INVESTIGATING THE EFFECT OF TEMPERATURE AND LIGHTING ON LEARNING PERFORMANCE OF STUDENTS USING PHYSIOLOGICAL RESPONSES

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ABSTRACT

Temperature and lighting level are relatively important parameters of indoor environment in a university classroom because they affect students' learning performance. Previous research primarily focused on analyzing students' learning performance, ignoring the learning process involved and the impact of physiological reactions to their learning environment. This study investigates the learning process as well as the influence of students' sensations/comfort and physiological responses. Experiments were carried out in a university classroom with 17 students performing cognitive tests while wearing an EEG headset and an ECG wristband at different temperatures (20-23°C, 23-26°C, 26-29°C) and lighting levels (100-300 lux, 300-600 lux,600-900 lux). The results showed brighter light improved concentration, while neutral temperature was important for working memory, and a comfortable environment and emotional state were important in increasing motivation for better learning performance. The findings can be used to develop an IEQ management plan that will contribute to improve the learning environment.

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1. INTRODUCTION

1.1. Research background

Indoor Environmental Quality (IEQ) refers to quality of the indoor environment related to the health of the occupants and is determined by occupant control over lighting and thermal comfort, air quality, access to daylight and views, and pleasant acoustic conditions (NIOSH, 2013; U.S. General Services Administration, 2015). Based on a survey involving 10,000 participants, on average people in US and Canada spend 90% of their time indoors during summer and 96-98% during winter season (Leech, Burnett, Nelson, Aaron, & Raizenne, 2000). An undesirable IEQ may not only lead to sick building syndrome symptoms such as eye, nose, and throat irritation but also affects the occupants' performance and productivity such as difficulties in concentrating, clear thinking and decreased self-performance (Witterseh, Wyon, & Clausen, 2004; Akimoto, Tanabe, Yanai, & Sasaki, 2010; McCartney & Humphreys, 2002). Hence, the indoor environmental condition of a building plays a crucial role in individuals’ health and wellbeing and for their efficiency.

Among the various types of building, educational buildings such as schools, universities, and colleges are some of the most important buildings where one-fifth of the world populations spends more than 30% of their time (Giuli, Pos, & Carli, 2012; Lizzio, Wilson, & Simons, 2002). A classroom is an essential learning environment where students carry out most of their daily activities, therefore, the indoor environmental quality are closely related to their performance and productivity as well as health and wellbeing.

Previous studies investigated the effect of thermal sensation on students’ learning performance and found that thermal dissatisfaction with indoor thermal conditions had a significant impact on students' learning performance and thermal discomfort could be partly mitigated by lighting that results in a higher perceived lighting comfort (Lee M. C., et al., 2012; Barbic, et al., 2019; Kulve, Schlangen, & Lichtenbelt, 2018). Previous research studied the impact of three indoor environments factors- temperature, lighting and noise on learning efficiency and found that influence of the environmental factors on learning efficiency varied with the type of cognitive tasks performed (Xiong, et al., 2018).

Recently, physiological responses such as heart rate, blood volume pressure, skin temperature, brain activities have drawn attention as quantitative variables of IEQ and learning performance. The electroencephalograph (EEG) and electrocardiogram (ECG) have been widely used as an objective measure to support traditional subjective methods and learning performance evaluation. Previous research focused on the psychophysiological effect of the thermal conditions on students' learning performance through EEG measurement and concluded that the thermal condition helped increase the task load by stimulating the students' psychophysiological response, which influenced their learning performance (Kim, Hong, Kim, & Yeom, 2020). Lan, Lian, Pan, & Ye (2009) investigated the neurobehavioral effect of temperature on subjects using finger temperature measurement and found that the thermal effect on task performance would be counteracted by subjects' motivation to perform well. Wang, Li, Menassa, & Kamat (2019) used EEG to examine the impact of indoor thermal environment on occupants' mental workload and found that slightly warm environment was associated with increased mental workload, which however, did not result in higher task performance.

As such, numerous studies have examined the effects of thermal and lighting conditions on students' performance. However, previous studies are limited in that experiments were mostly conducted in a controlled environment such as a climate chamber and considered thermal condition or lighting condition separately. This means that there are limited studies that analyzed the effects of temperature and lighting conditions on the learning performance in real classroom environments. In addition, although a few of previous studies analyzed the learning performance using physiological responses of the indoor thermal conditions or lighting conditions, they didn't take into account of learning process or mechanism involved. To augment the existing learning environment-related standards and create a management plan that can improve the learning environment for students, it is critical to understand the mechanism involved in the effects of temperature and lighting conditions on the learning performance of students.

1.2. Research aim

This study aims to investigate the mechanisms involved in the relationships between temperature and lighting conditions on learning performance considering students' sensation/comfort and physiological responses.

1.3. Thesis outline

The first chapter is Introduction, it provides background information for the research to identify the rationale for the study. Literature Review is the second chapter in which the importance of thermal and lighting comfort, and the current state of knowledge with regards to association of temperature, lighting and physiological response to learning performance of students is discussed. Furthermore, cognitive functions regarding the learning performance of the students and overview of brain activity is covered. Also, highlighting the knowledge gap from previous study which this research aims to fulfil.

The third chapter is Methodology, it provides information on the analysis model, experimental design, the experiment procedure, and the analysis method carried out. Results is the fourth chapter, it discusses the results obtained through observation, analysis of the collect data as well as the subjective questionnaire. Following the Results chapter is Discussion, this chapter further discusses the findings as well as the reasoning behind the findings of the research. The final chapter is Conclusion and Future Work that concludes with the highlighted results of the study as well as discusses the contributions and limitations of the study.

2. LITERATURE REVIEW

2.1. Thermal comfort

Thermal comfort is a principal factor of IEQ that plays a critical role in occupant's comfort and satisfaction. It can be categorized into two parameters- environmental that consists of factors such as air temperature, air velocity, air relative humidity and air mean radiant and personal parameter that consists of human body insulation through clothing and their metabolic rates (Katafygiotou & Serghides, 2015). The thermal adoption per individuals as objectives inside the building is defined by factors such as physiological adaptation, behavioral adjustment, and psychological habituation or expectation (Nikolopoulou & Steemers, 2003).

One of the issues with air-conditioned classrooms in warm climate or in cold climates when the classroom has windows and a door closed is the acclimatization process during lecture hours that the students go through. As students move into and adapt to their classroom environment their thermal sensation changes significantly as the time inside the classroom increases and the immediate response phase after the indoor-outdoor transition has the most considerable differences (Mishra & Ramgopal, 2015; Mishra, Derks, Kooi, Loomans, & Kort, 2017).

An operative temperature of thermal neutrality of 25.4 °C in dormitories was found in a field-study conducted by (Cheng, Hwang, & Lin, 2008) in classrooms, dormitories, and outdoor spaces of universities in Taiwan and preference to cooler rather than neutral thermal conditions in dormitories and classrooms was shown as results. The study conducted by Liu, Yang, Jiang, Qiu, & Liu (2019) in Xi'an in the north-west of China where the outdoor temperature is lower than 10 °C found that the neutral temperature was 20.6 °C, the thermal comfort temperature range was between 19.5 °C and 21.8 °C and the occupants' preference temperature was 22.78 °C.

2.2. Lighting comfort

Lighting is a key factor of IEQ that is known to correlate in affecting their physical and psychological behavior. The result study conducted by (Burgess, Sharkey, & Eastman, 2002) to find a correlation between the quality of indoor environment light and human performance indicated that being exposed to insufficient or inappropriate light has can disrupt human standard rhythms, hence, might have adverse results for human performance, safety, and health. (Wilkins, Nimmo-Smith, Slater, & Bedocs, 1989) investigated the relation of light comfort to human behavior and the result indicated that a decrease in the amount of flicker in light, i.e., the magnitude of the rapid cyclic change in illuminance over time may be associated with a decrease in a headache and eye strain which resulted in an increase over worker performance. Hwang & Kim (2010) concluded that lighting environment can influence an occupant's safety, the level of fatigue, comfort, as well as work efficiency and accuracy. The study conducted by Kulve, Schlangen, & Lichtenbelt (2018) concluded that lighting comfort could partly compensate for thermal discomfort.

2.3. Learning performance

Learning performance is the measure of students' academic performance. Task or test performance is a common measure of performance that reflects accuracy, speed, and productivity. Cognition is defined as the process to organize information- acquire or perceive information, select information (attention), represent information (understanding), and retain information (memory) and use the retained information to reason and coordinate motor outputs (Bostrom & Sandberg, 2009). Students' learning performance refers to their short-term and long-term academic performance (Wang & Degol, 2016). Cognitive performance tests or school exercise are used to quantify short-term academic performance (Wargocki & Wyon, 2017; Wargocki, et al., 2002) while long-term performance is focused on the performance of students for a course or for an academic year (Pawlowska, Westerman, Bergman, & Huelsman, 2014; Gaihre, Semple, Miller, Fielding, & Turner, 2014).

Learning performance is indicated by the cognitive capacity of the student (Xiong, et al., 2018). Cognitive functions are brain-based skills that are associated with the mechanism of learning, remembering, reasoning and problem solving and are required to perform tasks of distinct levels of difficulty (Wang, et al., 2021). Previous review work on cognition and human performance classified cognitive function into attention, memory, perceptual-motor performance, judgment, and decision making while another categorization of cognition includes memory, attention, reasoning, visual perception, language function, problem-solving and planning (Staal, 2004; Eysenck & Brysbaert, 2018). Among the various cognitive functions, we plan to examine attention, perception, working memory ability and thinking ability.

2.3.1. Attention

Attention refers to the ability of an individual to concentrate on specific information. Unless experienced with the task that enables automatic processing, individuals are unable to easily focus on more than one stimulus at a time as attention has a limited capacity (Cowan, 2001; Wang, et al., 2021). Conceptualization theories assume that attention is responsible for limited capacity for working memory and proposed attention in three versions: as a resource for storage and processing, a shared resource for perceptual attention and memory maintenance, and as a resource for the control of attention (Oberauer, 2019).

Attention is categorized as Sustained attention, Selective attention, Alternative attention and divided attention, each type of attention results in different learning efficiency. While influenced by mood and emotion, it is possible for an individual to acquire attention bias that infers to the tendency to selectively attend to certain category of stimuli in the environment while tending to overlook, ignore or disregard other kinds of stimuli, it also impacts the learning efficiency as it serves purpose for selective learning (Ekhtiari & Paulus, 2016).

2.3.2. Perception

Perception is a cognitive process that allows us to capture, organize, identify, and interpret- to take in information through sensory organs, to utilize and understand the information presented to respond and interact with the surrounding world. While perception and sensation are different processes they are closely related. Sensation involves the process of detecting the environment and perception involves interpreting what has been sensed. Perception is more involved with top-down processing which itself is influenced by an individual's expectations and knowledge rather than simply by the stimulus itself (Eysenck & Brysbaert, 2018).

Perception may be biased based on the influence of emotion individual differences such as different sensitivity of tone sequences, personal context, belief and expectations (Lui, Huang, Wand, Gong, & Chan, 2012; Postma-Nilsenová & Postma, 2013; Schlee, Curren, Harich, & Kiesler, 2007; Pronin, 2007). The different modes of perception are auditory perception, visual perception, speech perception, taste perception, touch/haptic perception, and olfactory perception. An individual's motivational state can affect visual stimuli as humans' motivation can influence the optical system to indicate the content of conscious perception (Balcetis & Dunning, 2006; Wang, et al., 2021).

2.3.3. Working memory ability

Working memory refers to an individual's ability to hold and manipulate information temporarily. Oberauer (2019) defined working memory as the mechanisms and processes that hold the mental representations currently most needed for an ongoing cognitive task available for processing. It is a modern conceptualization of short-term memory (Baddeley & Hitch, 2002). Working memory involves the processing of information such as solving arithmetic problems while remembering given words during span tasks as well as executive control of attention (Wang, et al., 2021).

The process of conversion of external stimuli to memorized information involves three steps: stimuli are processed through sensory memory that holds information presented to various sensory systems, then the working memory processor encodes the information and holds it temporarily, meanwhile searching and activating data from previous-stored memories (Shiffrin & Atkinson, 1969; Gomes, et al., 1999; Baddeley, 1966). Lastly, the added information is integrated and stored in long term memory (Baddeley, 1966). Working memory contributes to controlling perceptual attention – by holding templates for targets of perceptual selection – and controlling action – by holding task sets to implement our current goals (Oberauer, 2019).

2.3.4. Thinking ability

Thinking ability involving reasoning and decision-making is a higher order cognition process that involves the ability to understand and implement the steps necessary to solve problems, establish new areas of learning and thinking creatively (Akella, 2019). Reasoning refers to the central activity in intelligent thinking for problem solving by establishing logical relationships between different problem elements (Zimmerman, 2000). General reasoning skills involve inferential reasoning, deductive reasoning, analogical reasoning, conditional reasoning, and automated reasoning (Alexander, White, & Haensly, 1987). Decision-making is a cognitive process that chooses a preferred option or a course of actions from among a set of alternatives based on criteria or strategies (Wang, et al., 2021; Wilson & Keil, 1999).

2.4. Indoor thermal and lighting conditions and learning performance

The study of the effect of indoor thermal condition in educational facilities on students' intellectual abilities by evaluating their learning performance in the climatic chamber by Pepler & Warner (1968) showed an inverse U-shaped relationship between indoor thermal condition and learning performance. Lee M. C., et al. (2012) examined the relationship between thermal condition and learning performance in an air-conditioned university through subjective assessment and objective measurement and found that the students' thermal dissatisfaction with indoor thermal condition had a strong impact on their learning performance.

Xiong, et al. (2018) studied the impact of three indoor physical environments (i.e., temperature, noise, and illuminance) on learning efficiency in several types of tasks. The results showed that based on the four-task type (perception, memory, problem solving and attention-oriented tasks) ambient temperature, noise and illuminance exerted significant main effect on learning performance and the highest learning efficiency in thermoneutral, relatively quiet and bright conditions for perception task, warm, relatively quiet and moderate light for memory, thermoneutral, fairly quiet and moderate light for problem-solving and cool, fairly quiet, and bright environment for attention. Yang & Moon (2019) conducted experiments to investigate the combined effects of acoustics, thermal and illumination conditions on the comfort of discrete senses and overall indoor environment in an environmentally controlled laboratory and concluded that indoor environmental comfort increases with decrease of noise level at thermoneutrality in brighter conditions.

Hoque & Weil (2016) studied the thermal environment, thermal comfort, and test scores of students as indicator of short-term academic performance and found student who experienced no thermal discomfort performed better than students who experienced thermal discomfort. Bajc, Banjac, Todorovic, & Stevanovic (2018) investigated the thermal comfort and working productivity loss in university classroom. The results indicated thermal comfort as an important factor that impact productivity as well as the personal feeling regarding the thermal comfort.

2.5. Physiological responses and learning performance

Physiological responses are the autonomic reaction to stimuli from an organisms' bodily part. It is fight or flight response, to withstand changes in environmental condition that are outside their optimal range or to trigger behavioral reaction in response to threat in response to a stimulus (Elliott & Quintino, 2018; Jansen, Nguyen, Karpitskiy, Mettenleiter, & Loewy, 1995). The sensation of discomfort and stress leads to physical and mental uneasiness and annoyance which are the key measures for indoor environmental quality and performance and productivity. Some examples of biosensing techniques for measuring physiological responses are Brain- EEG, Heart-ECG, heart rate (HR), heart rate variability (HRV), blood volume pressure (BVP), Skin-skin temperature (SKT), thermal infrared imaging (TII), electrodermal activity (EDA), photoplethysmography (PPG), Auxiliary-facial expression, posture/gestures, voice stress analysis (VSA), Eyes- pupil diameter (PD), eye activity (EA)/ eye tracking (ET), electrooculogram (EOG) etc.

Hu & Maeda (2020) studied the productivity and physiological responses during exposure to varying air temperature and clothing condition and found a higher relative overall performance of sustained attention at 16 °C than 26 °C for the 0.3 clo clothing condition. Zhu, Liu, & Wargocki (2019) measured the changes in EEG signals during the cognitive activity at varying air temperature and relative humidity and concluded the best performance for working memory when the temperature was 30°C and the accuracies and speed of mental arithmetic test were highest and lowest respectively at 30°C. Lan & Lian (2009) used neurobehavioral tests to evaluate the effects of indoor environment quality on productivity. The result showed highest correct ratio for perception when temperature was 17°C and shortest response time when temperature was 21°C. Tanabe & Nishihara (2004) evaluated the productivity and fatigue under different lighting conditions using number addition test and found no significant difference in performance and lighting condition.

Yang, Hu, Zhang, Zhu, & Wang (2021) investigated the students' short-term memory performance and thermal sensation with heart rate variability under different temperature and correlated color temperature (CCT) in summer using subjective questionnaire and physiological measurements while performing cognitive task. Results showed that the short-term memory performance of students is not affected by the conditions investigated. Kulve, Schlangen, & Lichtenbelt (2018) tested the effect of the correlated colored temperature of light and its intensity on thermal perception. The results showed a positive relationship among the change in visual comfort and the change in thermal comfort between different light sensation and hence it was concluded that thermal discomfort can be partly compensated by lighting that results in a higher perceived visual comfort. Lan, Lian, Pan, & Ye (2009) conducted experiment on the neurobehavioral effect of room temperature on subjects using psychometric tests and found that the subjects' motivation to perform well would offset the thermal effect on task performance.

Barbic, et al. (2019) conducted an experiment to examine the effects of different classroom temperatures on cardiac autonomic control and cognitive performance in undergraduate students while attending a lecture and performing cognitive tasks through ECG measurements. It was found that in the presence of thermal discomfort cognitive performance was reduced. Wang, Li, Menassa, & Kamat (2019) investigated the effect of indoor thermal environment on occupants' mental workload was using EEG in an experiment. The results concluded that most subjects have higher mental workload in a slightly warm environment, however it varies in different tasks and different individuals. Due to the impact of the thermal environment, higher mental load exerted by the subject did not result in higher task performance on the same task (Wang, Li, Menassa, & Kamat, 2019). Zhang R. , et al. (2020) conducted subject-within experiment taking EEG based attention measurements under five different lighting setups. The result concluded that attention of people in 20s is not affected by the experimental lighting conditions and people in high illumination are more inclined to sustain attention despite discomfort and dissatisfaction.

Kim, Hong, Kim, & Yeom (2020) examined the psychophysiological effect of indoor thermal condition on college students' learning performance through EEG measurement- using mental workload, mental fatigue, mental stresses, alertness as four neurophysiological indices to assess subjects' psychophysiological responses. The results showed that the indoor thermal conditions do not have a direct effect on the students' learning performance, however they help increase the task load by activating the students' psychophysiological response. The psychophysiology theory claims that some perceptions cause physiological reactions and the feelings corresponding to these physiological reactions are referred to as emotions (Norman, Necka, & Berntson, 2016; Kim, Hong, Kim, & Yeom, 2020). Emotional state is another neurophysiological index that can impact the academic performance of students. Jebelli, Hwang, & Lee, (2017) measured the feasibility of field measurement of construction workers' emotional states by calculating their valence level. Hwang, Jebelli, Choi, Choi, & Lee (2018) quantified the workers' emotional state during construction tasks applying a bipolar emotional model, valence and arousal, wearable EEG sensor during their ongoing task. Valence is the level of pleasantness that an event can produce, with positive valence referring to positive emotion and negative valence referring to negative emotion, whereas Arousal is the level of autonomic activation that an event generates.

2.6. Knowledge gap

As shown in Table 1, previous studies have mostly conducted experiments in a controlled environment such as a climate chamber and considered thermal conditions or lighting conditions separately. In addition, previous studies have primarily focused on analyzing students' learning performance, not considering the impact of students' physiological responses related to the environment. Although a few previous studies analyzed the learning performance using physiological responses to indoor thermal conditions or lighting conditions, they did not take into account of learning process or mechanism involved. The learning process involves the use of sensory organs to perceive the environment and serve as a direct route to transfer information to the brain. In response, physiological changes occur that influence learning performance. Students who experience thermal dissatisfaction tend to lose motivation and concentration which lowers their learning performance (Wang D. , et al., 2018). To improve the conditions of learning environments, understanding the mechanisms involved in the effect of thermal and lighting conditions on the learning performance of students are necessary.

