepared to file, IP owned by Data Tellit Inc.).

Version "S"

A.2 Research Project Kick-off Meeting

Time: 15:30 to 16:30, March 4, 2019

Location: Gu'an Chengxi Public School

Host: Mr. Erchao Liu, Secretary General of the Education Equipment Industry Association of China

Meeting Participants:

- Mr. Zongchen Li, Education Bureau of Langfang City
- Mr. Shulin Yang, Education Bureau of Gu'an County
- Mr. Yao, Cheng, Principal of Gu'an Chengxi Public School
- Mr. Weiguang, Hu, Vice Principal of Gu'an Chengxi Public School

- Mr. Yaobin, Tang, Project Manager of DataTellIt Inc.
- Mr. Baoshi Sun, University of Waterloo
- Prof. Shi Cao, University of Waterloo (Remote attendance)

A.4 Background Material

A.4.1 Syllabus of the School

河北省义务教育课程设置及课时安排表（小学）

	一年级	二年级	三年级	四年级	五年级	六年级
品德与生活	3	3	2	2	3	3
科学			2	2	3	3
语文	8	8	7	7	6	6
数学	4	4	4	4	4	4
外语			2	2	2	2
体育	5	5	3	3	3	3
音乐	2	2	2	2	1.5	1.5
美术	2	2	2	2	1.5	1.5
综合实践活动			3	3	3	3
地方与学校课程	2	2	3	3	3	3
周总课时数（节）	26	26	30	30	30	30
学年总课时（节）	910	910	1050	1050	1050	1050

综合实践活动指信息技术、研究性学习、社区服务与社会实践、劳动与技术教育；地方与学校课程指心理健康教育、校本课程（如经典诵读、弟子规等）。

A.4.2 Class Schedule Example: Grade 1, Class 5

课 程 表

一（5）班

	节次 \ 星期	一	二	三	四	五
上午	1	数学	数学	数学	数学	数学
	2	语文	语文	语文	语文	语文
	3	象棋	音乐	习惯养成	体育	道德与法制
	4	数学	科学	道德与法制	阅读	语文
下午	5	体育	书法	武术	音乐	美术
	6	队会 综合实践	美术	语文	健康	社团