Table 1: Summary of previous studies

Author (year)	IEQ		Physiological status	Psychophysiological status	Learning performance	Experimental environment
	Thermal	Light				
(Xiong, et al., 2018)	v	v	N/A	N/A	Attention, memory, perception, problem-solving	Classroom
(Yang, Hu, Zhang, Zhu, & Wang, 2021)	v	v	Heart rate variability	N/A	Short term memory	Environmental Chamber
(Wang, Li, Menassa, & Kamat, 2019)	v		N/A	Mental workload	Thinking, working memory, reaction, perception	Research office
(Barbic, et al., 2019)	v		Heart rate variability	N/A	Reasoning, short-term memory, verbal activity	Classroom
(Wang D. , et al., 2018)	v		Blood pressure, heart rate, body temperature	N/A	Perception, concentration, learning memory, thinking	Controlled indoor environment
(Kim, Hong, Kim, & Yeom, 2020)	v		N/A	Mental workload, mental fatigue, mental stress, alertness	Attention, perception, working memory, executive ability	Climatic chamber
(Hong, Kim, & Lee, 2018)	v		N/A	N/A	Attention, perception, selective attention, visuo-spatial short-term memory, working memory, fast finger	Climatic Chamber
(Jaber, Dejan, & Marcella, 2017)	v		N/A	N/A	Continuous performance test, match to sample etc.	Classroom
(Liu, et al., 2022)	v	v	Brain waves	N/A	Attention, relaxation	Environmental chamber
Our study	**v**	**v**	**Heart rate, Skin temperature**	**Mental workload, mental stress, mental fatigue, alertness, emotional state**	**Working attention, working perception, memory ability, thinking ability**	**Classroom**

2.7. Brain and brain activity

Cerebrum is the largest and uppermost portion of the brain that consists of the cerebral hemispheres and is responsible for integrating sensory impulses, directing motor activity, and controlling higher intellectual functions. The brain can be divided into left and right cerebral hemispheres. The cerebral cortex includes the following: the frontal lobe, the temporal lobe, occipital lobe, parietal lobe, and the central sulcus.

The Frontal lobe: The frontal lobe is in front of the parietal lobe. It plays a vital part in impulse control, judgment, language production, working memory, motor function, problem solving, sexual behavior, socialization, and spontaneity. The frontal lobe also assists in planning, coordinating, controlling, and executing behavior (Cheng & Hsu, 2011).

The Temporal lobe: The temporal lobe is located at the side of the brain, beneath the lateral fissure. It plays a vital part in auditory processing, as it is home to the primary auditory cortex and is involved in semantics both in speech and vision. The functions of the temporal lobe are extended to memory formation, comprehension, naming, verbal memory, and other language functions.

The occipital lobe: The occipital lobe is in the rearmost part of the brain and is the visual processing center. These are specialized for different visual tasks such as visuospatial processing, color discrimination and motor perception (Cheng & Hsu, 2011).

Parietal lobe: The parietal lobe consists of the somatosensory cortex and the dorsal stream of the visual system that enables it to integrate sensory information from different modalities, to map objects perceived visually into body coordinate positions. It plays an important part in integrating sensory information from various parts of the body, knowledge of numbers and their relations and the manipulation of objects (Cheng & Hsu, 2011).

Central sulcus: The central sulcus is a fold in the cerebral cortex that separates the parietal lobe and the frontal lobe, the primary motor cortex, and the primary somatosensory cortex.

2.7.1. EEG

An EEG is a non-invasive technique that monitors and records the brain's electrical activity through the electrodes attached to the scalp (Kim, Hong, Kim, & Yeom, 2020). Changes in voltage occur in the cell membrane as the neuron in the brain is activated. Because of changes in the voltage that occur simultaneously in tens of thousands of neurons, the electrodes can perceive the electric potential. EEG can exhibit the subjects' neurophysiological responses as it allows direct verification of the activities of the central nervous system. The EEG signal is composed of waves in the range of frequency of 0-60 Hz band. Based on extracted frequency content recorded oscillations, different brain states and activities can be recognized.

i. Delta (δ) waves have a frequency range from 0.5-4 Hz and are associated with a state of deep sleep. These are high amplitude, low frequency waves that are caused by lack of processing by neurons.

ii. Theta (θ) waves have a frequency range from 4-8 Hz and are associated with the transition period between drowsiness and consciousness. They can also correspond to anxiety, epilepsy, and traumatic brain injury.

iii. Alpha (α) waves have a frequency range from 8-13 Hz and are associated with the state of relaxed awareness or wakefulness, that attenuates or disappears with concentration or attention. The amplitude of alpha waves ranges from 10 to 50 mV (Georgieva, Silva, Milanova, & Kasabov, 2014)

iv. Sensorimotor (mu) rhythms that have a frequency range from 8-12 Hz and are associated with sensory motor cortex and can be used to recognize intention or preparation of movement and imaginary motor movement (Georgieva, Silva, Milanova, & Kasabov, 2014)

v. Beta (β) waves have a frequency range from 13-30 Hz and are associated with states of active thinking: alertness, concentration, attention, and arousal. These waves are fast with low amplitude.

vi. Gamma (γ) waves have a frequency range from 30-45 Hz and are characterized by mental activities such as perception, problem-solving and creativity (Georgieva, Silva, Milanova, & Kasabov, 2014)

2.7.1.1. Mental workload

Rabbi, Zony, Leon, & Rezai (2012) assessed the mental workload with response to tasks performed studying the relative power of the four fundamental EEG bands: delta, theta, alpha and beta band. The four EEG power bands, specifically theta, alpha and beta, reveal the state of the brain. Based on the recommendations of the past researchers to use the combination of the three bands instead of the power bands alone that are incapable to produce a strong outcome. Variation in the brain state while performing different tasks was investigated using the EEG index.

Kim, Hong, Kim, & Yeom (2020) evaluated mental workload using relative band power as the absolute intensity of brainwaves differs between individuals; defined the index for mental workload as:

$$Mental\ workload\ index = \frac{\beta\ frontal}{\alpha\ frontal + \theta frontal} \qquad \text{Eq (1)}$$

where $\beta\, frontal$ represent average relative β power from frontal lobe, $\alpha\, frontal$ represent average relative α power from frontal lobe and $\theta frontal$ represent average relative θ power from frontal lobe.

2.7.1.2. Mental stress

Sulaiman N. , et al. (2012) assessed mental stress with changes in the EEG beta and alpha power- decrease in alpha power and increase in beta power. The reduction of alpha during the task is more likely due to increased stress occurring during the task (Tran, Thuraisingham, Wijesuriya, Nguyen, & Craig, 2007).

Kim, Hong, Kim, & Yeom (2020) defined mental stress as:

$$Mental\ stress\ index\ = \frac{\theta frontal}{\alpha\ parietal} \qquad \text{Eq (2)}$$

where $\theta frontal$ represent average relative θ power from frontal lobe and $\alpha\ parietal$ represent average relative α power from parietal lobe.

2.7.1.3. Alertness

Olbrich, Mulert, Karch, Trenner, & Leicht (2009) analyzed the different EEG-vigilance stages occurring during transition from full alertness to sleep onset based on posterior alpha during the state of relaxed alertness, decrease in alpha peak frequency corresponding to transition to drowsiness, disappearance of alpha and increase in delta and theta activity corresponding to increase in subjective drowsiness.

Kim, Hong, Kim, & Yeom (2020) defined alertness index as

$$Alertness\ = \frac{mu\ frontal + mid\ \beta\ frontal}{\theta\ frontal} \qquad \text{Eq (3)}$$

where $mu\ frontal$ represent relative sensory motor rhythm from frontal lobe, $mid\ \beta\ frontal$ represent mid β power from frontal lobe and $\theta frontal$ represent average relative θ power from frontal lobe.

2.7.1.4. Mental fatigue

Cheng & Hsu (2011) analyzed the relationship between basic EEG indices of relative power of theta, relative power of alpha and relative power of beta and ratio indices of (relative power of theta/relative power of alpha), (relative power of beta/relative power of alpha) and ((relative power of alpha+ relative power of theta)/relative power of beta).

Kim, Hong, Kim, & Yeom (2020) evaluated mental fatigue index as:

$$Mental\ fatigue\ = \frac{\beta\ frontal}{\alpha\ frontal} \qquad \text{Eq (4)}$$

where $\beta\ frontal$ represent average relative β power from frontal lobe and $\alpha\ frontal$ represent average relative α power from frontal lobe.

2.7.1.5. Emotional state

Previous studies have linked positive emotions with academic performance and have concluded that positive emotions help students to envision goals and challenges and open their minds to productive ways of thinking and problem solving, and hence making them feel more engaged in their studies and achieve higher academic performance (Pekrun, Goetz, Titz, & Perry, 2002) (Pekrun, Goetz, Titz, & Perry, 2002). There has been an agreement that by mapping the emotion onto space of the bipolar dimension of valence and arousal, emotional state can be identified, this can also represent the intensity of emotion (Russell, Weiss, & Mendelsohn, 1989; Burkhardt, 2001).

Valence refers to the level of pleasantness that an event can generate and is defined along the continuum of positive and negative while, Arousal is the level of autonomic activation that an event creates, and ranges from calm to excited (Bestelmeyer, Kotz, & Belin, 2017). The changes in arousal and valence level corresponds to the change in emotional state of the subject. While positive valence corresponds to more activation of left frontal area of the brain, and positive or pleasant emotions, negative valence corresponds to activation of right frontal area and negative emotions. Arousal is referred as degree of vigilance during wakefulness and a higher arousal value indicates more aroused emotional state of an individual.

Hwang, Jebelli, Choi, Choi, & Lee (2018) have defined valence as,

$$Valence = \frac{\alpha(F4)}{\beta(F4)} - \frac{\alpha(F3)}{\beta(F3)} \qquad \text{Eq (5)}$$

which indicates the relative activation between two areas to show valence level and arousal as:

$$Arousal = \frac{\alpha(AF3 + AF4 + F3 + F4)}{\beta(AF3 + AF4 + F3 + F4)} \qquad \text{Eq(6)}$$

which indicates the arousal level by calculating the alpha/beta ratio (Lewis, Weekes, & Wang, 2007; Davidson, Ekman, Saron, Senulis, & Friesen, 1990).

3. METHODOLOGY

3.1. Analysis model

This study investigates not only the effects of temperature and lighting level on the learning performance of students but also the mechanisms involved in the relationships between them considering students' perception/comfort and physiological responses. To this end, this study conducts several analyses as shown in Fig. 1. First, the effects of the temperature/lighting level on the learning performance are investigated (analysis 1). Then, the relationships between temperature/lighting level and sensation/comfort as well as physiological responses are analyzed (analysis 2, 3, and 4). The relationships between sensation/comfort and physiological responses are also explored. Finally, this study examines the effect of sensation/comfort and physiological responses on the learning performance of students under different temperature/lighting level (analysis 5 and 6).

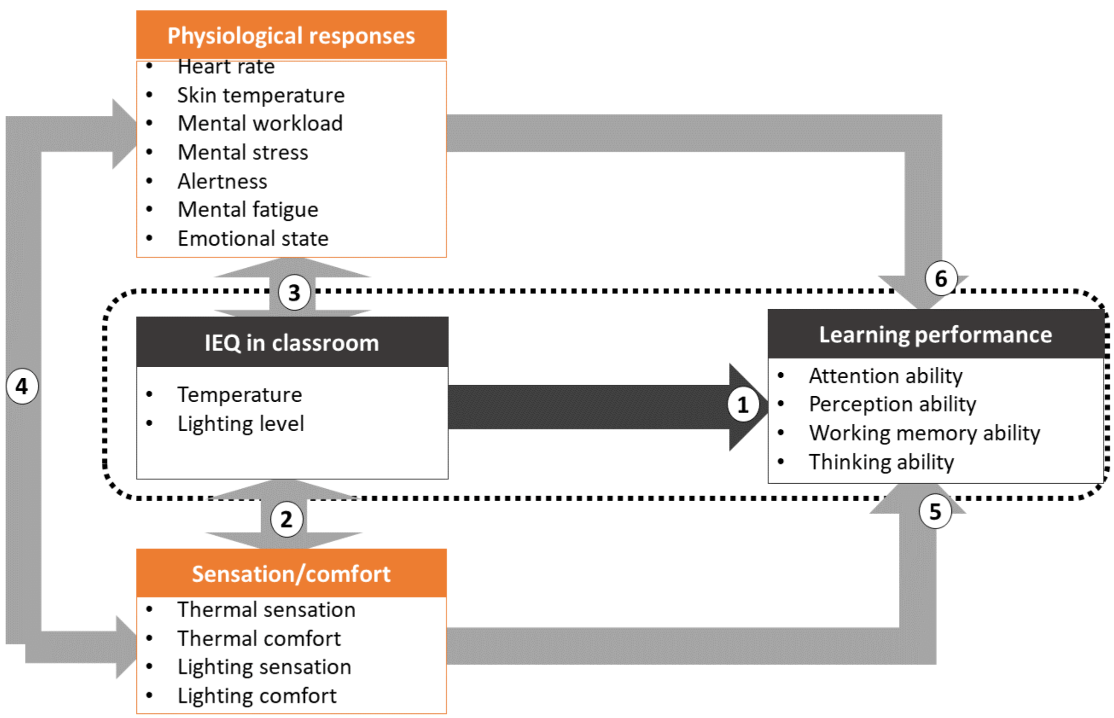

Figure 1: Analysis model

3.2. Measurements

The IEQ factors measured in order to adjust the room parameter and meet the experimental set up conditions were the indoor air temperature (°C), relative humidity (%), globe temperature (°C), illuminance (lx). Air temperature and illuminance were measured using thermal meter and illumination meter. Measurement equipment used are shown in Table 4. All instruments were calibrated before the experiment and the measurement data were recorded automatically.

Table 2: Measurement equipment

Parameter	Range	Accuracy
Air temperature	-30°C - 60°C	+/- 0.5°C / +/-1.5°C
Relative humidity	0 – 100%RH	+/- 3% RH/ +/- 4.5%RH
Globe temperature	Min: 8°C- 21°C Max: 22°C-38°C	
Illuminance	0 – 200k lux	

(a) (b) (c) (d)

Figure 2: Sensors for data collection (a. Thermal meter b. Illumination meter c. E4 wristband d. EEG headset)

3.2.1. Indoor thermal and lighting conditions

The indoor thermal condition was measured using thermal meter and the lighting conditions was measured using illumination meter. The temperature was controlled using air-conditioning system linked to a thermostat in the classroom that allowed the temperature to be freely changed in the range from 20°C to 30°C. The lighting condition was controlled by monitoring the number of lightings. The combined effect of temperature and illumination on thermal sensation and comfort and lighting satisfaction were evaluated using a subjective questionnaire. Thermal Sensation Vote (TSV) of seven-level scale of ASHRAE (ASHRAE 55, 2021) standard : hot (+3), warm (+2), slightly warm (+1), neutral (0), slightly cool (-1), cool (-2), cold (-3) and Thermal Comfort Vote (TCV) of seven level scale of ASHRAE standard: very satisfied (+3), satisfied (+2), slightly satisfied (+1) neutral (0), unsatisfied (-1), slightly unsatisfied (-2) very unsatisfied (-3) was used was used. Lighting perception used seven level scale: Too bright (+3), Bright (+2), Slightly bright (+1), About right (0), Slightly dim (-1), Dim (-2), Too dim (-3) and Lighting satisfaction vote adopted seven level scale: Very satisfied (+3), satisfied (+2), slightly satisfied (+1) neutral (0), unsatisfied (-1), slightly unsatisfied (-2) very unsatisfied (-3).

3.2.2. Physiological responses

Physiological data- measurement data of heart rate and skin temperature were collected through Empatica E4 wristband which combines EDA and PPG sensors simultaneously enabling measurement of sympathetic nervous system activity and heart rate.

Physiological responses from the brain were recorded using EEG device by recording the brain waves from the cerebral cortex. An EEG is a non-invasive technique that monitors and records the brain's electrical activity through the electrodes attached to the scalp (Kim, Hong, Kim, & Yeom, 2020). Emotiv Epoc X with 14 channels of active electrodes was used to record brainwaves (i) frontal lobe: AF3, AF4, F3, F4, F7, F8, FC5 and FC6 (ii) temporal lobe: T7 and T8 (iii) occipital lobe: O1 and O2 and (iv) parietal lobe: P7 and P8 (Lievesley, Wozencroft, & Ewins , 2011). The brainwaves consist of not only real brain activities but also unwanted artefacts such as eye flicker, muscle movement, etc. which creates obstacles to accuracy in analyzing brainwaves. Hence, it is important to remove such artefacts through signal processing during earliest stage of analysis. Signal processing was carried out using EEGLAB v.2020. Firstly, to reduce linearity of EEG signals and remove artefacts generated from skin and sweat and facial muscles, raw EEG signals of frequency range 1-30Hz were passed through EEG finite-impulse response (FIR) filter. Then, Independent Component Analysis (ICA) filter was applied to separate artefacts and real brain activities from the EEG signals. After the completion of EEG preprocessing, power spectral density (PSD) was computed using Welch's periodogram to classify the brain waves using Python 3.4.7.

3.2.3. Cognitive tasks

Learning performance is indicated by the cognitive capacity of the student (Xiong, et al., 2018). Cognitive functions are brain-based skills that are associated with the mechanism of learning, remembering, reasoning and problem solving and are required to perform tasks of distinct levels of difficulty (Wang, et al., 2021). Therefore, four tests representing each category of cognition was selected, were conducted to measure the efficiency of different types of learning tasks in this study.

(1) Attention task: Stroop task was conducted to test attention. The subjects were instructed to press the first letter of the written color name as fast and correctly as they could. For example, if the word "red" was displayed in yellow color they had to press "R" not "Y".

(2) Perception: Mental rotation was conducted to test perception. Three stimuli, one on top and two on bottom was seen on screen. The subjects were required to mentally rotate the stimuli and select the one that matches the one on top as fast and precisely as possible.

(3) Working memory ability: Working memory was measured using N-back test. A sequence of stimuli was presented on screen one-by-one. For each stimulus, the subjects were instructed to press the space key if the current stimuli were as same as the one N trials ago.

(4) Thinking ability: Thinking ability was measured using mental arithmetic. A series of addition and subtraction problems was presented on screen one by one, and the subjects were asked to do the calculation mentally and select the correct answer. For the given tasks, response time (RT, in milliseconds) and accuracy (ACC, %) are to be used as the main indicators for measuring the learning performance (Wang D. , et al., 2018; Xiong, et al., 2018; Kim, Hong, Kim, & Yeom, 2020).

$$Learning\ performance = (Accuracy)x \frac{1}{(Response\ time)} \qquad \text{Eq(7)}$$

3.3. Experimental design

A comprehensive framework was created to study the effect of thermal environment and lighting on occupants' learning performance by evaluating how temperature and lighting level impact subjects' heart rate and skin temperature and mental workload, mental fatigue, mental stress, emotional state and alertness, then investigating how these factors affects subjects' learning performance. Learning performance was evaluated by four cognitive tasks- Stroop task, N-back task, Mental rotation, and Mental Arithmetic representing Attention ability, Perception, working memory and Thinking ability as cognitive functions. The cognitive tests were performed in online portal: www.psytoolkit.org and www. quizizz.com (Gijsbert , 2010; Gijsbert , 2017). The subjects' heart rate and skin temperature were measured using Empatica E4 Wristband and brain activities were measured using Emotiv Epoc x-14 channel wireless EEG headset while they performed the cognitive tasks.

3.3.1. Subjects

A total of 17 healthy subjects (10 male and 7 female) were recruited as participants for the experiments. All subjects were students (mean age: 27.41, age range: 20- 350.5, standard deviation: 2.65). Subjects with no history of disorder such as color blindness, neurological errors, allergy, and alcohol addiction were selected. The subjects were asked to get sufficient sleep for 7 hours and refrain from drinking alcohol, tobacco, caffeinated drinks, or other drinks that can cause excitement or drowsiness during the three-day experiment period. The subjects were asked to wash and dry their hair without hair care products before coming to the experiment. The clothing insulation of the subjects was standardized to 0.61 clo. (0.41 clo, 0.61 clo, 0.5 clo according to ASHRAE standard 55 (ASHRAE 55, 2021), 1.0 clo based on local climate), and the subjects were asked to wear the same clothes and shoes throughout the experiment. The metabolic rate assumed to be 1.1 met.

Table 3: Physical information of subjects

No.	Gender	Body mass (kg)	Height (cm)	Age (year)	Ethnicity
Subject #1	Male	68	178	28	Asian
Subject #2	Male	76	168	31	Asian
Subject #3	Male	78	168	31	Asian
Subject #4	Male	74	164	28	Asian
Subject #5	Female	43	155	27	Asian
Subject #6	Male	74	177	24	Asian
Subject #7	Male	80	180	31	Asian
Subject #8	Female	63	168	25	Asian
Subject #9	Female	109	168	23	White
Subject #10	Male	68	178	26	Asian
Subject #11	Male	62	171	26	Asian
Subject #12	Female	72	162	25	Black or African American
Subject #13	Male	65	177	29	Asian
Subject #14	Female	63	171	29	White
Subject #15	Female	82	155	29	Black or African American
Subject #16	Female	56	158	30	Asian
Subject #17	Male	159	204	24	White

3.3.2. Experimental environment

Experiments were conducted in a classroom at North Dakota State University, Fargo, ND over summer, from 9th June to 8th August, 2022. The classroom is 13m in length, 8.5 in width and 3m in height, as shown in Fig 3. The air conditioning and mechanical ventilation system for the room is a central air conditioning system that can control the temperature between 20°C to 30°C. Since a comfortable indoor temperature range from (22°C±1°C) in summer with air conditioning and under heating in winter in Fargo, ND, this study chose the temperature ranges of 20-23 °C, 23-26 °C and 26-29 °C. The relative humidity was maintained at about 22-24% under these three conditions. The noise level was maintained between 50-55 dB, and the windows were kept closed in an attempt to keep the CO_2 level consistent. The recommended average illumination requirement of people for classroom space is 300 lux (Loe, et al., 1999). The lighting level of a classroom with two single-sided windows at North Dakota State University ranges from 300- 900 lux with lights turned on, 60-90 lux with light turned off and 900-1100 lux in areas receiving direct combined natural and artificial light. Based on this, this study selected lighting level ranges of 100-300 lux, 300-600 lux, and 600-900 lux. Since the experiment was conducted in a real classroom, it was difficult to carry out the experiment under a relatively precise temperature and lighting level due to the effects of external force. Therefore, this study used temperature and lighting levels in ranges. During the experiments, the indoor temperature was controlled using a thermostat and the lighting level was controlled by the number of lights and switching seats. Experiments were conducted in nine different temperatures and lighting level conditions.

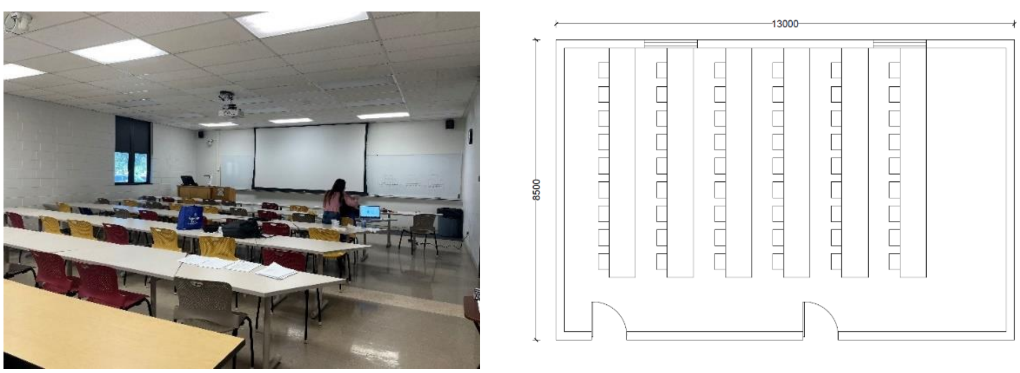

Figure 3: Classroom environment and classroom floor plan

3.3.3. Experimental scenario and procedures

A three-day experiment was designed maintain the classroom temperature under the range of 20-23°C, 23-26°C and 26-29°C and illumination level of 100-300 lux, 300-600 lux and 600-

900 lux. Every participant performed the cognitive tests under nine different environmental conditions.

Table 4: Environmental scenarios

	20-23°C	23-26°C	26-29°C
100-300 lux	20-23°C, 100-300 lux	23-26°C, 100-300 lux	26-29°C, 100-300 lux
300-600 lux	20-23°C, 300-600 lux	23-26°C, 300-600 lux	26-29°C, 300-600 lux
600-900 lux	20-23°C, 600-900 lux	23-26°C, 600-900 lux	26-29°C, 600-900 lux

Before the formal experiment, the participants were explained about the experimental arrangements, subjective questionnaires, the contents of the cognitive tests and practiced the four tests. Additionally. They were informed of role of the wristband and EEG headset for the measurement of physiological-heart rate and skin temperature and their brain activities. After the experiment brief, wristband and EEG headset was put on the subject.

The classroom was arranged within a specific temperature range, and each subject participated in only one temperature condition each day. The experiment scenario was divided into three phases of lighting under each temperature conditions. Each experiment lasted about 70-80 minutes and the participants could not move about the classroom or leave the classroom until all tests were completed. The experiment procedure is shown in Figure 4. Firstly, the participants entered the classroom and were instructed to sit under the lighting condition of 100-300 lux to acclimate with the thermal as well as lighting condition for the first phase of the experiment. After 10 min, they performed the four cognitive tests an filled out a survey regarding their thermal and lighting perception (Zhang G. , Yang, Zheng, & Zhang, 2007). After the completion of first phase, the participants were instructed to sit under the lighting conditions of 300-600 lux to acclimate with the lighting conditions of the second phase. The performed the four cognitive tests after 10 min of acclimation period and filled out survey regarding their thermal and lighting perception.

The experiment was lastly performed in the lighting conditions of 600-900 lux and filled out the thermal and lighting perception survey. The wristband and EEG headset recorded the heart rate and skin temperature and the brain activity throughout the experiment.

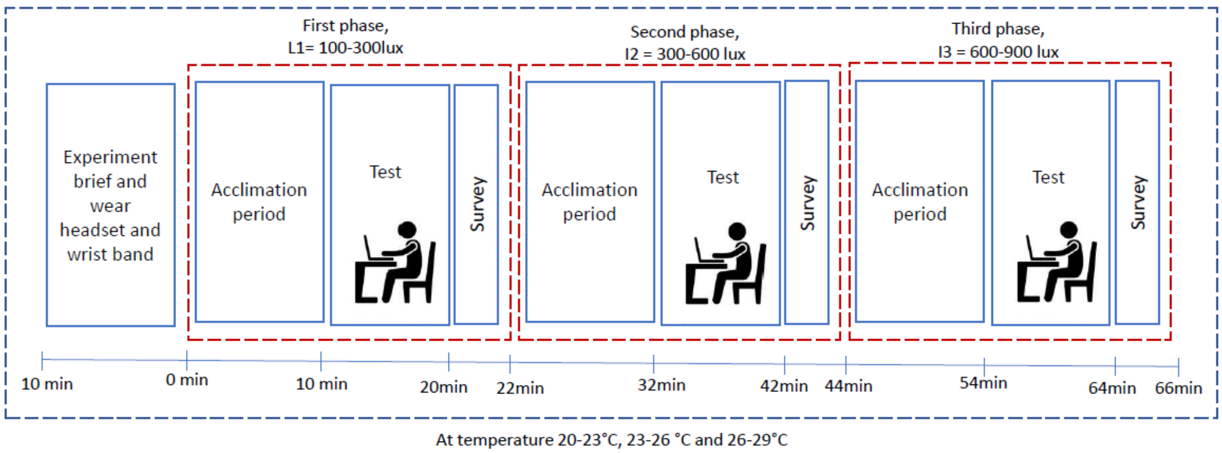

Figure 4: Experiment procedure

3.3.4. Analysis method

The statistical analysis was conducted using SPSS 28. The Kolmogorov-Smirnov test was first used to check if the data were normally distributed. The non-normal data were computed with fractional rank transformation. This study employed a factorial analysis of variance (ANOVA) to examine the effects of the temperature/lighting level on learning performance (analysis 1). A factorial ANOVA can be used to explore the influence of two or more independent variables on a dependent variable. This study used temperature/lighting levels with nine different conditions to predict changes in attention ability, perception ability, working memory ability, and thinking ability, separately. In this study, to analyze correlation and the strength of correlation between temperature/lighting level, sensation and comfort, and physiological responses, this study used Spearman's rank correlation coefficient which is a non-parametric test (analysis 2, 3 and 4). Spearman's rank correlation was used to measure the degree of association between two variables. In addition, this study employed multiple regression analysis to examine the effect of sensation/comfort and physiological responses on learning performance under nine different temperatures and lighting levels (analysis 5 and 6). Multiple regression was used to identify the sensation/comfort and physiological responses whose values are known to predict the value of the learning performance. This study used the beta coefficient, which is the standardized coefficient of each independent variable. Before analysis, the variance inflation factor (VIF) was carried out to check the multicollinearity between the variables of the regression model. Multicollinearity is considered to be acceptable if VIF is between 1 and 10. Durbin-Watson statistical measures were also employed to test for autocorrelation in a regression model's output. A value of Durbin-Watson close to 2 is considered appropriate, whereas a value closer to 0 or 4 is considered inappropriate. In this study, the significance levels for all the tests were set to 0.01 and 0.05, therefore, a value less than 0.01 ($p < 0.01$) and 0.05 ($p < 0.05$) means the results were statistically significant.

4. RESULTS

4.1. Effects of temperature and lighting level on learning performance

This study investigated the effect of temperature and lighting level on the learning performance. As shown in Table 5, the students showed the highest attention ability (114.77) under the classroom condition of 26-29°C 600-900 lux, the highest perception ability (60.93) under the classroom condition of 20-23°C 600-900 lux, the highest memory ability (159.48) under the classroom condition of 23-26°C 100-300lux and 23-26°C 300-600 lux, and the highest thinking ability (26.34) under the classroom condition of 23-26°C 600-900 lux and 23-26°C 600-900 lux.

Table 5: Learning performance under different temperature and lighting level

Temperature	Lighting level	Attention ability		Perception ability		Working Memory ability		Thinking ability	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
20-23°C	100-300 lux	104.68	-29.34	54.56	-17.95	158.42	-34.94	24.66	-8.39
	300-600 lux	110.03	-27.05	56.39	-18.87	148.29	-36.59	25.14	-8.39
	600-900 lux	110.46	-27.93	60.93	-19.15	149.59	-37.75	25.38	-9.34
23-26°C	100-300 lux	109.61	-29.23	53.05	-16.04	159.48	-36.9	25.17	8.03
	300-600 lux	112.85	-30.71	55.77	-17.07	159.48	-36.9	25.87	9.67
	600-900 lux	114.15	-30.4	60.24	-17.59	155.50	-34.29	26.34	10.06
26-29°C	100-300 lux	109.80	-28.46	53.22	-16.86	151.58	-36.63	25.45	8.39
	300-600 lux	112.64	-28.58	56.85	-18.47	157.04	-34.8	25.80	8.76
	600-900 lux	114.77	-29.94	58.46	-19.88	156.65	-36.87	25.78	9.79

Fig. 5. shows the results of learning performance trends under different temperature and lighting conditions. Attention ability and perception ability increased as the light level increased and the environment was brighter (20-23°C: 104.68, 110.03, 110.46, 23-26°C: 109.61, 112.85, 114.15, 26-29°C: 109.80, 112.64, 114,77 for attention) (20-23°C: 54.56, 56.39, 60.93, 23-26°C: 53.05, 55.77, 60.24, 26-29°C: 53.22, 56.85, 58.46 for perception). For working memory ability, under lower light condition, maximum learning performance was observed for lower and neutral thermal conditions while under higher thermal condition, maximum learning performance was

observed in neutral light level (20-23°C: 158.42, 23-26°C: 159.48, 26-29°C: 157.04). For thinking ability, increase in learning performance was observed as the light level increased and the environment shifted to brighter under lower and neutral thermal conditions (20-23°C: 24.66, 25.14, 25.38, 23-26°C: 25.17, 25.87, 26.34).

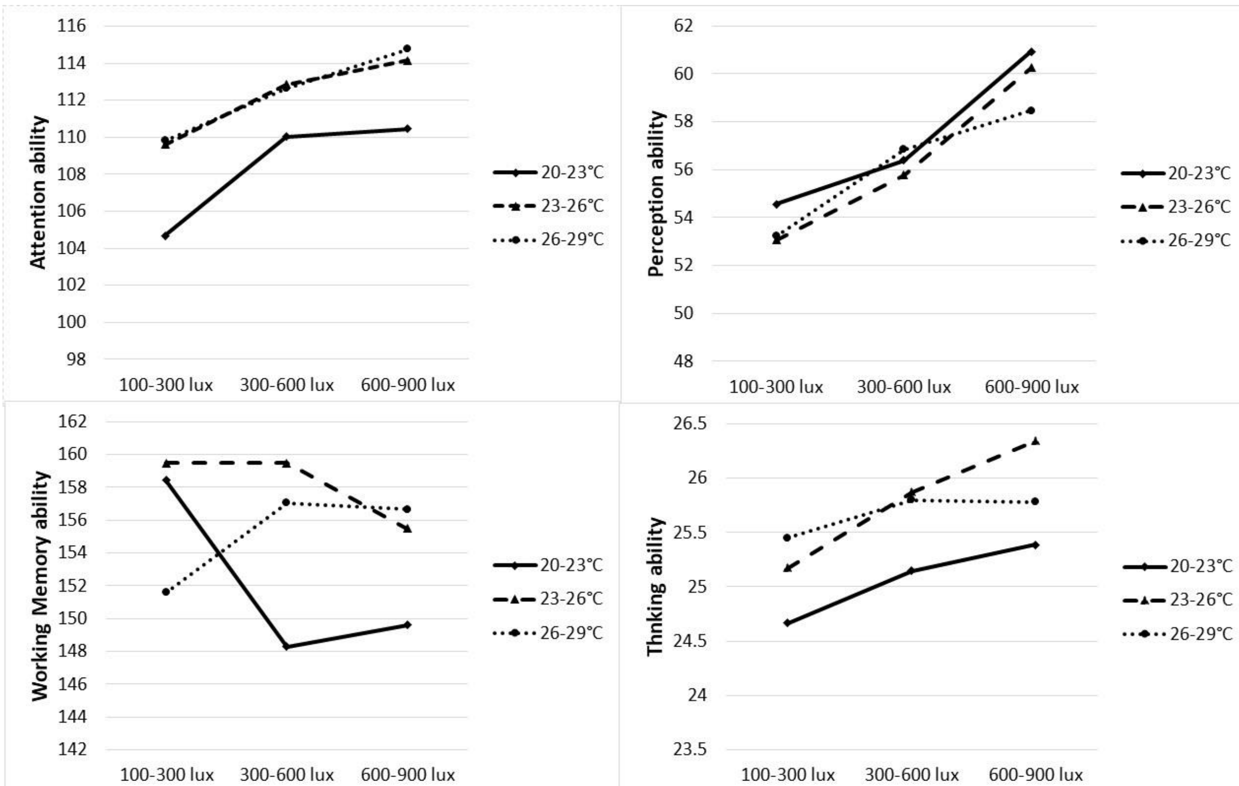

Figure 5: Learning performance trends under different temperature and lighting level

A factorial ANOVA was performed to investigate the effects of temperatures/lighting levels on the learning performance of students. The main effect occurs when the mean difference between nine different conditions of temperature/lighting levels is statistically significant. The type III sum of the square indicates that analysis does not depend on the order of the design if the design is unbalanced and does not assume the interaction is zero. Meanwhile, df is the degrees of freedom indicating the number of independent values that can vary in analysis without breaking any constraints, it is equal to the number of levels (k) for a factor minus 1. Temperature and light level both had three group each (k), which summed up the df as 4 with interaction of temperature and lighting. Mean square is the mean with df as the number things that are summed, which is calculated as type III sum of the square divided by df. F statistics indicates if the means between two groups are significantly different while the p-value measures the probability of obtaining the observed results. Higher F-value for attention ability and working memory indicates that variability of group means is large relative to within group variability. An interaction is found when the influence of one condition of temperature and lighting level on the learning performance change across the level of another condition of temperature and lighting level. As shown in Table 6, the result indicated that the interaction of temperature and lighting level influenced ‘attention ability’ and ‘working memory ability’ at a 95% of significant level ($p = 0.043$, $p = 0.020$), exhibiting a statistically significant difference in learning performance due to the interaction of temperature and lighting level.

Table 6: Interaction effect between the temperature and lighting level and learning performance

Learning performance		Type III Sum of Squares	df	Mean Square	F	*p*-value
Attention ability		3877.813	4	969.453	2.460	0.043*
Perception ability		859.100	4	214.775	0.658	0.621
Working Memory ability		14195.059	4	3548.765	2.920	0.020*
Thinking ability		16.160	4	4.040	0.056	0.994

Note: * Correlation is significant at the 0.05 level (2-tailed)

To access the significance of difference between pair of group means, the Tukey’s HSD post-hoc analysis was also performed. As shown in Table 7 and 8, the result showed significant differences in temperature 20-23°C and 26-29°C, and lighting level 100-300 lux and 300-600 lux, 100-300 lux and 600-900 lux for attention ability. Similarly, for the working memory ability, temperatures 20-23°C and 23-26°C had statistically significant differences. In contrast, temperature groups did not have any significant effect for perception ability and thinking ability while lighting level group 100-300 lux and 600-900 lux, 300-600 lux and 600-900 lux had significant effect for perception ability.

Table 7: Tukey's HSD post hoc test for different temperature group

Learning performance	Temperature group		Mean Difference (I-J)	Std. Error	*p*-value
Attention ability	20-23°C	23-26°C	-1.3438	0.64994	0.097
		26-29°C	-1.7921*	0.65155	0.016
	23-26°C	20-23°C	1.3438	0.64994	0.097
		26-29°C	-0.4483	0.66401	0.778
	26-29°C	20-23°C	1.7921*	0.65155	0.016
		23-26°C	0.4483	0.66401	0.778
Perception ability	20-23°C	23-26°C	0.2359	1.22703	0.980
		26-29°C	1.2603	1.23505	0.564
	23-26°C	20-23°C	-0.2359	1.22703	0.980
		26-29°C	1.0244	1.23716	0.686
	26-29°C	20-23°C	-1.2603	1.23505	0.564
		23-26°C	-1.0244	1.23716	0.686
Working memory ability	20-23°C	23-26°C	-5.6237*	2.33343	0.042
		26-29°C	-1.9667	2.33217	0.676
	23-26°C	20-23°C	5.6237*	2.33343	0.042
		26-29°C	3.6571	2.31511	0.255
	26-29°C	20-23°C	1.9667	2.33217	0.676
		23-26°C	-3.6571	2.31511	0.255
Thinking ability	20-23°C	23-26°C	-0.7114	0.66471	0.533
		26-29°C	-0.9540	0.65298	0.310
	23-26°C	20-23°C	0.7114	0.66471	0.533
		26-29°C	-0.2426	0.65609	0.927
	26-29°C	20-23°C	0.9540	0.65298	0.310
		23-26°C	0.2426	0.65609	0.927

Table 8: Tukey's HSD post hoc test for different lighting level group

Learning performance	Lighting level group		Mean Difference (I-J)	Std. Error	*p*-value
Attention ability	100-300 lux	300-600 lux	-2.1043*	0.65146	0.004
		600-900 lux	-2.7661*	0.65042	0.000
	300-600 lux	100-300 lux	2.1043*	0.65146	0.004
		600-900 lux	-0.6617	0.66345	0.579
	600-900 lux	100-300 lux	2.7661*	0.65042	0.000
		300-600 lux	0.6617	0.66345	0.579
Perception ability	100-300 lux	300-600 lux	-2.5426	1.27012	0.112
		600-900 lux	-6.0448*	1.24092	0.000
	300-600 lux	100-300 lux	2.5426	1.27012	0.112
		600-900 lux	-3.5022*	1.20188	0.010
	600-900 lux	100-300 lux	6.0448*	1.24092	0.000
		300-600 lux	3.5022*	1.20188	0.010
Working memory ability	100-300 lux	300-600 lux	1.8367	2.35611	0.716
		600-900 lux	3.0322	2.32521	0.393
	300-600 lux	100-300 lux	-1.8367	2.35611	0.716
		600-900 lux	1.1955	2.30331	0.862
	600-900 lux	100-300 lux	-3.0322	2.32521	0.393
		300-600 lux	-1.1955	2.30331	0.862
Thinking ability	100-300 lux	300-600 lux	-0.2122	0.65814	0.944
		600-900 lux	-0.4734	0.65764	0.752
	300-600 lux	100-300 lux	0.2122	0.65814	0.944
		600-900 lux	-0.2612	0.65715	0.917
	600-900 lux	100-300 lux	0.4734	0.65764	0.752
		300-600 lux	0.2612	0.65715	0.917

4.2. Temperature and light level and thermal and light sensation and comfort

This study analyzed the relationship between temperature/lighting level and sensation/comfort. Fig. 6. Illustrated thermal sensation and thermal comfort of students according to the different temperature and lighting level conditions. Thermal sensation at 20-23°C centered on slightly cool (100-300 lux, 41%; 300-600 lux, 47% and 600-900 lux, 29%), at 23-26°C centered on neutral (100-300 lux, 41%; 300-600 lux, 53% and 600-900, 53%) and slightly warm (100-300 lux, 53%; 300-600 lux, 12% and 600-900, 18%) and at 26-29°C centered on slightly warm (100-300 lux, 41%; 300-600 lux, 59% and 600-900, 47%) and neutral (100-300 lux, 29%; 300-600 lux, 35% and 600-900, 35%). At 20-23°C, thermal sensation shifted from neutral at 100-300 lux lighting, to slightly cool, cool and cold at 300-600 and 600-900 lux. At 23-26°C, thermal sensation shifted from slightly warm at 100-300 lux to neutral at 300-600 and 600-900 lux. At 26-29°C thermal sensation centered on slightly warm.

In addition, at 20-23°C, thermal comfort centered on satisfied (100-300 lux, 29%; 300-600 lux, 29% and 600-900, 29%), on neutral (100-300 lux, 24%; 300-600 lux, 18% and 600-900, 24%), and slightly dissatisfied (100-300 lux, 12%; 300-600 lux, 35% and 600-900, 29%). The thermal comfort centered on satisfied (100-300 lux, 41%:300-600 lux, 47% and 600-900, 47%) at 23-26°C. At 26-29°C, thermal comfort centered on satisfied (100-300 lux, 24%; 300-600 lux,29% and 600-900, 24%), on neutral (100-300 lux, 24%; 300-600 lux, 24% and 600-900, 24%), and slightly dissatisfied (100-300 lux, 18%; 300-600 lux, 18% and 600-900, 24%). At 20-23°C, thermal comfort shifted from satisfied at 100-300 lux lighting, to slightly dissatisfied at 300-600 and 600-900 lux. At 23-26°C, thermal comfort centered on satisfied while at 26-29°C thermal comfort was almost equally distributed among all lighting conditions.

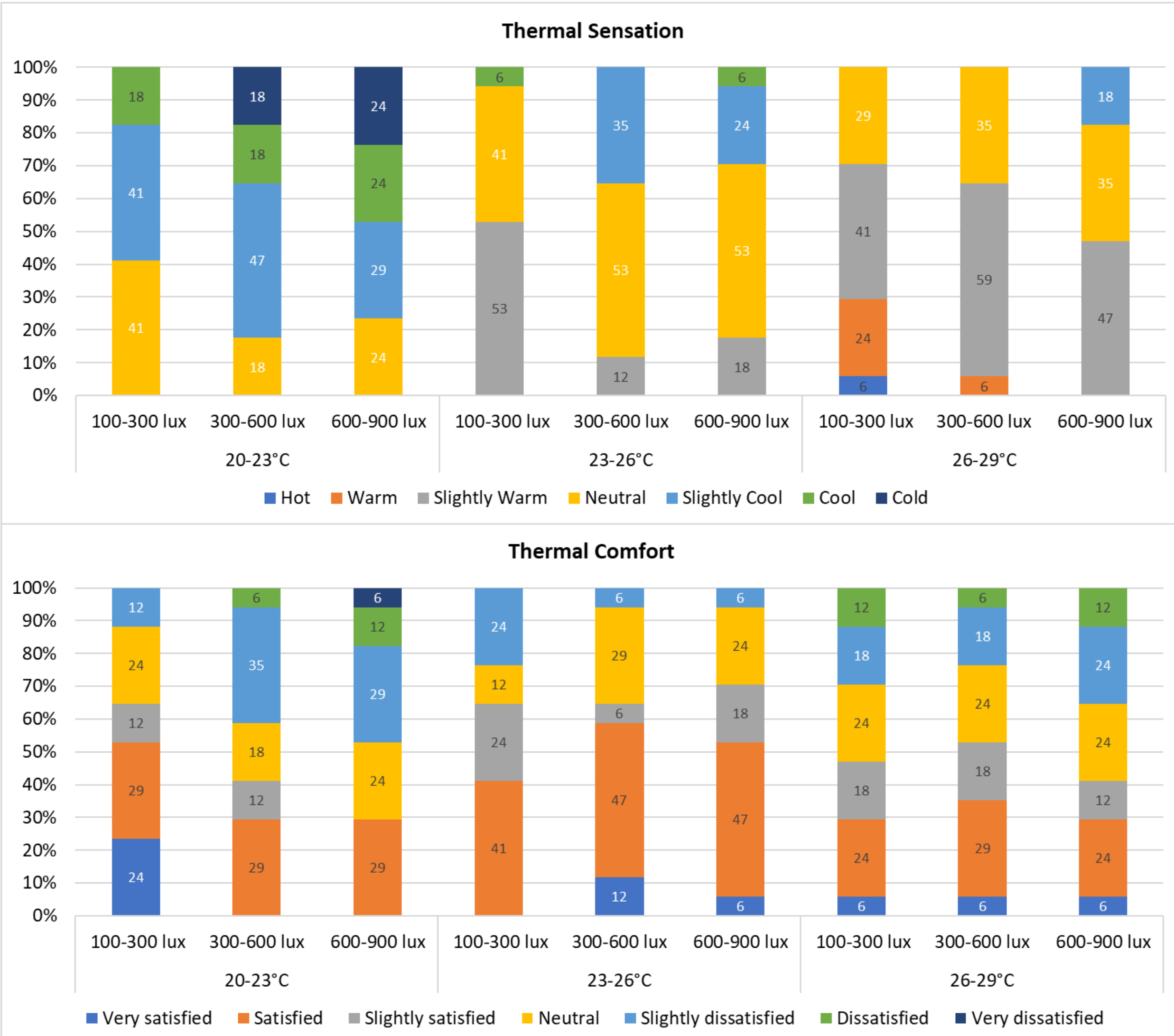

Figure 6: Thermal sensation and thermal comfort under different temperature and lighting level conditions

Fig. 7 shows that lighting sensation at 20-23°C centered on about right (100-300 lux, 47%; 300-600 lux, 59% and 600-900 lux, 29%), at 23-26°C centered on bright (100-300 lux, 12%; 300-600 lux, 35% and 600-900, 59%)and about right (100-300 lux, 41%; 300-600 lux, 29% and 600-900, 12%) and at 26-29°C centered on bright (300-600 lux, 18%; 600-900 lux 47%), about right (100-300 lux, 41%; 300-600 lux, 41% and 600-900, 35%) and slightly dim (100-300 lux, 47%; 300-600 lux, 18%).

In addition, at 20-23°C, lighting comfort centered on satisfied (100-300 lux, 29%; 300-600 lux, 29% and 600-900, 29%), on neutral (100-300 lux, 24%; 300-600 lux, 18% and 600-900, 24%), and slightly dissatisfied (100-300 lux, 12%; 300-600 lux, 35% and 600-900, 29%). The lighting comfort centered on satisfied (100-300 lux, 41%: 300-600 lux, 47% and 600-900, 47%) at 23-26°C. At 26-29°C, thermal comfort centered on satisfied (100-300 lux, 24%; 300-600 lux, 29% and 600-900, 24%), on neutral (100-300 lux, 24%; 300-600 lux, 24% and 600-900, 24%), and slightly dissatisfied (100-300 lux, 18%; 300-600 lux, 18% and 600-900, 24%). At 20-23°C, brighter lighting conditions 600-900 lux had most lighting comfort votes for satisfied while at 26-29°C, neutral lighting condition 300-600 lux had most lighting comfort votes for satisfied.

This study also analyzed the correlation between temperature, lighting level, thermal sensation, thermal comfort, lighting perception, and lighting comfort using Spearman's rank correlation coefficient. As shown in table 9-10, temperature had significant positive correlation with thermal sensation, thermal comfort, and lighting perception suggesting increase in these variables with increase in temperature. Similarly, lighting level had significant positive correlation with thermal comfort and significant negative correlation with light comfort, indicating increase in thermal comfort as light level increases or the environment is brighter while decrease in light comfort.

Table 9: Correlation between temperature and lighting level and sensation and comfort

	Temperature	Lighting	Thermal sensation	Thermal Comfort	Lighting sensation	Lighting Comfort
Temperature	1.000	-	-	-	-	-
Lighting level	0.397**	1.000	-	-	-	-
Thermal sensation	0.577**	0.022	1.000	-	-	-
Thermal Comfort	0.168**	0.109**	0.093**	1.000	0.315**	-
Lighting perception	0.037*	-0.027	-0.080**	0.315**	1.000	-0.012
Lighting Comfort	-0.023	-0.107**	-0.007	0.111**	-0.012	1.000

Note: * Correlation is significant at the 0.05 level (2-tailed), ** Correlation is significant at the 0.01 level (2-tailed).

Table 10: Degree of correlation between temperature and lighting level and sensation and comfort

	Temperature	Lighting
Thermal sensation	Moderate correlation	No correlation
Thermal Comfort	Negligible correlation	Negligible correlation
Lighting perception	Negligible correlation	No correlation
Lighting Comfort	No correlation	Negligible correlation

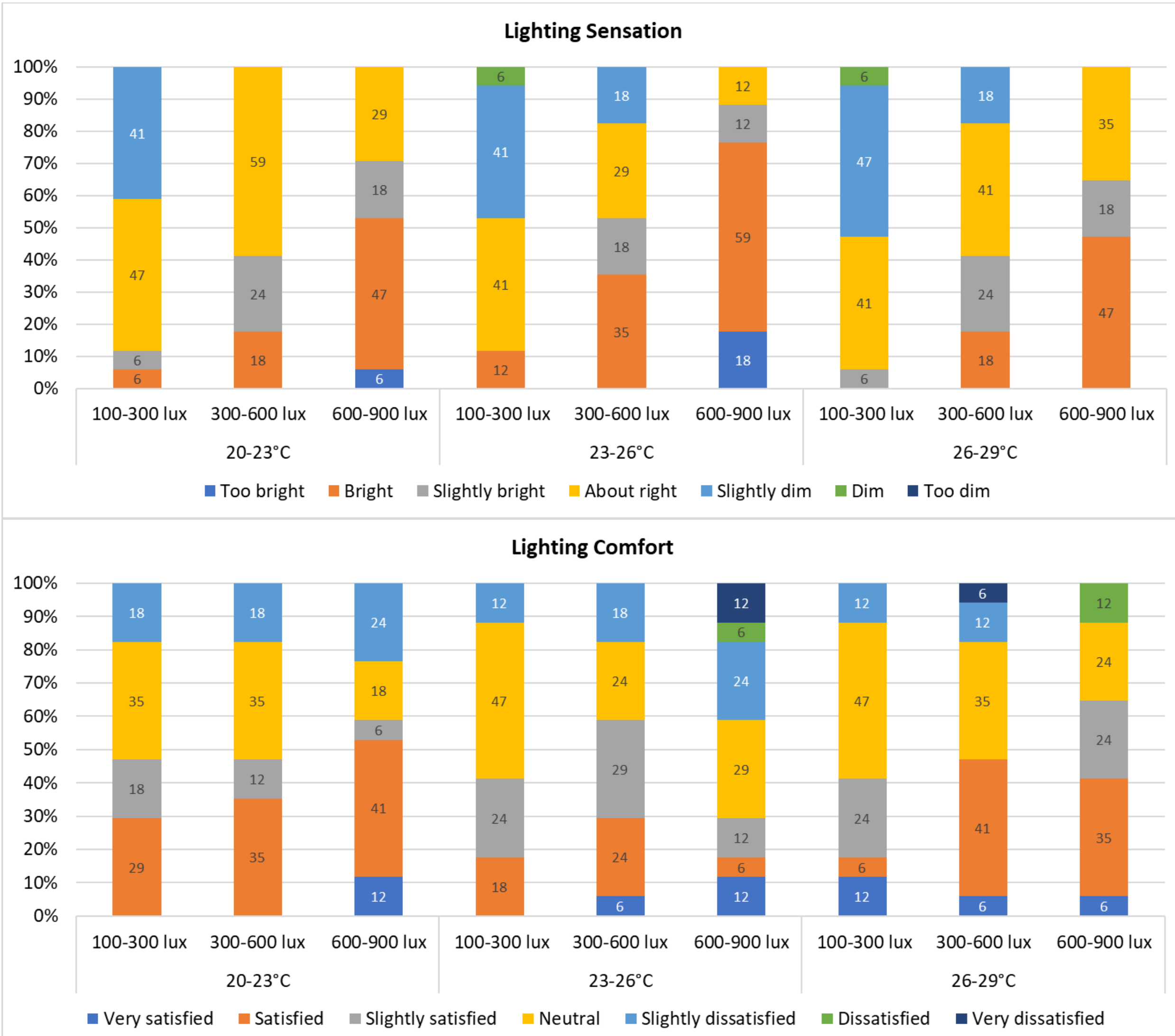

Figure 7: Lighting sensation and lighting comfort under different temperature and lighting level

4.3. Effect of sensation and comfort for the temperature and level on learning performance

The interaction of temperature and lighting had statistically significant difference for attention ability and working memory, while no significant difference was observed for perception and thinking ability. Hence, to analyze the effect of sensation, perception and comfort of temperature and lighting on learning performance, regression analysis was carried out for attention ability and working memory. Multicollinearity was tested with VIF and the results showed VIF for thermal sensation and comfort and light perception and comfort ranged from 1 to 4, suggesting that multicollinearity does not exist. Durbin-Watson test was performed, and the results confirmed that no autocorrelation exists.

Table 11-12 indicates the regression results for attention ability and working memory ability. For attention ability, under 20-23°C thermal condition, thermal sensation and lighting comfort had negative significant effect while thermal comfort and light perception had positive significant effect on learning performance for light level 100-300 lux, suggesting increased in learning performance in a comfortable thermal condition and bright light perception. Under light level 300-600 lux, light comfort had positive significant effect while thermal sensation, thermal comfort and light perception did not have any significant influence on learning performance, indicating a comfortable lighting condition contributing to higher learning performance. Thermal sensation and light perception had negative significant effect while thermal and light comfort had positive significant effect on learning performance under 600-900 lux, indicating comfortable environment improving the learning performance. For working memory, thermal sensation had positive significant effect on learning performance under 100-300 lux, suggesting higher learning performance in this thermal environment. The results showed no significant influence of sensation and comfort of temperature and light under 300-600 lux and 600-900 lux.

Under 23-26°C, for attention ability, thermal sensation and light comfort had positive significant effect and light perception negative significant effect on learning performance under 100-300 lux, suggesting higher learning performance in this thermal environment with comfortable lighting level. Thermal sensation and light comfort had negative significant effect on learning performance under 300-600 lux while all sensation and comfort variable of temperature and light had negative significant effect under 600-900 lux light condition, suggesting increase in learning performance as the sensation and comfort to this environment decreased. For working memory, thermal sensation and comfort, light perception had positive significant effect under 100-300 lux, indicating increase in these variables increasing learning performance and light comfort had significant positive effect on learning performance under 300-600 lux. No significant effect was observed under 600-900 lux.

Under 26-29°C thermal condition, for attention ability thermal and light comfort had negative significant effect on learning performance under 100-300 lux light condition, indicating decrease in learning performance as thermal and lighting comfort to the environment increased and light perception and comfort had negative significant effect under 300-600 lux. Under 600-900 lux lighting condition, light comfort had significant positive effect on learning performance, suggesting higher learning performance in comfortable light environment. For working memory, under 100-300 lux light comfort had positive significant effect on learning performance, thermal comfort had positive significant effect under 300-600 lux and thermal sensation had negative significant effect under 600-900 lux, suggesting learning performance changed as the sensation and perception of comfort to a given environment changed.

Table 11: Effect sensation and comfort on Learning performance for attention ability under nine indoor environments

	20-23°C			23-26 °C			26-29 °C		
	100-300 lux	300-600 lux	600-900 lux	100-300 lux	300-600 lux	600-900 lux	100-300 lux	300-600 lux	600-900 lux
Thermal sensation	-0.385** (2.094)	0.024 (2.238)	-0.133* (1.824)	0.174** (2.421)	-0.123* (3.334)	-0.091* (2.255)	-0.078 (2.342)	0.005 (3.504)	0.082 (2.138)
Thermal comfort	0.268** (1.058)	-0.067 (1.644)	0.178** (1.255)	-0.059 (1.173)	-0.036 (1.696)	-0.150** (1.564)	-0.221** (1.418)	-0.039 (1.721)	-0.102 (1.156)
Light perception	0.112* (2.083)	0.010 (1.701)	-0.158** (1.394)	-0.127** (1.342)	0.012 (1.534)	-0.210** (2.036)	0.058 (2.602)	-0.145** (1.588)	-0.085 (1.659)
Light comfort	-0.257** (1.500)	0.353** (1.189)	0.147** (0.849)	0.231** (1.521)	-0.337** (1.495)	-0.126** (0.870)	-0.201** (1.437)	-0.144** (1.391)	0.090* (1.123)
R^2 (Adj R^2)	0.172 (0.167)	0.111 (0.106)	0.052 (0.046)	0.068 (0.062)	0.109 (0.103)	0.089 (0.083)	0.079 (0.074)	0.049 (0.043)	0.033 (0.026)
F	34.806	20.079	8.820	11.766	17.548	14.537	13.594	7.704	4.987
Durbin-Watson	1.275	1.267	1.360	1.0974	0.976	1.327	1.372	1.134	1.542

Note: Standard errors are in parenthesis; ** $p < 0.01$, * $p < 0.05$

Table 12: Effect sensation and comfort on Learning performance for working memory ability under nine indoor environments

	20-23°C			23-26 °C			26-29 °C		
	100-300 lux	300-600 lux	600-900 lux	100-300 lux	300-600 lux	600-900 lux	100-300 lux	300-600 lux	600-900 lux
Thermal sensation	0.261* (4.641)	0.069 (4.827)	0.236 (4.681)	0.271* (5.629)	0.044 (6.125)	-0.053 (3.720)	-0.173 (4.407)	-0.006 (5.867)	-0.250* (4.865)
Thermal comfort	-0.107 (3.078)	-0.024 (3.780)	-0.208 (2.834)	0.264** (3.253)	-0.097 (3.040)	-0.039 (3.197)	-0.121 (2.925)	0.252* (2.971)	-0.055 (2.399)
Light perception	-0.207 (4.533)	0.091 (4.502)	0.183 (3.659)	0.266** (3.421)	-0.059 (2.422)	0.031 (2.794)	-0.146 (4.986)	0.089 (3.142)	0.178 (3.934)
Light comfort	0.150 (4.186)	0.102 (3.176)	-0.128 (2.132)	0.044 (3.948)	0.433** (2.865)	0.154 (1.478)	0.200* (3.297)	-0.078 (2.637)	-0.162 (2.174)
R^2 (Adj R^2)	0.068 (0.040)	0.026 (-0.001)	0.053 (0.027)	0.171 (0.147)	0.171 (0.147)	0.024 (0.000)	0.060 (0.034)	0.040 0.015)	0.074 (0.049)
F	2.423	0.954	2.060	7.131	7.131	0.100	2.278	1.566	2.950
Durbin-Watson	1.113	0.850	0.855	0.876	0.876	0.808	0.827	0.995	0.904

Note: Standard errors are in parenthesis; ** $p < 0.01$, * $p < 0.05$

4.4. Effect of temperature and lighting level on physiological responses

This study analyzed the relationship between temperature/lighting level and physiological responses. Fig 8 shows the physiological responses under nine different temperature and lighting level conditions. Table 13 shows the mean and standard deviation of physiological responses under different indoor environment. Comparative higher heart rate was observed in lower light level (20-23°C: 79.022, 23-26°C: 82.018 and 26-29°C: 79.575). Skin temperature was relatively higher under lower and neutral light level under lower and higher temperatures while the difference in neutral conditions was minimal (20-23°C: 32.861, 32.556 and 26-29°C: 33.733, 33.903). Under lower and higher temperature conditions, mental workload increased as the room was brighter (20-23°C: 0.426, 0.548, 0.822 and 26-29°C: 0.508, 0.576, 0.749). Conversely, the difference in mental stress was minimal under higher temperature conditions while it was observed maximum under lower light conditions (20-23°C: 2.319 and 23-26°C: 2.447). As the room shifted from less brighter conditions to brighter, alertness while performing the cognitive tasks increased (20-23°C: 0.365, 0.512, 0.847, 23-26°C: 0.428, 0.554, 0.603, 26-28°C: 0.512, 0.531, 0.874). Mental fatigue was observed minimal under lower lighting conditions (20-23°C: 1.238, 23-26°C: 1.253, 26-29°C: 1.232). Negative valence indicates higher negative emotions, neutral lighting under lower temperature and higher lighting under higher temperature higher negative emotion was observed (20-23°C: -0.029, 26-29°C: -0.023). Lower temperature contributed for higher wakefulness under lower light condition, while brighter light contributed for higher wakefulness under neutral temperature (20-23°C: 0.987, 23-26°C: 0.991).

This study also investigated the correlation and degree of correlation of temperature and lighting level on physiological responses by conducting the Spearman's correlation coefficient. As shown in Table 14-15, skin temperature had weak positive correlation with temperature, suggesting increase in skin temperature with rise in temperature. Mental workload, mental stress, mental fatigue and valence had negligible negative correlation with temperature, suggesting decrease in these variables with rise in temperature. Meanwhile, alertness and arousal had negligible positive correlation, indicating increase in these variables as temperature increases. Heart rate had negligible negative correlation with lighting, suggesting higher heart rate in lower lighting conditions. While mental workload, alertness and mental fatigue had negligible positive correlation with lighting, suggesting higher mental workload, alertness, and mental fatigue as brightness increases, mental stress and arousal had negligible negative correlation suggesting higher mental stress and arousal level at lower lighting condition.

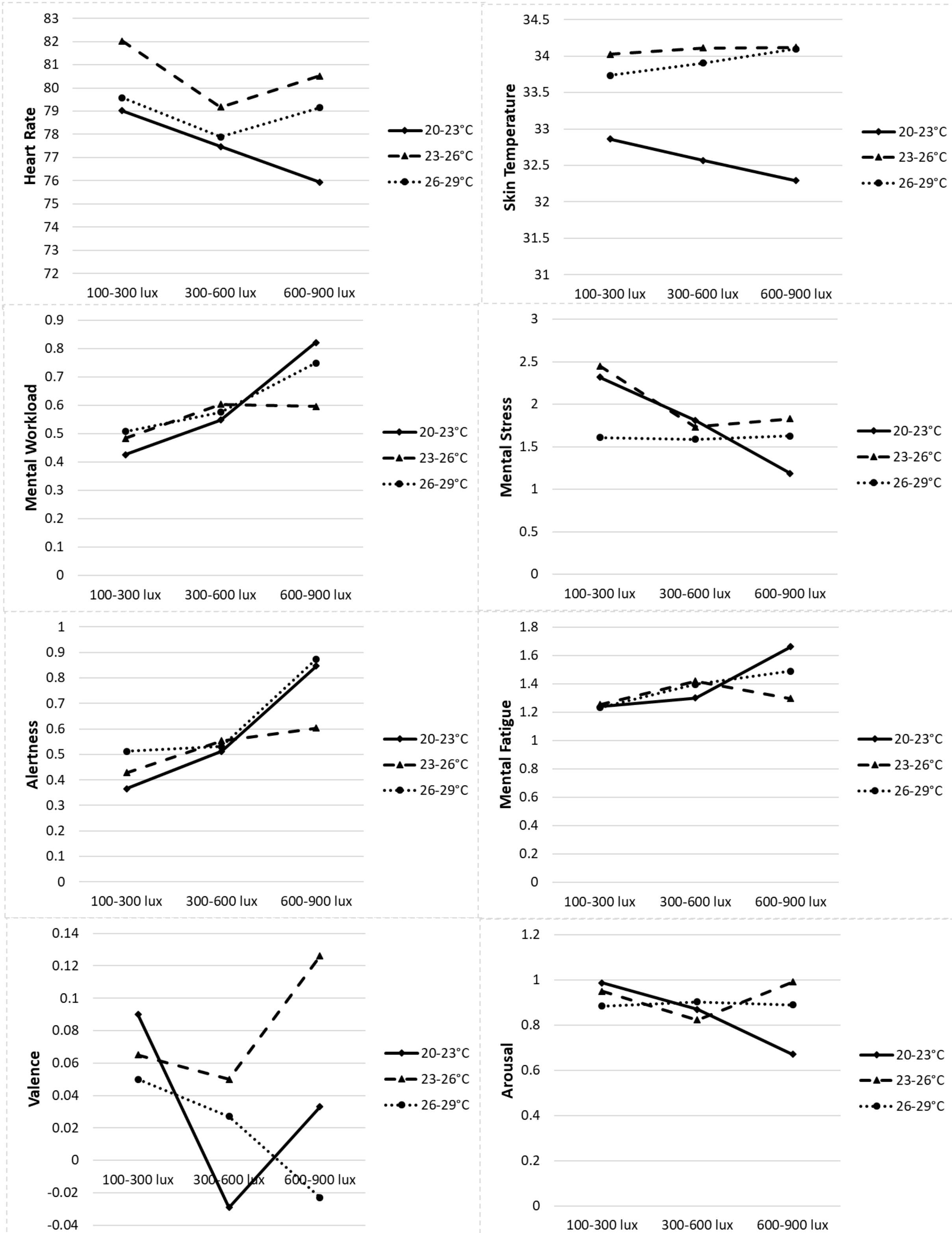

Figure 8: Physiological responses under different temperature and lighting level conditions

Table 13: Physiological responses under different temperature and lighting level

Temp.	Lighting level	Heart rate		Skin temperature		Mental workload		Mental stress		Alertness		Mental fatigue		Valence		Arousal	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
20-23°C	100-300 lux	79.022	10.78	32.861	1.82	0.426	0.26	2.319	1.69	0.365	0.29	1.238	0.53	0.09	0.29	0.987	0.58
	300-600 lux	77.477	11.34	32.566	1.91	0.548	0.25	1.812	1.14	0.512	0.28	1.3	0.41	-0.029	0.16	0.87	0.35
	600-900 lux	75.931	10.26	32.292	1.89	0.822	0.28	1.186	0.78	0.847	0.38	1.662	0.55	0.033	0.18	0.670	0.32
23-26°C	100-300 lux	82.018	10.11	34.023	1.55	0.483	0.27	2.447	2.18	0.428	0.29	1.253	0.47	0.065	0.26	0.950	0.45
	300-600 lux	79.172	8.72	34.110	1.55	0.603	0.33	1.734	1.55	0.554	0.35	1.420	0.53	0.050	0.20	0.823	0.46
	600-900 lux	80.514	9.69	34.120	1.57	0.596	0.40	1.829	2.13	0.603	0.52	1.296	0.62	0.126	0.43	0.991	0.53
26-29°C	100-300 lux	79.575	10.31	33.733	2.06	0.508	0.26	1.608	1.16	0.512	0.34	1.232	0.48	0.050	0.24	0.884	0.35
	300-600 lux	77.885	10.66	33.903	1.84	0.576	0.32	1.587	1.16	0.531	0.32	1.395	0.86	0.027	0.32	0.903	0.55
	600-900 lux	79.151	12.63	34.099	5.89	0.749	0.45	1.626	2.17	0.874	0.64	1.490	0.73	-0.023	0.20	0.890	0.58

Table 14: Correlation between temperature/lighting level and physiological responses

	Temp.	Lighting level	Heart rate	Skin temp.	Mental workload	Mental stress	Alertness	Mental fatigue	Valence	Arousal
Temperature	1.000	-	-	-	-	-	-	-	-	-
Lighting level	0.062**	1.000	-	-	-	-	-	-	-	-
Heart rate	-0.002	-0.107**	1.000	-	-	-	-	-	-	-
Skin temperature	0.360**	-0.015	0.317**	1.000	-	-	-	-	-	-
Mental workload	-0.030**	0.224**	0.004	0.059**	1.000	-	-	-	-	-
Mental stress	-0.077**	-0.193**	0.029**	0.117**	-0.512**	1.000	-	-	-	-
Alertness	0.022*	0.259**	0.014	-0.010	0.904**	-0.713**	1.000	-	-	-
Mental fatigue	-0.093**	0.117**	-0.007	0.135**	0.799**	-0.046**	0.516**	1.000	-	-
Valence	-0.091**	-0.013	0.040**	-0.046**	-0.005	-0.056**	0.001	-0.001	1.000	-
Arousal	0.045**	-0.088**	-0.016	-0.154**	-0.793**	0.061**	-0.538**	-0.930**	0.037**	1.000

Note: * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

Table 15: Degree of correlation between temperature/lighting level and physiological response

	Temperature	Lighting level
Heart rate	No correlation	Negligible correlation
Skin temperature	Weak correlation	No correlation
Mental workload	Negligible correlation	Negligible correlation
Mental stress	Negligible correlation	Negligible correlation
Alertness	Negligible correlation	Negligible correlation
Mental fatigue	Negligible correlation	Negligible correlation
Valence	Negligible correlation	No correlation
Arousal	Negligible correlation	Negligible correlation

4.5. Effect of sensation, comfort of temperature and lighting on physiological response

As the change in temperature and lighting was observed, it also changed the environmental sensation as well as the perception of comfort of the environments. Therefore, to check the change in sensation and comfort for the temperature and lighting conditions and changes in physiological responses, Spearman's correlation coefficient was carried out. As illustrated in table 16-17, the results showed that heart rate had negligible negative correlation with thermal and lighting comfort suggesting slightly higher heart rate in dissatisfactory environment. Weak positive correlation between thermal sensation and skin temperature suggests increase in skin temperature as the environment is sensed as warmer. Mental workload and alertness had weak negative correlation with thermal comfort suggesting higher mental workload and alertness in thermally dissatisfactory environment. Thermal sensation and lighting comfort had negative negligible/weak correlation with mental stress and mental fatigue indicating rise of mental stress and mental fatigue in uncomfortable environment. While negligible positive correlation of valence with thermal sensation indicates increase in positive emotion, negligible positive correlation of arousal suggests increase of wakefulness. Negligible negative correlation of arousal with lighting sensation indicates decrease in arousal level with brighter lighting conditions.

Table 16: Correlation between thermal and light sensation and comfort and physiological response

	Thermal sensation	Thermal comfort	Light sensation	Light comfort	Heart rate	Skin temp.	Mental workload	Mental stress	Alertness	Mental fatigue	Valence	Arousal
Thermal sensation	1.000	-	-	-	-	-	-	-	-	-	-	-
Thermal comfort	-.040**	1.000	-	-	-	-	-	-	-	-	-	-
Light perception	-.151**	.024*	1.000	-	-	-	-	-	-	-	-	-
Light comfort	-.035**	.269**	.121**	1.000	-	-	-	-	-	-	-	-
Heart rate	.015	-.061**	-.023*	-.048**	1.000	-	-	-	-	-	-	-
Skin temperature	.105**	-.011	-.029*	-.118**	.317**	1.000	-	-	-	-	-	-
Mental workload	-.004	-.047**	.043*	0.005	0.002	.056**	1.000	-	-	-	-	-
Mental stress	-.043**	.0.44**	-.051**	-.031**	.029**	.118**	-.511**	1.000	-	-	-	-
Alertness	.020	-.053**	.039**	.020	0.013	-0.013	.904**	-.713**	1.000	-	-	-
Mental fatigue	-.023*	-.014	.032**	-.014	-0.010	.133**	.798**	-.044**	.514**	1.000	-	-
Valence	.027*	-.010	.010	-.013	.041**	-.048**	-0.005	-.057**	0.002	-0.001	1.000	-
Arousal	.023*	0.010	-.021*	0.014	-0.014	-.152**	-.791**	.059**	-.535**	-.930**	.037**	1.000

Note: * Correlation is significant at the 0.05 level (2-tailed), ** Correlation is significant at the 0.01 level (2-tailed).

Table 17: Degree of correlation between thermal and light sensation and physiological responses

	Thermal sensation	Thermal comfort	Light sensation	Light comfort
Heart rate	No correlation	Negligible correlation	Negligible correlation	Negligible correlation
Skin temperature	Weak correlation	No correlation	Negligible correlation	Negligible correlation
Mental workload	No correlation	Negligible correlation	Negligible correlation	No correlation
Mental stress	Negligible correlation	Negligible correlation	Negligible correlation	Negligible correlation
Alertness	No correlation	Negligible correlation	Negligible correlation	No correlation
Mental fatigue	Negligible correlation	No correlation	Negligible correlation	No correlation
Valence	Negligible correlation	No correlation	No correlation	No correlation
Arousal	Negligible correlation	No correlation	Negligible correlation	No correlation

4.6. Effect of physiological responses on learning performance

As aforementioned, the interaction of temperature and lighting level had a statistically significant difference in attention ability and working memory ability in analysis 1. Therefore, Regression analysis was conducted for attention ability and working memory to analyze the influence of physiological responses on learning performance. Furthermore, multicollinearity was test with VIF and results showed VIF for mental workload was higher than 10, suggesting higher correlation and undermining the statistically significance of the independent variable. Therefore, mental workload variable was removed from the analysis. The results of the Durbin-Watson test confirmed that no autocorrelation exists. Table 18-19 indicates the regression analysis for attention ability and working memory.

For attention ability, under 20-23°C heart rate had negative significant effect and mental stress, alertness, mental fatigue, valence and arousal had positive significant effect on learning performance under 100-300 lux, suggesting increase in learning performance as heart rate lowered within the range of average heart rate and as mental stress, alertness, mental fatigue, positive valence and arousal was induced while performing cognitive task. Heart rate, mental fatigue and arousal had negative significant effect while skin temperature and mental stress had significant positive effect under 300-600 lux, suggesting decrease in learning performance as heart rate increased and the induced mental fatigue and arousal exceeded the satisfactory range. Under 600-900 lux light condition, mental stress, alertness, mental fatigue, and arousal had positive significant effect while valence had negative significant effect on learning performance, indicating mental stress, alertness, mental fatigue and arousal within the range that resulted increase in learning performance. For working memory, no significant effect was observed under 100-300 lux and 600-900 lux. Heart rate had negative significant effect on learning performance under 300-600 lux, indicating increase in learning performance as heart rate lowered within the range of average heart rate.

Under 23-26°C thermal condition, for attention ability heart rate, skin temperature, mental stress, alertness, mental fatigue, valence, and arousal had positive significant effect on learning performance under 100-300 lux, suggesting under neutral thermal range all physiological indices were within the range that increased learning performance. While heart rate, mental stress and valence had negative significant effect and alertness, mental fatigue and arousal had positive significant effect on learning performance under 300-600 lux, suggesting increase in learning performance as alertness, mental fatigue and arousal increased within a given satisfactory range. Under 600-900 lux, physiological response did not have any significant effect on learning performance. For working memory, the results showed no significant effect of physiological response on learning performance under 100-300 lux and 600-900 lux lighting condition. Arousal had positive significant effect on learning performance under 300-600 lux, suggesting increase in arousal level resulting higher learning performance.

At 26-29°C thermal condition, for attention ability, mental fatigue and valence had positive significant effect while alertness had negative significant effect on learning performance under 100-300 lux, suggesting decrease in learning performance with higher alertness. Mental stress, alertness, mental fatigue, valence and arousal had positive significant effect on learning performance under 300-600 lux, indicating these variables contributing to increase in learning performance. Under 600-900 lux light condition, skin temperature and alertness had positive significant effect on learning performance, indicating higher alertness level improved the learning performance. For working memory, under 100-300 lux alertness had negative significant effect while mental fatigue has positive significant effect on learning performance, suggesting mental fatigue within the range improving the learning performance while alertness exceeding the satisfactory level. Mental stress and alertness had negative significant effect and mental fatigue had positive significant effect under 300-600 lux, suggesting as mental stress and alertness increased learning performance dropped. Skin temperature and valence had positive significant effect and heart rate, mental stress and mental fatigue had negative significant effect on learning performance under 600-900 lux, indicating decrease in learning performance as heart rate, mental stress and mental fatigue increased.

Table 18: Effect of physiological responses on attention ability under nine indoor environments

Physiological responses	20-23°C			23-26 °C			26-29 °C		
	100-300 lux	300-600 lux	600-900 lux	100-300 lux	300-600 lux	600-900 lux	100-300 lux	300-600 lux	600-900 lux
Heart rate	-0.341** (0.111)	-0.208** (0.114)	0.028 (0.106)	0.169** (0.130)	-0.229** (0.190)	-0.011 (0.287)	-0.023 (0.154)	0.067 (0.145)	-0.006 (0.103)
Skin Temperature	-0.006 (0.754)	0.127** (0.699)	0.058 (0.684)	0.133** (0.941)	0.025 (1.533)	0.079 (1.865)	0.003 (0.668)	0.004 (0.809)	0.164** (0.642)
Mental Stress	0.474** (1.261)	0.286** (1.804)	0.270** (2.328)	0.141** (0.698)	-0.102* (2.789)	0.022 (1.091)	0.046 (2.641)	0.408** (4.429)	-0.031 (0.703)
Alertness	0.295** (5.323)	-0.111 (8.411)	0.317** (4.423)	0.181** (6.768)	0.495** (11.541)	0.069 (9.735)	-0.139* (6.483)	0.535** (13.461)	0.229** (2.800)
Mental fatigue	0.740** (4.554)	-0.363** (6.803)	0.538** (4.133)	0.317** (8.017)	0.350** (12.109)	0.008 (11.346)	0.374** (11.489)	0.341** (6.573)	-0.033 (4.132)
Valence	0.124** (4.144)	0.022 (12.851)	-0.234** (10.056)	0.164** (4.526)	-0.578** (11.776)	-0.062 (5.032)	0.295** (7.019)	0.344** (5.119)	-0.037 (7.519)
Arousal	0.657** (3.488)	-0.558** (3.155)	0.372** (7.996)	0.304** (7.016)	0.445** (8.553)	-0.080 (9.680)	0.060 (13.486)	0.502** (6.999)	0.147 (5.709)
R^2 (Adj R^2)	0.311 (0.306)	0.137 (0.130)	0.218 (0.211)	0.125 (0.118)	0.299 (0.293)	0.039 (0.031)	0.138 (0.131)	0.188 (0.181)	0.048 (0.040)
F	54.404	19.090	33.504	17.237	51.255	4.942	18.182	26.164	5.747
Durbin-Watson	1.489	1.324	1.648	1.155	1.297	1.217	1.446	1.400	1.594

Note: Standard error are in parenthesis; ** $p < 0.01$, * $p < 0.05$

Table 19: Effect of physiological responses on working memory ability under nine indoor environments

Physiological responses	20-23°C			23-26 °C			26-29 °C		
	100-300 lux	300-600 lux	600-900 lux	100-300 lux	300-600 lux	600-900 lux	100-300 lux	300-600 lux	600-900 lux
Heart rate	-0.085 (0.330)	-0.337** (0.420)	-0.152 (0.475)	0.132 (0.466)	-0.178 (0.361)	0.008 (0.340)	0.088 (0.340)	-0.028 (0.347)	-0.315** (0.354)
Skin Temperature	0.198 (2.190)	0.022 (1.944)	0.005 (3.398)	0.087 (3.303)	-0.069 (4.693)	-0.098 (3.804)	-0.090 (3.265)	0.153 (2.981)	0.704** (1.920)
Mental Stress	0.103 (3.086)	0.103 (3.875)	0.070 (6.726)	0.226 (3.387)	0.148 (1.735)	0.112 (5.811)	-0.207 (6.280)	-0.259* (2.834)	-0.325** (5.465)
Alertness	-0.051 (17.885)	0.159 (15.768)	0.273 (24.670)	0.211 (24.677)	-0.186 (25.145)	0.323 (31.904)	-0.422* (19.754)	-0.538** (15.449)	-0.048 (11.215)
Mental fatigue	0.346 (11.707)	0.238 (16.530)	-0.047 (11.092)	0.014 (10.811)	0.369 (22.865)	0.046 (25.543)	0.554** (13.118)	0.509* (8.847)	-0.281* (7.044)
Valence	0.027 (12.627)	-0.129 (12.118)	0.178 (14.712)	-0.185 (16.568)	-0.133 (15.220)	-0.063 (11.644)	-0.015 (21.307)	0.061 (8.126)	0.292* (22.128)
Arousal	0.236 (14.952)	-0.291 (33.899)	-0.165 (15.526)	0.009 (12.577)	0.581* (23.438)	0.094 (29.355)	0.135 (24.117)	0.106 (11.958)	0.123 (11.348)
R^2 (Adj R^2)	0.075 (0.025)	0.218 (0.180)	0.086 (0.042)	0.066 (0.020)	0.218 (0.177)	0.073 (0.033)	0.115 (0.070)	0.115 (0.068)	0.286 (0.249)
F	1.499	5.701	1.952	1.421	5.371	1.810	2.551	2.464	7.764
Durbin-Watson	1.103	0.975	0.900	0.933	0.917	0.876	0.828	1.055	1.053

Note: Standard error are in parenthesis; ** $p < 0.01$, * $p < 0.05$

Additionally, this study carried out polynomial regression to examine the range of changes in learning performance simply with each physiological response. The results of VIF and Durbin-Watson's residual test are found to be satisfactory. The quadratic relationship between average physiological response and learning performance for attention ability and working memory ability under nine environmental conditions are analyzed and predicted as shown in Fig 9-10. The quadratic relationship for attention ability, in which maximum learning performance was observed under 23-26°C, 600-900 lux (LP= 114.157, average HR= 80.81, average SKT= 34.11, Mental workload= 0.596, Mental stress= 1.829, Alertness= 0.603, Mental fatigue= 1.296, Valence= 0.126, Arousal=0.991) and 26-29°C, 600-900 lux (LP= 114.774, average HR= 79.62, average SKT= 33.57, Mental workload= 0.749, Mental stress= 1.626, Alertness= 0.874, Mental fatigue= 1.49, Valence= -0.023, Arousal= 0.89). Learning performance had 4.14% increase when light level shifted from 23-26°C, 100-300 lux to 23-26°C, 600-900 lux and 4.53% increase when light level increased from 26-29°C, 100-300 lux to 26-29°C, 600-900 lux. Learning performance had 2.96% decrease as heart rate increased from 80.12 to 82.46, 3.34% increase as skin temperature increased from 32.24 to 34.11, 3.91% decrease as mental workload increased from 0.749 to 0.822, 4.30 % decrease as mental stress increased from 1.829 to 2.447, 9.64% increase as alertness increased from 0.365 to 0.874, 3.89% decrease as mental fatigue increased from 1.49 to 1.662, 4.3% increase as valence level decreased from -0.023 to -0.029 and 3.41% increase as arousal level increased from 0.67 to 0.991.

Fig 10 shows the relationship for working memory ability, in which maximum learning performance was observed under 23-26°C, 100-300 lux (LP= 159.48, average HR= 78.64, average SKT= 33.945, Mental workload= 0.483, Mental stress= 2.447, Alertness= 0.428, Mental fatigue= 1.253, Valence= 0.065, Arousal=0.95) and 23-26°C, 300-600 lux (LP= 159.48, average HR=

77.53, average SKT= 34.424, Mental workload= 0.603, Mental stress= 1.734, Alertness= 0.554, Mental fatigue= 1.42, Valence= 0.05, Arousal=0.823). Under the same light condition 100-300 lux, learning performance had 0.04% increase between temperature 20-23°C to 23-26°C and 5.21% increase between temperature 26-29°C to 23-26°C and 7.54% increase between temperature 20-23°C and 23-26°C and 26-29°C and 23-26°C under 300-600 lux lighting. Learning performance had 2.55% decrease as heart rate increased from 78.64 to 81.23, 6.60% increase as skin temperature increased from 32.45 to 34.42, 6.60% decrease as mental workload increased from 0.603 to 0.822, 2.55% increase as mental stress increased from 1.829 to 2.447, 1.127% decrease as alertness increased from 0.365 to 0.874, 6.60% decrease as mental fatigue increased from 1.49 to 1.662, 5.63% increase as valence level decreased from -0.023 to -0.029 and 6.60% increase as arousal level increased from 0.67 to 0.95.

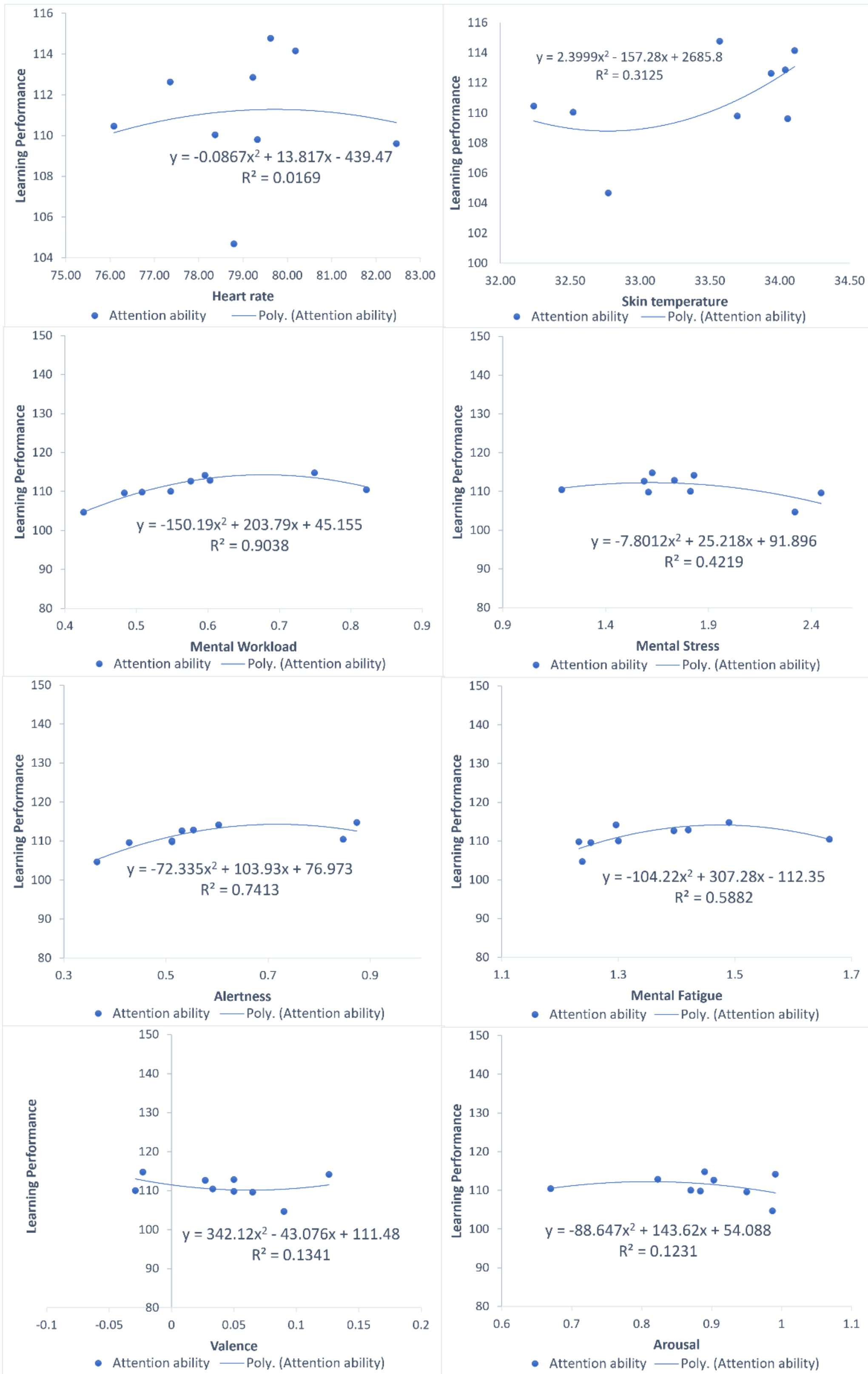

Figure 9: Quadratic relationship of physiological responses and learning performance for attention ability

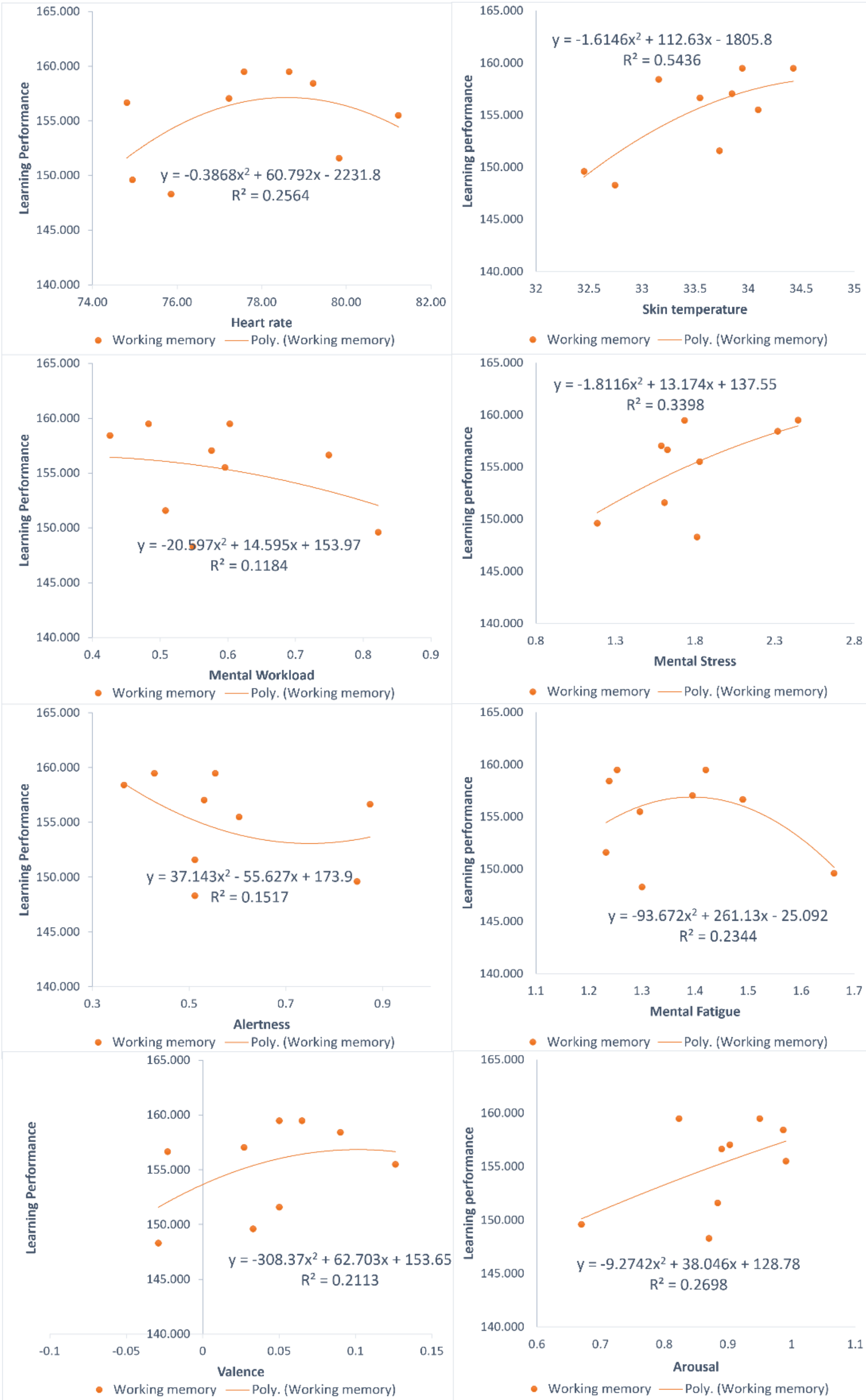

Figure 10: Quadratic relationship of physiological responses and learning performance for working memory

5. DISCUSSION

The current study was conducted in a university classroom, where the indoor thermal conditions were controlled using thermostat and the illumination levels were created controlling the number of lights and switching seats. Since the experiment was conducted in a real classroom, it was difficult to carry out the experiment under a relatively precise temperature and illumination level due to effects of external force, thermal and lighting conditions were considered in ranges, and the experiment was conducted in nine different indoor environment conditions. Additionally, both peripheral measurements such as heart rate and skin temperature, as well as measurement of activity of the central nervous system for metal workload, mental stress, alertness, mental fatigue, and emotional state of the subjects was used to investigate how subjects' learning performance was affected by the indoor environmental conditions.

Similar to previous studies the learning performance is significantly influenced by the interaction of different temperature and lighting level (Xiong, et al., 2018; Yang, Hu, Zhang, Zhu, & Wang, 2021; Liu, et al., 2022). The results in the present study were found significant for attention ability and working memory.

Stroop test, performed as attention test, measured the selective visual attention which helps to prioritize relevant information while ignore the irrelevant information. It is an integration of objective reality that reflects the human vision as dominant sensory organ (Lockhofen & Mulert, 2021). Hence, eye-hand coordination is an integral aspect for attention ability. According to physiological theory and cognitive psychological theory, up to 80% of the information received from outside is processed by the visual pathway, and color is regarded as the primary language (Xiong, et al., 2018; Haupt & Huber , 2008). The present study confirmed these results, showing that visual stimulation of lighting playing a much stronger and direct role. Therefore, illumination could be regarded as a primary factor for attention ability. As the lighting level increased from 100-300 lux to 300-600 lux, to 600-900 lux the learning performance of the subject increased corresponding to the increase in lighting under different thermal condition. Learning performance increased within the lighting range considered in this study, however, it could potentially decrease beyond the maximum threshold range for lighting. For attention ability, the maximum learning performance was observed under 23-26°C, 600-900 lux and 26-29°C, 600-900 lux.

Nback test, which measured the verbal working memory, is an articulatory or phonological loop (Baddeley & Hitch, Working Memory, 1974). Articulation is assumed to be composed of a store in which an acoustic or phonological memory trace is held, and the process of subvocal articulatory rehearsal that helps to refresh the memory trace as well as register visually presented but nameable material in phonological store (Tulving & Craik, 2000). While the interaction of temperature and lighting had some significant influence on working memory, with temperature having a stronger role, this study only considers two aspects of indoor environmental quality so, it is unverified that temperature plays a dominant role for verbal working memory. Under the same lighting range of 100-300 lux, learning performance had decrement of 5.20% from neutral temperature to higher temperature and 7.54% decrement from neutral temperature to lower temperature under 300-600 lux lighting. Hence the maximum learning performance for working memory was observed under 23-26°C, 100-300 lux and 23-26°C, 300-600 lux.

The results obtained from the relationship between thermal and lighting sensation and comfort and physiological responses suggest, comparatively higher heart rate in dissatisfactory environment and increase in skin temperature as the environment is sensed as warmer. Higher mental workload and alertness in thermally dissatisfactory environment while also, rise of mental stress and mental fatigue in thermally and visually uncomfortable environment. Decrease in negative emotion as well as increase in arousal as the thermal sensation of an environment is sensed as warmer while increase in positive emotions with brighter light conditions.

The state of our inside body determines how we interpret or respond to our surroundings. For instance, our responses to food stimuli alter depending on whether we are thirsty or hungry, and this influences our perceptions, cognitions, and memories. The thermal and lighting comfort or discomfort to the indoor environment alters depending on the sensation of the indoor environment, and this influences the physiological response. The fight-or-flight response is an innate physiological response to a stressful or terrifying event that stimulates the sympathetic nervous system and sets off an acute stress response, preparing the body to either fight or flee, according to Fight and Flight Theory (Cannon, 1915). When the body detects stressors, the initial coping mode is through aggressive fight-or-flight response, as the body experiences stress, the physiological system's defenses and behavioral arousal are activated and the increased stress levels promote the body's defense responses, which manifest as additional physiological responses (Fan, Liang, Cao, Pang, & Zhang, 2022).

The increase in the negative indices such as mental workload, mental stress, alertness, mental fatigue, negative valence, and arousal is result of triggering due to the cognitive task as well the indoor environment. In a dissatisfactory indoor environment, discomfort adds to the stress perceived by the human body and could increase the task load while decreasing in learning performance, however, based on the James–Lange theory of emotion that proposes emotional feelings arose from the mind perception of bodily changes in response to emotive stimuli to ‘color’ our thoughts (James, 1894; Lange , 1885; Critchley, 2009). While the Schachter-Singer theory of emotion focuses on interaction of physiological and cognitive arousal; physiological arousal requires some cognitive assessment and some interpretation of specific emotion in order to determine the state of physiological arousal (Schachter & Singer, 1962; Maia, 2010; Stanojlović, et al., 2021). The learning process is dependent on sensation and cognition of the learning event i.e., classroom activities such as taking test, attending lectures etc. and the sensation and comfort in a learning environment, which influences the physiological responses. The change in physiological responses might increase the task load and increase of task load beyond the threshold range might lead to decrease in learning performance. Fig 11 shows the learning process. The stress- negative emotions and physiological response perceived in a satisfactory environment could be stabilized due to the sense of comfort and instead lead to increase in learning performance.

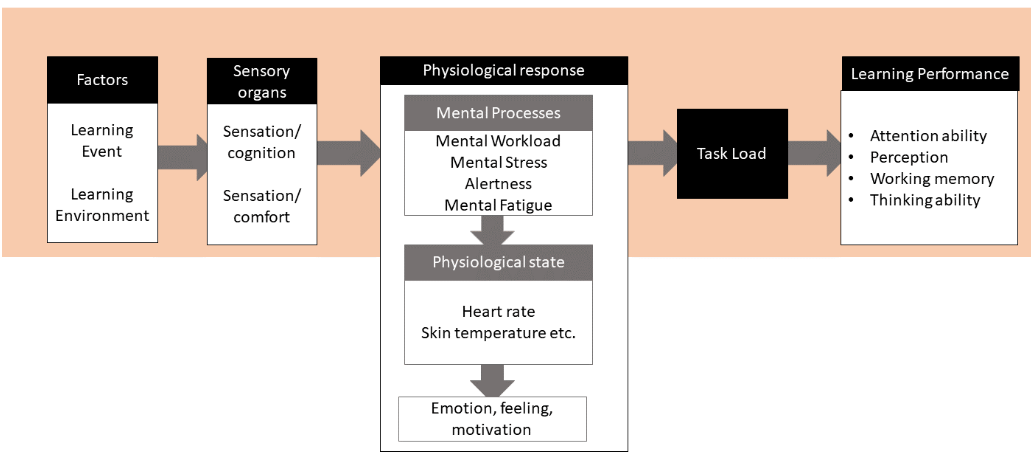

Figure 11: Learning Process

Emotional states of the subjects are further explored and their relationship with learning performance. Fig 12-13 shows the emotional state for attention ability and working memory under different environmental condition, and their average learning performance in that environment. The emotional identification graph shows subjects had positive and pleasant emotional state under all indoor environment except 20-23°C, 300-600 lux and 26-29°C, 600-900 lux for attention and 20-23°C, 600-900 lux, 23-26°C, 100-300 lux and 26-29°C, 100-300 lux for working memory, where the emotional state was observed to be stressed or tensed. In the satisfactory environment

26-29°C, 600-900 lux, despite the subjects projecting nervous or tensed emotion, their learning performance for attention was higher than in 20-23°C, 300-600 lux. Environmental comfort as well as the finding from this research-brighter lighting conditions increase the ability to concentrate, compensated for the negative emotion generated while performing the cognitive task, and therefore resulted in higher learning performance for attention. Similarly, the sensation of environmental comfort compensated for the negative emotions generated under 23-26°C, 100-300 lux for working memory, and resulted in maximum learning performance for working memory.

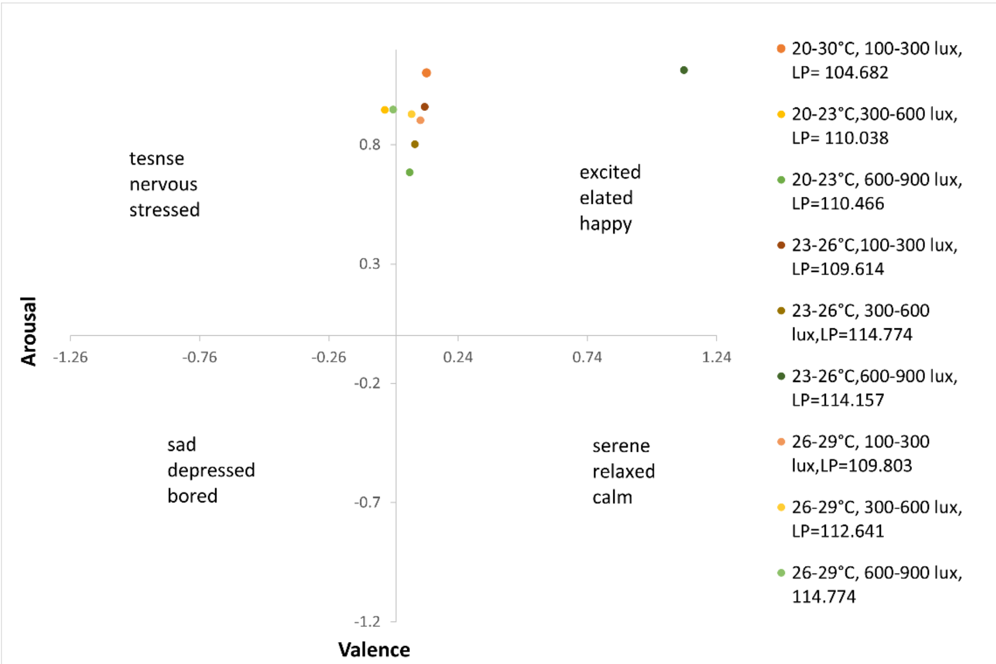

Figure 12: Emotional state at different indoor environment for attention ability

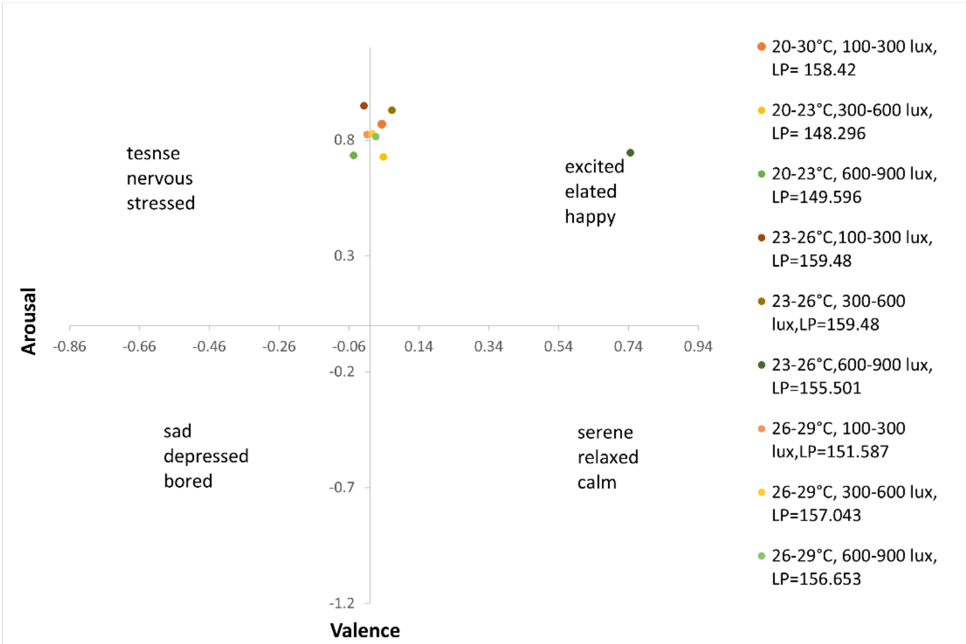

Figure 13: Emotional state at different indoor environment for working memory

6. CONCLUSION AND FUTURE WORK

In this study, four cognitive tests under nine different environmental condition, nine subjective questionnaires to assess environmental sensation and comfort and physiological response while performing the cognitive tasks were studied to investigate the effect of temperature and lighting on learning performance.

1. For attention and perception ability, which involved visual attention and perception, learning performance increased when the environment shifted to brighter conditions. For working memory, lower light level had maximum learning performance and conversely, neutral light level had maximum learning performance for thinking ability. Interaction of temperature and light had significant difference on learning performance for attention ability and working memory.
2. At lower thermal condition, brighter lighting provided more visual comfort while at neutral and higher thermal conditions, neutral lighting provided more visual comfort.
3. For attention ability, brighter environment (600-900 lux) at 20-23°C, thermal and light comfort and at 26-29°C, light comfort contributed to higher learning performance, under 23-26°C, light perception had negative significant effect on learning performance. For working memory, under lower light level (100-300 lux) at 20-23°C, thermal sensation contributed to higher learning performance. Under lower and neutral light level (100-300 lux, 300-600 lux) at 23-26°C, thermal sensation and light comfort contributed to higher learning performance, and under neutral light (300-600 lux) at 26-29°C, thermal comfort contributed to higher learning performance.
4. Changes in physiological responses was observed with change in indoor environment. Higher heart rate was observed in lower light level while skin temperature was relatively

higher under lower and neutral light level under lower and higher temperatures. Mental workload and alertness increased as the room was brighter, mental stress was maximum under lower light and conversely, mental fatigue was minimal under lower light conditions. Neutral lighting under lower temperature and higher lighting under higher temperature higher negative emotion was observed and lower temperature contributed for high arousal under lower light condition, while brighter light contributed for high arousal under neutral temperature. Also, both positive or pleasant emotions, as well as stressed or tensed emotions were observed in the different indoor environments.

5. Changes in physiological responses was observed with change in sensation and comfort of indoor environment.
6. For attention, brighter environment (600-900 lux) at 20-23°C, mental fatigue and at 26-29°C, alertness had maximum influence on learning performance. For working memory under neutral light level (300-600 lux) at 23-26°C arousal, and neutral light at 26-29°C, alertness had maximum influence on learning performance. Despite the increase in negative indices, the emotional state played an important factor contributing to higher learning performance.

The contribution of this study would be investigating the learning performance from perspective of indoor environment, physiological responses and learning process. First, learning performance depends on the type of task, the environmental factor that plays a stronger role based on the type of task and the sensory organs that is activated and act as direct pathway to transfer information to the brain. The finding from this research, brighter light increases the ability to focus on a task despite distracting stimuli could be used in real classroom environments to improve attention ability of students. Neutral temperature between 23-26°C played a dominant role for higher learning performance for working memory. This finding could be used in real classroom environment as the tasks followed in classroom such as taking notes, following a multi-step direction etc. are the working memory cognition. Therefore, the findings can be utilized to augment the existing indoor environment-related standards providing references on environmental interactions and create an IEQ management plan that can contribute to improving the learning environment for the students.

Second, the indoor environment sensation and comfort as well as the event-cognitive task, generating mental processes that influence the physiological state, which influences the thoughts, feelings, or emotions. Hence, in a neutral or comfortable environment, the mental and physiological processes generated while performing tasks are neutralized to some extent which increases the learning performance. Emotional state of students plays an important role in motivating students to perform well. Therefore, this study is an attempt to measure the mental processes including valence and arousal level to better understand the emotional states of students in a classroom despite the difficulty of controlling many emotions related factors.

The following limitation need to be addressed in future research. Firstly, this research only considered two factors of indoor environmental quality, temperature, and artificial lighting level, which might not reflect the indoor environment quality entirely as the indoor environment comfort reflects not only thermal and visual comfort but also acoustic, air quality and overall comfort. As the experiments were carried out in real classroom environment, it was difficult to control or keep the parameters of indoor environment consistent. Also, the experiments were conducted with summer clothing, future studies could consider conducting the experiment in winter clothing. Secondly, the cognitive tasks performed as part of the study is different from the realistic college works. Future work could explore regarding the impact of performing the same cognitive tasks repeatedly and, under one-on-one supervision with wearable devices set up on them and the difference in the level of effort applied for real college works. Thirdly, the sample size of 17 people is relatively low, while the sex ratio of male, female or others was not equally planned when recruiting the subjects for the experiment. Future study could consider difference in results between genders. Also, the ethnicity of the subjects recruited were predominantly Asian, future study could explore the impact of different ethnicity and cultural group on the results.

REFERENCES

Akella, N. (2019). Designing Caring and Inclusive Online Classroom Environments for Non-Traditional Learners: A Case Study Exploring the Andragogical Teaching and Learning Model. *IGI Global*, 63-87.

Akimoto, T., Tanabe, S., Yanai, T., & Sasaki, M. (2010). Thermal comfort and productivity - evaluation of workplace environment in a task conditioned office. *Building and Environment, 45*(1), 45-50.

Alexander, P. A., White, C. S., & Haensly, P. A. (1987). Training in Analogical Reasoning. *American Educational Research Journal, 24*, 387-404.

ASHRAE . (2010-2016). *ASHRAE Guideline 10-2016: Interactions Affecting the Achievement of Acceptable Indoor Environments.* Atlanta, USA: ASHRAE.

ASHRAE 55. (2021). *Thermal Environment Conditions for Human Occupancy.* Atlanta, GA: CiNii Books.

Baddeley, A. (1966). Short-term Memory for Word Sequences as a Function of Acoustic, Semantic and Formal Similarity. *Quarterly Journal of Experimental Psychology, 18*(4).

Baddeley, A. (1966). The Influence of Acoustic and Semantic Similarity on Long-term Memory for Word Sequences. *Quarterly Journal of Experimental Psychology, 18*(4).

Baddeley, A., & Hitch, G. (1974). Working Memory. *Psychology of Learning and Motivation*, 47-89. doi:https://doi.org/10.1016/S0079-7421(08)60452-1

Baddeley, A., & Hitch, G. (2002). Is Working Memory Still Working? *European Psychologist, 7*(2).

Bajc, T. S., Banjac, M. J., Todorovic, M. N., & Stevanovic, Z. Z. (2018). Experimental and statistical survey on local thermal comfort impact on working productivity loss in university classrooms. *Thermal Science*, 379-392.

Balcetis, E., & Dunning, D. (2006). See what you want to see: motivational influences on visual perception. *Journal of personality and social psychology, 91*.

Barbic, F., Minonzio, M., Cairo, B., Shiffer, D., Dipasquale, A., Cerina, L., . . . Furlan, R. (2019). Effects of different classroom temperatures on cardiac autonomic control and cognitive performances in undergraduate students. *Physiological Measurement, 40*(5).

Bestelmeyer, P. E., Kotz, S. A., & Belin, P. (2017). Effects of emotional valence and arousal on the voice perception network. *Social Cognitive and Affective Neuroscience*, 1351-1358.

Bostrom, N., & Sandberg , A. (2009). Cognitive Enhancement: Methods, Ethics, Regulatory Challenges. *Science and Engineering Ethics, 15*, 311–341.

Burgess, H. J., Sharkey, K. M., & Eastman, C. I. (2002). Bright light, dark and melatonin can promote circadian adaptation in night shift workers. *Sleep Medicine Reviews, 6*(5), 407-420.

Burkhardt, F. (2001). Simulation of emotional speech with speech synthesis methods. *Maastricht, Netherlands: Shaker*.

Cannon, W. B. (1915). *Bodily changes in pain, hunger, fear and rage: An account of recent researches into the function of emotional excitement.* D Appleton & Company.

Cheng, M. J., Hwang, R. L., & Lin, T. P. (2008). Field experiments on thermal comfort requirements for campus dormitories in Taiwan. *Indoor Built Environment, 17*, 191-202.

Cheng, S.-Y., & Hsu, H.-T. (2011). Mental Fatigue Measurement Using EEG. *Risk Management Trends*.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Science, 24*(1), 87-114.

Critchley, H. D. (2009). Psychophysiology of neural, cognitive and affective integration: fMRI and autonomic indicants. *International Journal of Psychophysiology*, *73*(2), 88-94.

Davidson, R. J., Ekman, P., Saron, C. D., Senulis, J. A., & Friesen, W. V. (1990). Approach-withdrawal and cerebral asymmetry: Emotional expression and brain physiology: I. *Journal of Personality and Social Psychology*, *58*(2), 330–341.

Ekhtiari, H., & Paulus, M. (2016). Neuroscience for Addiction Medicine: From Prevention to Rehabilitation - Methods and Interventions. In *Progress in Brain Research* (pp. 2-461). Elsevier.

Elliott , M., & Quintino, V. (2018). The Estuarine Quality Paradox Concept,. In *Encyclopedia of Ecology.* Elsevier Science & Technology.

Eysenck, M. W., & Brysbaert, M. (2018). *Fundamentals of Cognition.* Routledge.

Fan, Y., Liang, J., Cao, X., Pang, L., & Zhang, J. (2022). Effects of Noise Exposure and Mental Workload on Physiological Responses during Task Execution. *International Journal of Environmental Research and Public Health*. doi:https://doi.org/10.3390/ijerph191912434

Gaihre, S., Semple, S., Miller, J., Fielding, S., & Turner, S. (2014). Classroom Carbon Dioxide Concentration, School Attendance, and Educational Attainment. *Journal of School Health*.

Georgieva, P., Silva, F., Milanova, M., & Kasabov, N. K. (2014). EEG Signal Processing for Brain–Computer Interfaces. In *Molecular networks, their analysis and representation, Springer Handbook of Bio- and Neuroinformatics* (pp. 797-812). Springer.

Gijsbert , S. (2010). PsyToolkit: A software package for programming psychological experiments using Linux. *Behavior Research Methods*, 1096-1104.

Gijsbert , S. (2017). PsyToolkit: A Novel Web-Based Method for Running Online Questionnaires and Reaction-Time Experiments. *Teaching of Psychology*, 24-31.

Giuli, V. D., Pos, O. D., & Carli, M. D. (2012). Indoor environmental quality and pupil perception in Italian primary schools. *Building and Environment*, 335-345.

Gomes, H., Sussman, E., Ritter, W., Kurtzberg, D., Cowan, N., Vaughan, J., & Herbert, G. (1999). Electrophysiological evidence of developmental changes in the duration of auditory sensory memory. *American Psychological Association, 35*(1), 294-302.

Haupt, C., & Huber , A. B. (2008). How axons see their way – axonal guidance in the visual system. *Frontiers in Bioscience*, 3136-3149.

Hoque, S., & Weil, B. (2016). The relationship between comfort perceptions and academic performance in university classroom buildings. *Journal of Green Building*, 108-117.

Hu, S., & Maeda, T. (2020). Productivity and physiological responses during exposure to varying air temperatures and clothing conditions. *Indoor Air, International Journal of Indoor Environment and Health, 30*(2), 251-263. doi:https://doi.org/10.1111/ina.12628

Huang, L., Zhu, Y., Ouyang, Q., & Cao, B. (2012). A study on the effects on thermal, luminous and acoustic environments on indoor environmental comfort in offices. *Building and Environment, 49*, 304-309.

Hwang, S., Jebelli, H., Choi, B., Choi, M., & Lee, S. H. (2018). Measuring Workers' Emotional State during Construction Tasks Using Wearable EEG. *Journal of Construction Engineering and Management, 144*(7).

Jaakkola, J. J., Heinonen, O. P., & Seppänen, O. (1989). Sick building syndrome, sensation of dryness and thermal comfort in relation to room temperature in an office building: need for individual control of temperature. *Environment International, 15*(1-6), 163-168.

James, W. (1894). Discussion: The physical basis of emotion. *Psychological Review, 1*(5), 516-529.

Jansen, A. S., Nguyen, X. V., Karpitskiy, V., Mettenleiter, T. C., & Loewy, A. D. (1995). Central command neurons of the sympathetic nervous system: basis of the fight-or-flight response. *Science Magazine, 270*(5236), 644-646. doi:https://doi.org/10.1126/science.270.5236.644

Jebelli, H., Hwang, S., & Lee, S. H. (2017). Feasibility of Field Measurement of Construction Workers' Valence Using a Wearable EEG Device. *ASCE International Workshop on Computing in Civil Engineering*, 99-106.

Katafygiotou, M., & Serghides, D. (2015). Bioclimatic chart analysis in three climate zones in Cyprus. *Indoor and Built Environment, 24*(6), 746-760.

Kim, H., Hong, T., Kim, J., & Yeom, S. (2020). A psychophysiological effect of indoor thermal condition on college students' learning performance through EEG measurement. *Building and Environment, 184*.

Kulve, M. t., Schlangen, L., & Lichtenbelt, W. v. (2018). Interactions between the perception of light and temperature. *Indoor Air, 28*(6), 881-891. doi:https://doi.org/10.1111/ina.12500

Lan, L., & Lian, Z. (2009). Use of neurobehavioral tests to evaluate the effects of indoor environment quality on productivity. *Building and Environment, 44*(11), 2208-2217. doi:https://doi.org/10.1016/j.buildenv.2009.02.001

Lan, L., Lian, Z., Pan, L., & Ye, Q. (2009). Neurobehavioral approach for evaluation of office workers' productivity: The effects of room temperature. *Building and Environment, 44*(8), 1578-1588.

Lange , C. G. (1885). The mechanism of the emotions. *The classical psychologists*, 672-685.

Lee, M. C., Mui, K. W., Wong, L. T., Chan, W. Y., Lee, E. M., & Cheung, C. T. (2012). Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms. *Building and Environment, 49*, 238-244.

Leech, J. A., Burnett, R., Nelson, W., Aaron, S. D., & Raizenne, M. (2000). Outdoor air pollution epidemiologic studies. *American Journal of Respiration and Critical Care Medicine, 161*(3), A308.

Lewis, R. S., Weekes, N. Y., & Wang, T. H. (2007). The effect of a naturalistic stressor on frontal EEG asymmetry, stress, and health. *Biological Psychology, 75*(3), 239-247.

Lievesley, R., Wozencroft, M., & Ewins , D. (2011). The Emotiv EPOC neuroheadset: an inexpensive method of controlling assistive technologies using facial expressions and thoughts? *Journal of Assistive Technologies, 5*(2), 67-82. Retrieved from https://doi.org/10.1108/17549451111149278

Liu, C., Sun, L., Jing, X., Zhang, Y., Meng, X., Jia, C., & Gao, W. (2022). How correlated color temperature (CCT) affects undergraduates: A. *Journal of Building Engineering, 45*. doi:https://doi.org/10.1016/j.jobe.2021.103573

Liu, J., Yang, X., Jiang, Q., Qiu, J., & Liu, Y. (2019). Occupants' thermal comfort and perceived air quality in naturally ventilated classrooms during cold days. *Building and Environment, 158*, 73-82.

Lizzio, A., Wilson, K., & Simons, R. (2002). University Students' Perceptions of the Learning Environment and Academic Outcomes: Implications for theory and practice. *Studies in Higher Education*, 27-52.

Lockhofen, D. E., & Mulert, C. (2021). Neurochemistry of Visual Attention. *Frontiers in Neuroscience*.

Loe, D., Watson, N., Rowlands, E., Mansfield, K., Venning, B., & Baker, J. (1999). *Lighing Design for Schools.* London: Department for Education and Employment, London (England). Architects and Building Branch.

Lui, W.-h., Huang, J., Wand, L.-z., Gong, Q.-y., & Chan, R. C. (2012). Facial perception bias in patients with major depression. *Psychiastry Research, 197*, 217-220.

McCartney, K. J., & Humphreys, M. A. (2002). Thermal comfort and productivity. *Proceedings of Indoor Air*, 822-827.

Mishra, A. K., & Ramgopal, M. (2015). A thermal comfort field study of naturally ventilated classrooms in Kharagpur, India. *Building and Environment, 92*, 396-406.

Mishra, A. K., Derks, M. T., Kooi, L., Loomans, M. G., & Kort, H. S. (2017). Analysing thermal comfort perception of students through the class hour, during the heating season, in a university classroom. *Building and Environment, 125*, 464-474.

Nikolopoulou, M., & Steemers, K. (2003). Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy and Buildings, 35*(1), 95-101.

NIOSH. (2013, May 17). *The National Institute for Occupational Safety and Health (NIOSH)*. Retrieved from Centers for Disease Control and Prevention: https://www.cdc.gov/niosh/topics/indoorenv/default.html

Norman, G., Necka, E., & Berntson, G. G. (2016). The Psychophysiology of Emotions. *Emotion Measurement*, 83-98.

Oberauer, K. (2019). Working Memory and Attention – A Conceptual Analysis and Review. *Journal of cognition, 2*(1).

Olbrich, S., Mulert, C., Karch, S., Trenner, M., & Leicht, G. (2009). EEG-vigilance and BOLD effect during simultaneous EEG/fMRI measurement. *NeuroImage, 45,* 319-332.

Pawlowska, D. K., Westerman, J. W., Bergman, S. M., & Huelsman, T. J. (2014). Student personality, classroom environment, and student outcomes: A person–environment fit analysis. *Learning and Individual Differences, 36*, 180-193.

Pekrun, R., Goetz, T., Titz, W., & Perry, R. P. (2002). Academic Emotions in Students' Self-Regulated Learning and Achievement: A Program of Qualitative and Quantitative Research. *Educational Psychologist, 37*(2), 91-105.

Pepler, R., & Warner, R. (1968). Temperature and Learning: An experimental study. *Paper No 2089. Transactions of ASHRAE annual meeting , Lace Placid, 1967,,* 211-219.

Postma-Nilsenová, M., & Postma, E. (2013). Auditory perception bias in speech imitation. *Frontiers in Psychology, 4*.

Pronin, E. (2007). Perception and misperception of bias in human judgment. *Trends in Cognitive Sciences, 11*(1), 37-43.

Rabbi, A. F., Zony, A., Leon, P. d., & Rezai, R. F. (2012). Mental workload and task engagement evaluation based on changes in electroencephalogram. *Biomedical Engineering Letters, 2,* 139–146. Retrieved from https://doi.org/10.1007/s13534-012-0065-8

Russell, J. A., Weiss, A., & Mendelsohn, G. A. (1989). Affect Grid: A single-item scale of pleasure and arousal. *Journal of Personality and Social Psychology, 57*(3), 493–502.

Schachter, S., & Singer, J. (1962). Cognitive, social, and physiological determinants of emotional state. *Psychological Review*, 379–399.

Schlee, R., Curren, M., Harich, K., & Kiesler, T. (2007). Perception bias among undergraduate business students by major. *Journal of Education for Business, 82*(3), 169-177.

Shiffrin, R., & Atkinson, R. (1969). Storage and retrieval processes in long-term memory. *American Psychology Association, 76*(2), 179-193.

Staal, A. M. (2004). Stress, Cognition, and Human Performance: A Literature Review and Conceptual Framework.

Stanojlović, O., Šutulović, N., Hrnčić, D., Mladenović, D., Rašić-Marković, A., Radunović, N., & Vesković, M. (2021). Neural pathways underlying the interplay between emotional experience and behavior, from old theories to modern insight. *Archives of Biological Sciences*, 361-370.

Sulaiman, N., Taib, M. N., Lias, S., Murat, Z. H., Mohd Aris, S. A., Mustafa, M., & Rashid, N. A. (2012). Development of EEG-based stress index. *International Conference on Biomedical Engineering*, 27-28.

Tanabe, S., & Nishihara, N. (2004). Productivity and fatigue. *Indoor Air, International Journal of Indoor Environment and Health, 14*(s7), 126-133. doi:https://doi.org/10.1111/j.1600-0668.2004.00281.x

Tran, Y., Thuraisingham, R. A., Wijesuriya, N., Nguyen, H. T., & Craig, A. (2007). Detecting neural changes during stress and fatigue effectively: a comparison of spectral analysis and sample entropy. *Proceedings of the 3rd International IEEE EMBS Conference on Neural Engineering*.

Tulving, E., & Craik, F. I. (2000). *The Oxford Handbook of Memory.* Oxford University Press, USA. Retrieved from https://www.google.com/books/edition/The_Oxford_Handbook_of_Memory/r0yjoYvv3_YC?hl=en&gbpv=1&pg=PA77&printsec=frontcover

Wang, C., Zhang, F., Wang, J., Doyle, J. K., Hancock, P. A., Mak, C. M., & Liu, S. (2021). How indoor environmental quality affects occupants' cognitive functions: A systematic review. *Building and Environment, 193*. doi:https://doi.org/10.1016/j.buildenv.2021.107647

Wang, D., Xu, Y., Liu, Y., Wang, Y., Jiang, J., & Wang, X. (2018). Experimental investigation of the effect of indoor air temperature on students' learning performance under the summer condition in China. *Building and Environment, 140*, 140-152.

Wang, M.-T., & Degol, J. (2016). School Climate: a Review of the Construct, Measurement, and Impact on Student Outcomes. *Educational Psychological Review, 28*, 315-352.

Wang, X., Li, D., Menassa, C. C., & Kamat, V. R. (2019). Investigating the effect of indoor thermal environment on occupants' mental workload and task performance using electroencephalogram. *Building and Environment, 158*, 120-132.

Wargocki, P., & Wyon, D. P. (2017). Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. *Building and Environment, 112*, 359-366.

Wargocki, P., Sundell, J., Fanger, P. O., Bischof, W., Brundrett, G., Gyntelberg, F., . . . Wouters, P. (2002). Ventilation and health in non-industrial indoor environments: report from a European multidisciplinary scientific consensus meeting (EUROVEN). *International Journal of Indoor Environment and Health*.

Wargocki, P., Wyon, D. P., Sundell, J., Clausen, G., & Fanger, P. O. (2000). The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. *Indoor Air, 10*(4), 222-236.

Wilkins, A., Nimmo-Smith, I., Slater, A., & Bedocs, L. (1989). Fluorescent lighting, headaches and eyestrain. *Lighting Research and Technology, 21*(1), 11-18.

Wilson, R. A., & Keil, F. C. (1999). *The MIT Encyclopedia of the Cognitive Sciences.* The MIT Press.

Witterseh, T., Wyon, D., & Clausen, G. (2004). The effects of moderate heat stress and open-plan office noise distraction on SBS symptoms and on the performance. *Indoor Air, 14*(8), 30-40.

Xiong, L., Huang, X., Li , J., Mao, P., Wang, X., Wang, R., & Tang , M. (2018). Impact of Indoor Physical Environment on Learning Efficiency in Different Types of Tasks: A 3 × 4 × 3 Full Factorial Design Analysis. *International Journal of Environmental Research and Public Health, 16*(6). doi:https://doi.org/10.3390/ijerph15061256

Yang, W., & Moon, H. J. (2019). Combined effects of acoustic, thermal, and illumination conditions on the comfort of discrete senses and overall indoor environment. *Building and Environment, 148*, 623-633. doi:https://doi.org/10.1016/j.buildenv.2018.11.040

Yang, Y., Hu, L., Zhang, R., Zhu, X., & Wang, M. (2021). Investigation of students' short-term memory performance and thermal sensation with heart rate variability under different environments in summer. *Building and Environment, 195*(3).

Zhang, R., Yang , Y., Fang, Q., Liu , Y., Zhu , X., Wang , M., & Su , L. (2020). Effect of Indoors Artificial Lighting Conditions on Computer-Based Learning Performance. *International Journal of Enviromental Research and Public Health, 17*(7). doi:https://doi.org/10.3390/ijerph17072537

Zhu, M., Liu, W., & Wargocki , P. (2019). Changes in EEG signals during the cognitive activity at varying air temperature and relative humidity. *Journal of Exposure Science & Environmental Epidemiology, 30*, pages285–298.

Zimmerman, C. (2000). The Development of Scientific Reasoning Skills. *Developmental Review, 20*(1), 99-149.

APPENDIX A : IRB APPROVAL

NDSU NORTH DAKOTA STATE UNIVERSITY

04/06/2022

Dr. Youjin Jang
Civil, Construction & Env Eng

IRB Approval of Protocol #IRB0004109, "Investigating the effect of indoor environmental quality (IEQ) on physiological and psychophysiological responses and learning performance of occupants in the university classroom"

Co-investigator(s) and research team:

- Youjin Jang
- Surakshya Pradhan

Approval Date: 04/06/2022
Expiration Date: 04/05/2025
Research site(s): The research will be conducted in a classroom in NDSU.
Funding Agency:
Review Type: Expedited category # 4,7

The above referenced protocol has been reviewed in accordance with federal regulations (Code of Federal Regulations, Title 45, Part 46, *Protection of Human Subjects*).

Additional approval from the IRB is required:

- Prior to implementation of any changes to the protocol.
- For continuation of the project beyond the approval period. A task will automatically generate for the PI and Co-PI 8 weeks prior to the expiration date. To avoid a lapse in approval, suspension of recruitment, and/or data collection, a report must be received, and the protocol reviewed and approved for continuation prior to the expiration date.

Other institutional approvals:

- Research projects may be subject to further review and approval processes.

A report is required for:

- Any research-related injuries, adverse events, or other unanticipated problems involving risks to participants or others within 72 hours of known occurrence.
- Protocol Deviations
- Any significant new findings that may affect risks to participants.

Thank you for cooperating with NDSU IRB procedures, and best wishes for a successful study.

NDSU has an approved FederalWide Assurance with the Department of Health and Human Services: FWA00002439.

APPENDIX B : CONSENT FORM

Department of Civil, Construction and Environmental Engineering
1410 North 14th Avenue, CIE 201, Fargo, ND 58102
Fargo, ND 58108-6050
701.231.7244

Investigating the effect of indoor environmental quality (IEQ) on physiological and psychophysiological responses and learning performance of occupants in the university classroom

This study is being conducted by: Surakshya Pradhan, surakshya.pradhan@ndsu.edu and Dr. Youjin Jang (PI), y.jang@ndsu.edu for primary researcher(s).

Key Information about this study:

This consent form is designed to inform you about the study you are being asked to participate in. Here you will find a brief summary about the study; however you can find more detailed information later on in the form.

- If you are between the ages of 20-35 and in good health with no history of disorders such as color blindness, neurological disorders, allergy and alcohol addiction.
- The risk/discomfort associated with the experiment is discomfort due to wearing the headset and wristband.
- The experiment needs to run under 3 different environmental scenarios, each for 60-80 minutes. Hence, it will require your participation for 3 days.
- No identifiable information will be collected from you. Your age, height, weight and history of no disorder will, however, be collected.

Why am I being asked to take part in this study?

The purpose of this research is to study how the indoor environmental conditions such as temperature and lighting affects how efficiently students can learn in the given environment. You are being asked to take part in this study because (i) you are between the age 20-35 (ii) are of good health with no history of disorders such as color blindness, neurological disorders, allergy and alcohol addiction.

What will I be asked to do?

Before participating in the experiment, you will be asked to get sufficient sleep of 7 hours and refrain from drinking alcohol, tobacco, caffeinated drinks or other drinks that can cause any kind of excitement or drowsiness during the day of the experiment. You will be asked to wear the same clothes and shoes during each day of the experiment. You will be asked to wash and dry your hair without hair products before coming to the experiment.

Before starting the experiment, your height and weight will be measured and you will be asked to fill out a participant information questionnaire that include information such as your age, sex, height, weight, health screening questions and experiment screening questions.

An Electroencephalogram (EEG) headset that will collect your brain responses and the E4 Wristband that will collect your heart rate and skin temperature will be set on you before the start of the experiment. These are non-invasive and only involves passive measurement of the brain's electrical activity, heart rate and skin temperature.

You will watch some videos or read a paragraph for 10 min so that you can adjust with the environmental scenario we have prepared with different temperatures and lighting conditions. You will then perform a series of cognitive tests on the screen. The cognitive tests, namely: Stroop task for Attention test, Mental rotation task for Perception test, N-Back task for Working Memory and Mental arithmetic for Thinking test.

In Stroop test, you will be required to pay attention to the color of the word, not what the word says. For e.g. For the word BLUE, you should type "r" for the color red.

In Mental rotation test, you will see three stimuli. The two stimuli at the bottom are rotated, of which one will match with the stimuli at top. You will need to mentally rotate (imagine what they look like when it is rotated) and select the stimuli that matches the one at the top.

In N-Back task, you will be presented a sequence of stimuli one-by-one. For each stimulus, you will need to decide if the current stimulus is the same as the one N trials ago. N can be 1 trial, 2 trial 3 trial etc.

In Mental arithmetic, you will see some addition and subtraction problems, do the calculation mentally and select the correct answer.

Lastly, you will fill out a questionnaire regarding your thermal sensation- if the classroom was too cold or neutral or too warm and task load- if you found the task to be easy or difficult.

You will perform these tests in three different environmental conditions, each of which will run about 70 minutes or more. During these experiments your heart rate and skin temperature will be collected through the wristband and your brain activity through the EEG headset.

Where is the study going to take place, and how long will it take?

The experiment will be conducted in a classroom in North Dakota State University. You will be required to participate in the experiment for 3 days, 60-80 min on each day.

What are the risks and discomforts?

The study may result in discomfort caused due to the EEG headset being set on your head and the wristband being too tight. Reasonable safeguards have been taken to minimize known risks, however, it is not possible to identify all potential risks in research. We will tell you about any new findings developed during the course of the research which may change your willingness to participate.

What are the expected benefits of this research?

Societal Benefits: The societal benefits of the study will be to find how different thermal and lighting conditions affect learning performance, analyzing the change in heart rate and skin temperature and the activities of the brain namely- mental stress, mental fatigue, alertness, mental workload and emotional state.

It is expected that the outcome of the research will suggest an IEQ management plan that can contribute to improving the learning environment for the students.

Do I have to take part in this study?

Your participation in this research is your choice. If you decide to participate in the study, you may change your mind and stop participating at any time without penalty or loss of benefits to which you are already entitled.

What are the alternatives to being in this study?

There are no alternatives to being in this study.

Who will have access to my information?

No identifiable information and biospecimen will be collected during the course of the research. The information that will be collected from you would be: your age, height and weight and history of no disorder such as color blindness, neurological disorders, allergy and alcohol addiction. The student conducting the research and the PI will have access to your information.

Can my participation in the study end early?

The research requires the subject to receive sufficient 7 hours of sleep and refrain from drinking alcohol, tobacco, caffeinated drinks or other drinks that can cause excitement or drowsiness, and wash their hair without hair care products before coming to the experiment. Your participation in the study might end early in case these requirements are not fulfilled.

Will I receive any compensation for participating in the study?

You will not receive compensation for participating in the study.

What if I have questions?

Before you decide whether you'd like to participate in this study, please ask any questions that come to mind now. Later, if you have questions about the study, you can contact Dr. Youjin Jang (PI) y.jang@ndsu.edu, or Surakshya Pradhan at surakshya.pradhan@ndsu.edu.

What are my rights as a research participant?

You have rights as a research participant. All research with human participants is reviewed by a committee called the *Institutional Review Board (IRB)* which works to protect your rights and welfare. If you have questions about your rights, an unresolved question, a concern or complaint about this research you may contact the IRB office at 701.231.8995, toll-free at 855-800-6717 or via email (ndsu.irb@ndsu.edu).

Documentation of Informed Consent:

You are freely making a decision whether to be in this research study. Signing this form means that

1. you have read and understood this consent form
2. you have had your questions answered, and
3. you have decided to be in the study.

You will be given a copy of this consent form to keep.

Your signature	Date
Your printed name	Date
Signature of researcher explaining study	Date
Printed name of researcher explaining study	

APPENDIX C : THERMAL PERCEPTION SURVEY

Thermal Perception Survey

Subject no : ___________

Date : ________________ Time:___________________

1. Personal Information

(i) Sex : ☐Male ☐Female ☐Other

(ii) Age : ____

2. Subject's Clothing

Please check the clothing you correspond to at the moment.

Long sleeve- T-shirt or shirt (Thick/Thin)	☐
Short sleeve- T-shirt or shirt	☐
Sleeveless- T-shirt or shirt	☐
Sweater (Thick/ Thin)	☐
Woolen vest (Thick/ Thin)	☐
Coat (Thick/ Thin)	☐
Cotton- padded coat (Thick,/ Thin)	☐
Down Coat (Thick/ Thin)	☐
Outerwear trousers (Thick/ Thin)	☐
Cotton padded trousers	☐
Woolen trousers	☐
Short skirt (Thick/Thin)	☐
One-piece dress	☐
Sport shoes	☐
Leather shoes	☐
Sandals	☐
Hat	☐
Scarf	☐

3. Thermal Perception

(i) How do you feel about the temperature at the moment?

- ☐ Cold
- ☐ Cool
- ☐ Slightly Cool
- ☐ Neutral
- ☐ Slightly Warm
- ☐ Warm
- ☐ Hot

(ii) How comfortable do you feel in the temperature?

- ☐ Very dissatisfied
- ☐ Dissatisfied
- ☐ Slightly dissatisfied
- ☐ Neutral
- ☐ Slightly satisfied
- ☐ Satisfied
- ☐ Very satisfied

(iii) How do you feel about the humidity?

- ☐ Too dry
- ☐ Dry
- ☐ Slightly dry
- ☐ About right
- ☐ Slightly humid
- ☐ Humid
- ☐ Too humid

(iv)How do you feel about the lighting condition?

☐Too bright
☐Slightly bright
☐Bright
☐About right
☐Slightly dim
☐Dim
☐Too dim

(v) How comfortable do you feel in the lighting condition?

☐Very dissatisfied
☐Dissatisfied
☐Slightly dissatisfied
☐Neutral
☐Slightly satisfied
☐Satisfied
☐Very satisfied

(vi) How do you like the thermal indoor environmental condition?

☐Acceptable
☐Unacceptable

(v) Would add or lose an article of clothing in the environmental condition?

☐Lose an article: ____

☐Add an article: ____

Reference

Zhang, Guoqiang, et al. "Thermal Comfort Investigation of Naturally Ventilated Classrooms in Subtropical Region." *Indoor and Built Environment*, vol. 16, no. 2, 2007, pp. 148-158.

APPENDIX D : PARTICIPANT SCREENING QUESTIONNAIRE

Participant Screening Questionnaire

Name: ______________________________

Subject no: ______________________________

Sex: ______________________________

Age: ______________________________

Email: ______________________________

Health Screening

1. Do you have any history of lungs problem?

   ☐ Yes ☐ No

   If yes, explain briefly.

   ____

   ____

2. Do you have a history of heart problem or surgery?

   ☐ Yes ☐ No

   If yes, explain briefly.

   ____

   ____

3. Do you have a history of altered heart rate?

☐ Yes ☐ No

If yes, explain briefly.

____

____

4. Do you have a history of Chest, Neck or Arm pain?

☐ Yes ☐ No

If yes, explain briefly.

____

____

5. Do you have a history of color blindness?

☐ Yes ☐ No

6. Do you have a history of low blood pressure or elevated blood pressure?

☐ Yes ☐ No

If yes, explain briefly.

____

____

7. Do you have any history of neurological disorder?

☐ Yes ☐ No

If yes, list them down.

____

____

8. Do you have a history of any kind of allergy?

☐ Yes ☐ No

If yes, list them down.

____

____

9. Do you smoke or have a history of smoking previously?

☐ Yes ☐ No

10. Do you have a history of alcohol addiction?

☐ Yes ☐ No

APPENDIX E : PARTICIPANT INFORMATION QUESTIONNAIRE

Participant Information Questionnaire

Subject no: ______________________________

Sex: ______________________________

Age: ______________________________

Height: ______________________________

Weight: ______________________________

Health Screening

1. Do you have any history of color blindness?

   ☐ Yes ☐ No

2. Do you have any history of neurological disorder?

   ☐ Yes ☐ No

   If yes, list them down.

   ____

   ____

3. Do you have a history of any kind of allergy?

   ☐ Yes ☐ No

   If yes, list them down.

   ____

   ____

4. Do you have a history of alcohol addiction?

   ☐ Yes ☐ No

Additional Information

5. Did you get sufficient sleep for 7 hours before the day of the experiment?

   ☐ Yes ☐ No

6. If not, how many hours of sleep did you get? ____________________________

7. Did you intake alcohol, tobacco, caffeinated drinks or other drinks that can cause any kind of excitement or drowsiness during the day of the experiment?

   ☐ Yes ☐ No

8. If yes, List down the name and how long before the experiment did you intake.

   ____

   ____

9. Did you wash and dry your hair without hair products before coming to the experiment?

   ☐ Yes ☐ No

10. You are required to wear the same clothes and shoes during the days of the experiment. Are you wearing the same clothes and shoes as the last experiment?

    ☐ Yes ☐ No